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NATIONAL NUCLEAR LABORATORY

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

Assessment Matrix with Descriptions
Version 11

Subject System: EVOL or GIF Molten Salt Fast Reactor

Reference System: GWe-sized LWR

Date of Assessment: 15th September 2014

IDM
integrated decision management

Reference and Subject Systems

Reference System: GWe-sized LWR

Current technology representative modern design as being considered for UK new build.

Subject System: GIF of EVOL MSFR

The EVOL or GIF Molten Salt Fast Reactor (MSFR) chosen because the concept has been developed further than most molten salt concepts and has done so in an international context. It is expected that that the GIF MSFR will be used as the reference system for any future GFA for other molten salt concepts. GIF MSFR is a fast spectrum system with fluoride salt fuel/coolant. GIF MSFR is assumed to operate on the thorium fuel cycle, starting off with donor plutonium/minor actinides.

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Version Development

12.05.2014 – Version 11 with Strategic Attribute titles changed as agreed at MSRGFA Workshop on 25.04.2014

13.05.2014. 'effort' for 'risk' in 'security. Descriptions added to Strategic Attributes, Attributes and Metrics. These are still verbatim from NNL (11) 11491 Issue 3, where they were aimed at scorings and weighting attributes in a MADA. Wording needs to be changed in all of them to reflect current usage.

12.06.2014 During demonstrations of draft assessments, it proved difficult to quickly distinguish 'assessment' pages from 'explanation' pages. Explanation pages therefore coloured light green

22.10.2014 Application of Template 11 to MSR Assessment after taking into account comments by David Martin – for this in previous format see file *2014.09.15 GFA MSR - INCLUDES RESPONSE TO DAVE MARTIN'S COMMENTS - Kevin*

IDM
integrated decision management

What is Generic Feasibility Assessment?

The UK Government and nuclear sector are examining nuclear futures ranging up to 75GWe by 2050, and the potential to involve several reactor and fuel cycle systems in addition to the "once-through LWR" envisaged for the initial 16 GWe tranche of nuclear new build in the UK.

The Generic Feasibility Assessment (GFA) concept seeks to answer the high level strategic question:

"What are the attributes of a nuclear energy system which would justify investment in its future development with view to deployment in the UK?"

If the answer to this question is known, then investment can be focused onto reactors and fuel systems which will meet the energy market need, contribute to decarbonisation of the economy, and benefit the UK in terms of jobs and economic development.

What is Generic Feasibility Assessment?

The concept starts from the recognition that, in the UK context, safety, environmental and proliferation/security attributes are all covered by well-developed regulatory regimes – so that reactor system deployment is not about "*how safe, secure, and environmentally benign*" a system is – but rather how much *time* and *effort* must be expended to allow the system to conform with this tried and tested regulatory framework.

What is Generic Feasibility Assessment?

This leads to five further questions which any system seeking entry into the UK market must answer:

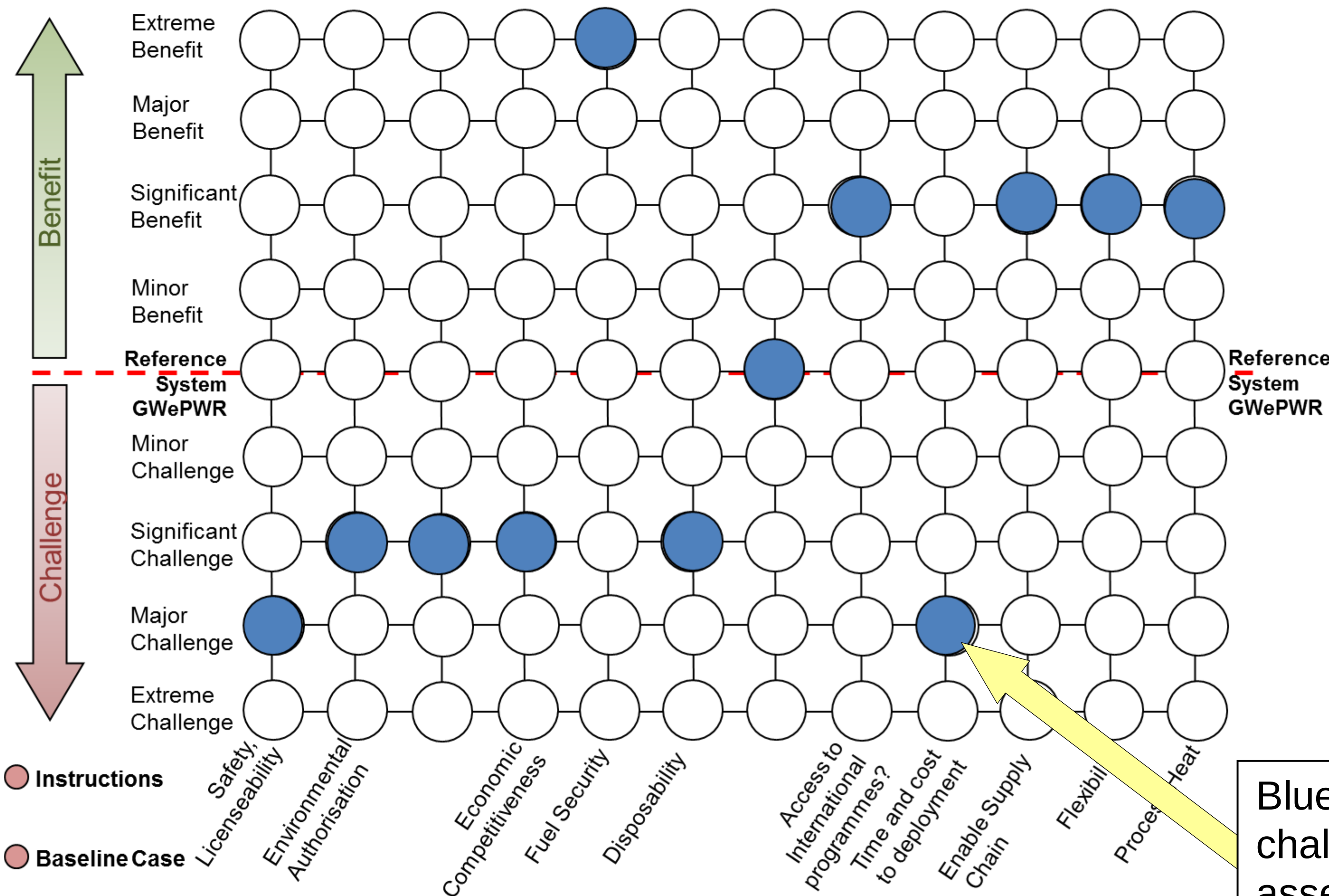
1. How much time and effort will be required to achieve regulatory approvals to deploy this nuclear energy system?
2. Is it likely that the nuclear energy system is capable of being economically competitive with the reference (once-through Pressurised Water Reactor) system?
3. If this system was deployed . . . . . ? (covers fuel supply, waste disposal and reactor/fuel cycle siting issues)
4. Is there a credible path between state-led R&D investment now and private sector deployment in the future?
5. Can it meet market demands (for e.g. flexibility, process heat)

What is Generic Feasibility Assessment?

To answer these 5 questions a system of 12 Strategic Attributes has been derived, which are underpinned by 28 Attributes and 42 metrics. GFA uses an Attribute Matrix, enabling comparison of Candidate Systems against a defined Reference System. A full description of how GFA was derived and developed is available at: www.dalton.manchester.ac.uk/gfa

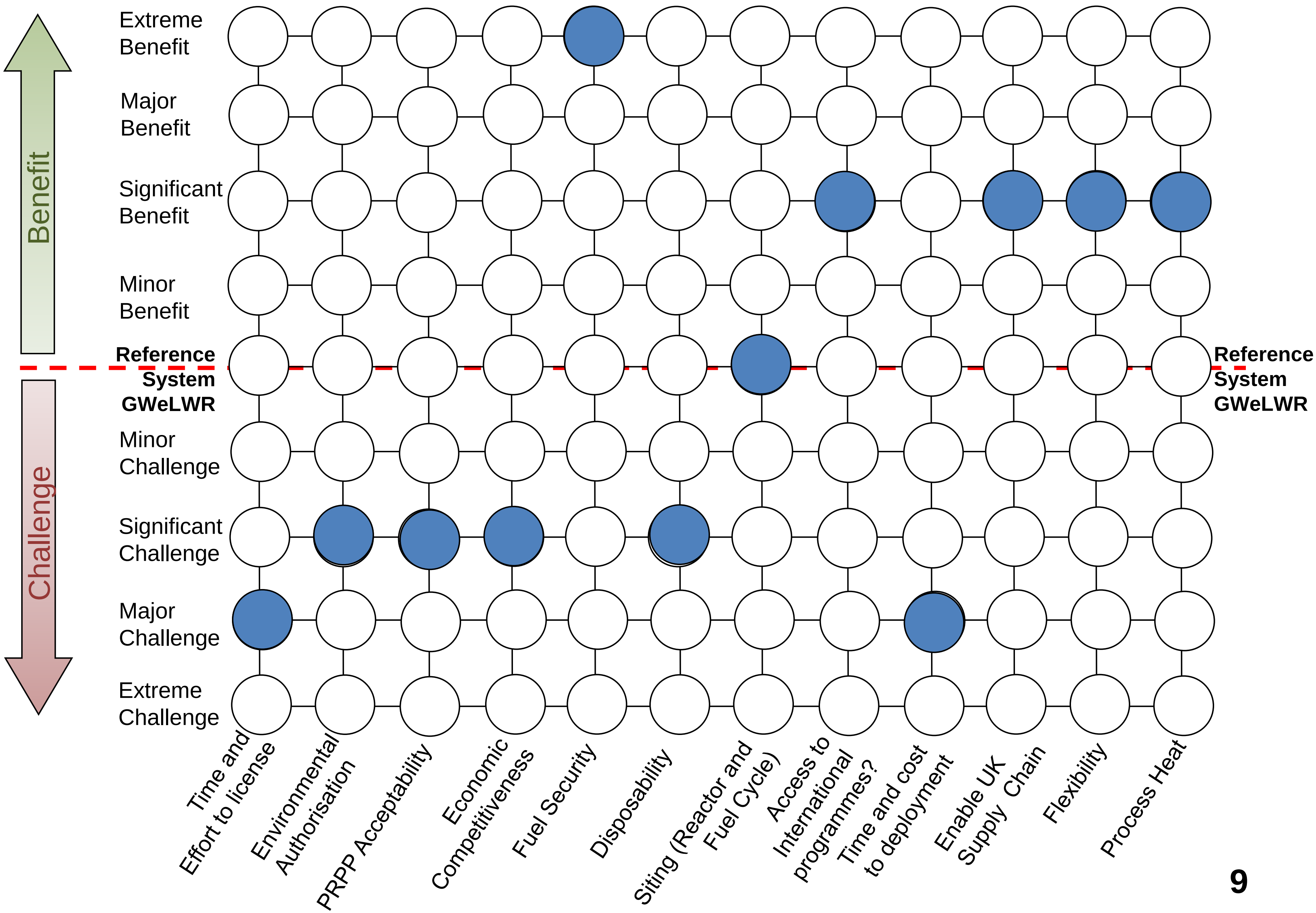
This Visualisation provides a guide to how GFA is built up, the definitions of Strategic Attributes, Attribute and Metrics, and demonstrates how the information and logic tree can be navigated.

GFA Assessment GIF MSFR versus GWe LWR as Reference System *– Work in Progress*



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

GFA Assessment GIF MSFR versus GWe LWR as Reference System – *Work in Progress*



1a. Time and Effort to License

Summary

The overall assessment is that GIF MSFR is at a very early stage of development and that it will pose major challenge to license.

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Description

1a.1 Effort to satisfy ONR Safety Assessment Principles

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

1a.3 Effort to meet radiological regulations

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 ONR's safety assessment principles (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 HSE for workers and members of the public? (Button 1a.3)***

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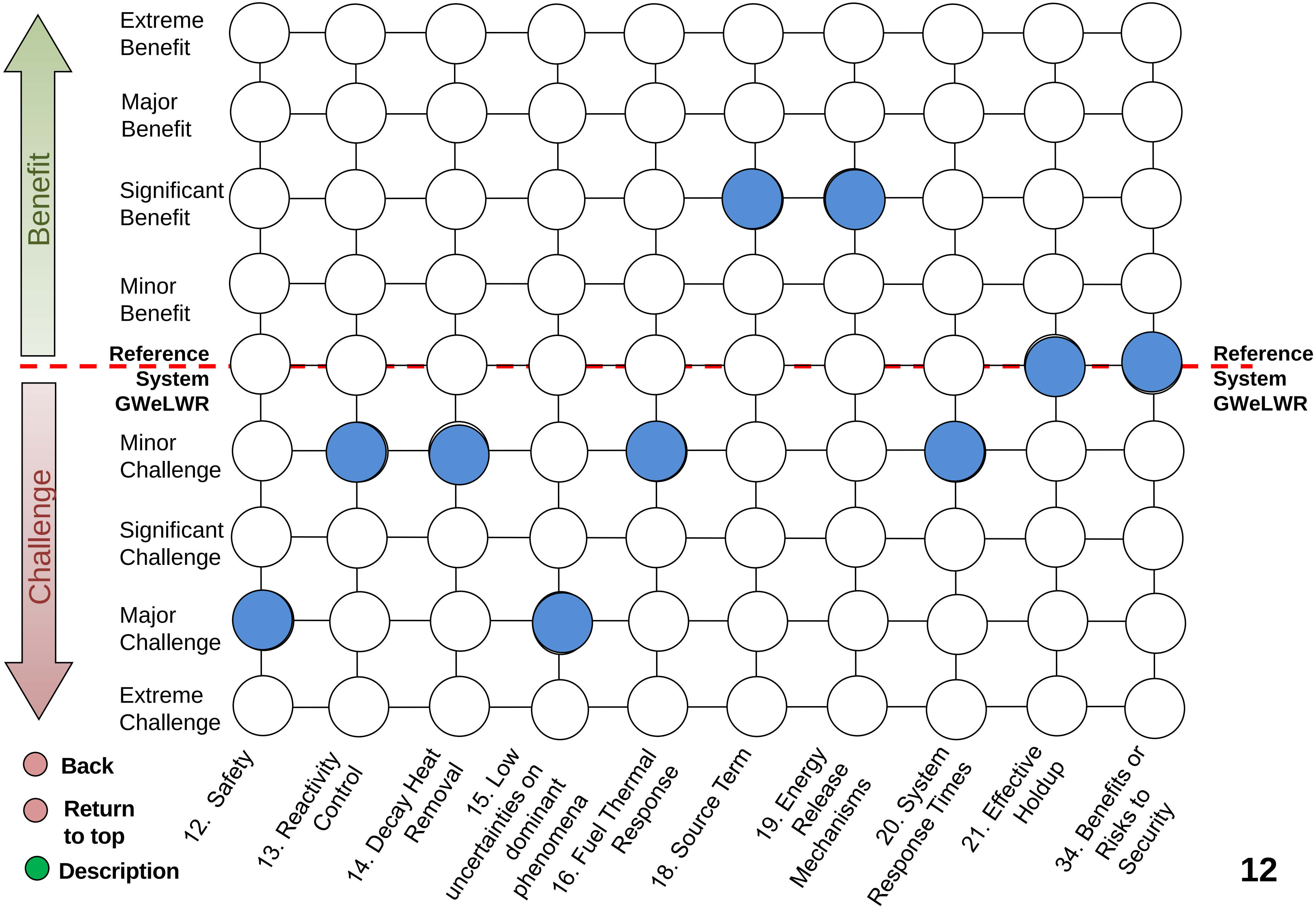
GFA Assessment GIF MSFR versus GWe LWR as Reference System *– Work in Progress*

1a.1 Effort to satisfy ONR Safety Assessment Principles



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Description

1a.1 Effort to satisfy ONR Safety Assessment Principles

1a.1 assesses the challenge faced by a reactor system in meeting the goals defined by the ONR SAPs. Illustrations of levels of challenge are:

LOW - Systems which are already deployed commercially or whose designs are already licensed in other countries.

MEDIUM - Systems which are not yet operating commercially or licensed in other countries that can be considered evolutionary developments of current technologies.

HIGH - Systems which are not yet operating commercially or licensed in other countries that rely on innovative or radical new technologies.

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12. Safety

MSR will require a major re-think of the licensing approach. With no firm designs available, it is too soon to say whether or how this could be done. The best indication to date comes from the conceptual design for the Molten Salt Fast Reactor (GIF MSFR) from Gen IV. This envisages several layers of containment to isolate the molten salt from the environment.

Meltdown accident scenarios are not an issue for a liquid fuel plant. However a coolant leak scenario will be a more significant issue due to the presence of fissile material and fission products within the salt. Molten salts do not undergo violent reactions with air or water, although the use of fluoride compounds can lead to the production of corrosive and toxic HF gas in some scenarios.

12. Safety

Any new reactor system deployed in the UK would need to meet very stringent safety standards and safety would not therefore be a strong discriminator. However, some of the systems considered here rely on passive safety and this might distinguish them from other systems that rely on conventional active safety systems. This is why the discriminating power has been set to medium.

Safety is of high relevance to the UK and would be one of the main areas to be addressed in justifying a new reactor system.

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12. Safety - references

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13. Reactivity Control

Currently, it is not clear how GIF MSFR would meet the basic Safety Assessment Principles (SAPs) for safe shutdown and safe startup. GIF MSFR is currently envisaged as not having control rods and would rely on dumping the core salt to decay tanks to achieve cold shutdown.

In conventional reactors there is a requirement is for a safe controlled approach to criticality and it is not clear how this could be achieved without control rods or other devices (such as moveable reflectors). The SAPs also require the reactor to shutdown (be in a sub-critical state) on demand within a short timescale (usually a few seconds) and it is not clear whether dumping the molten salt to sub-critical tanks would be fast enough. There is also a requirement for cold shutdown to be achievable over a longer timescales and in this case salt dumping would suffice.

It has been cited that GIF MSFR will be controllable through its negative temperature coefficients. However, negative temperature coefficients cannot achieve a sub-critical condition. Conventional reactors rely on negative temperature coefficients for controllability, but not to achieve shutdown.

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References

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. This is why the discriminating power and UK relevance have been set to medium.

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13. Reactivity Control - references

The ORNL Molten Salt Reactor Experiment (MSRE) had three Al_2O_3/Gd_2O_3 control rods, one of which was used for regulation and two for shutdown which would have allowed the conventional start-up and shutdown approaches to be used. The total worth of the three rods was 6.7% Δk.

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14. Decay Heat Removal

The current GIF MSFR conceptual design claims passive decay heat removal, by dumping the core salt in sub-critical tanks and relying on passive mechanisms to remove the decay heat. It does not appear that any of the conceptual designs have yet progressed to detailed engineering assessment of the thermal performance of the tanks, materials and safety.

The dump tanks will have similar engineering requirements to the core spreader in LWR and will require a comparable level of engineering.

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Description

References

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. This is why the discriminating power and relevance have been set to medium.

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14. Decay Heat Removal - references

The ORNL Molten Salt Reactor Experiment (MSRE) had water cooled tanks to contain the fuel salt during shutdowns.

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15. Low uncertainties on dominant phenomena

GIF MSFR is only at the conceptual design stage and the understanding of the materials and engineering fundamentals is not developed. R&D to underpin the fundamentals will determine the minimum time to commercial readiness.

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. Therefore this area is assigned low discriminating power and low relevance to the UK.

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15. Low uncertainties on dominant phenomena - references

The Molten Salt Reactor Experiment (MSRE) was graphite moderated and ran at a low specific rating. Its lifetime load factor was low, so that the accumulated irradiation was only the equivalent of 1 or 2 full power years. These considerations limits its relevance to GIF MSFR.

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16. Fuel Thermal Response

The fuel thermal response for GIF MSFR is comparable to that of LWR. The specific power density of GIF MSFR is 180 MW/m^3 compared with 100 MW/m^3 for LWR. This suggests the fuel thermal response time will be or the order of seconds to minutes. The ORNL Molten Salt Reactor Experiment (MSRE) was low rated (17 MW/m^3) and therefore had a slower fuel thermal response.

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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. Therefore this area is assigned low discriminating power and low relevance to the UK.

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16. Fuel Thermal Response - references

Insert here

18. Source Term

The source term for GIF MSFR will be lower than for conventional reactors because the fission products are actively removed during operation. 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.

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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.

In conventional LWR cores the releasable inventory consists of a small fraction (usually about 1%) of volatile radionuclides such as I-131 that are generated in the fuel. The main inventory of volatile radionuclides is retained in the fuel pellets and is not available for release and only the small fraction that is released from the porosity of the fuel pellets into the fuel rod open volume is available for release.

In some of the systems considered (VHTR), the release fraction would be much lower because of the ceramic fuel used and its high robustness. In other systems, the passive approach to safety is expected to result in no accident sequences within the Design Basis that result in radiological release. In both these cases, off-site evacuation would not be a requirement.

It is for this reason that the source term has been assigned high discriminating power. It is also a topic that is considered of high relevance to the UK.

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18. Source Term - references

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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 GIF MSFR scores highly compared with conventional reactors because of the absence of fuel cladding that can undergo energetic oxidation.

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References

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. Therefore this area is assigned only medium discriminating power and medium relevance to the UK

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19. Energy Release Mechanisms - references

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20. System response times

The system response for GIF MSFR is comparable to that of LWR. For example, the specific power density of GIF MSFR is 180 MW/m^3 compared with 100 MW/m^3 for LWR. This suggests the fuel thermal response time will be or the order of seconds to minutes.

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. Therefore this area is assigned low discriminating power and low relevance to the UK.

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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. Holdup of volatile fission products will depend on the details of the specific design of the containment. There are large uncertainties associated with holdup calculations for GIF MSFR that will require integral systems testing.

21. Effective Holdup

Effective hold-up refers to mechanisms in the design of a plant for containing radioactive material following an accident condition. In LWRs it is normal practice to have either a containment dome or a system of interconnected volumes that can contain steam released in the event of an accident condition leading to a depressurisation of the primary pressure circuit. The containment system is equipped with mechanisms for condensing the steam and preventing further pressure build-up and retaining any radiological inventory. The containment capability is an important input determining whether there is a requirement for off-site evacuation procedures to be in place.

Effective hold-up is a very detailed technical consideration that would not be expected to be a prominent issue in high level assessments such as these. Therefore this area is assigned medium discriminating power and medium relevance to the UK.

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21. Effective Holdup - references

Insert here

34. Benefits or challenges for security

Given the immature design of GIF MSFR, it is difficult to assess the possible benefits or risks for security.

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Description

References

34. Benefits or challenges for security

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

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34. Benefits or challenges for security - references

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1a.2 Timescale required to demonstrate that SAPs 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 GIF MSFR there is currently no expertise within ONR. ONR would require an application for a GDA from an GIF MSFR vendor 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 GIF MSFR vendor 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 competed for GIF MSFR.

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References

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

1a.2 assesses how long it might reasonably be expected to take to demonstrate that the system can satisfy the ONR SAPs. Illustrations of timescales to be expected are:

- SHORT - Systems which are already deployed commercially or whose designs are already licensed in other countries.
- MEDIUM - Systems which are not yet operating commercially or licensed in other countries, if they can be considered evolutionary developments of current technologies.
- LONG - Systems which are not yet operating commercially or licensed in other countries if they rely on innovative technologies.
- VERY LONG - This category is intended for systems deploying very novel, radical technologies that are still at a low Technological Readiness Level (TRL).

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

Insert here

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 GIF 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.

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Description

11. Worker Exposures

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 HSE, noting that this includes the reactor and its fuel cycle. Illustrations of levels of challenge are:

LOW - Systems which are already deployed commercially or whose designs are already licensed in other countries.

MEDIUM - Systems which are not yet operating commercially or licensed in other countries if they can be considered evolutionary developments of current technologies.

HIGH - Systems which are not yet operating commercially or licensed in other countries if they rely on innovative or radical technologies

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1a.3 Effort to meet radiological regulations - references

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11. Worker Exposures

In the absence of engineered designs, it is not possible at this stage to assess the ability of GIF 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.

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

GIF MSFR will be significantly different to current reactors and will require a different approach to environmental authorisation.

Effort to meet environmental regulations

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Description

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, 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.

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1b.1 Effort to meet environmental regulations

This is interpreted as referring to routine environmental discharges.

GIF MSFR incorporates a gas bubbling system that extracts fission gases and traps them for retention. Engineered designs for gas processing systems have yet to be developed. The fission gases are heat producing, so the systems will need to be engineered to reject decay heat. In terms of gaseous emissions, GIF MSFR could be considered to be more akin to a reprocessing plant than a reactor, but with the important difference that it would need to deal with short lived gases that have normally decayed at the time of reprocessing in a conventional system. Tritium production and retention is likely to be a challenging issue, especially for fuel salts based on lithium. The use of ^{7}Li would be a mitigating strategy, though would not entirely eliminate tritium production.

There will also be a solid fission product processing plant for which similar comments apply. The environmental discharges from these plants could represent a major challenge.

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 EA, noting that this includes the reactor and its fuel cycle. Illustrations of levels of challenge are:

LOW - Systems which are already deployed commercially or whose designs are already licensed in other countries.

MEDIUM - Systems which are not yet operating commercially or licensed in other countries if they can be considered evolutionary developments of current technologies.

HIGH - Systems which are not yet operating commercially or licensed in other countries if they rely on innovative or radical technologies.

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1b.1 Effort to meet environmental regulations - references

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06. Environmental Impact

This is interpreted as referring to routine environmental discharges.

GIF MSFR incorporates a gas bubbling system that extracts fission gases and traps them for retention. Engineered designs for gas processing systems have yet to be developed. The fission gases are heat producing, so the systems will need to be engineered to reject decay heat. In terms of gaseous emissions, GIF MSFR could be considered to be more akin to a reprocessing plant than a reactor, but with the important difference that it would need to deal with short lived gases that have normally decayed at the time of reprocessing in a conventional system. Tritium production and retention is likely to be a challenging issue, especially for fuel salts based on lithium. The use of ^{7}Li would be a mitigating strategy, though would not entirely eliminate tritium production.

There will also be a solid fission product processing plant for which similar comments apply. The environmental discharges from these plants could represent a 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.
For these reasons, the discriminating power and UK relevance are assigned medium categorisations.

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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 PRPP assessments. An GIF MSFR operating with a thorium fuel cycle potentially has some advantageous features, but nevertheless might struggle to improve on once-through LWR, given that U-233 is weapons useable.

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Description

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

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

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

GIF MSFR will perform significantly differently to LWRs in respect of separated materials. For the once-through LWR system, there are essentially no separated nuclear materials. For a GIF MSFR with a Th-232 breeder blanket, there is the potential to separate U-233. This is a fissile nuclide with considerable attractiveness for a potential proliferator. U-233 is classified by IAEA in the same category as high enriched uranium (HEU). Unlike plutonium, the fissile fraction of U-233 does not change significantly with irradiation, which is adverse in this context. The presence of ppm concentrations of U-232 is a potential complicating factor for a proliferator, but because work-rounds can be postulated it may not be possible to take full credit for U-232.

07. Separated Materials

37. Proliferation Resistance

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Description

References

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

1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage? 1c.1 (Separated fissile materials form). This attribute accounts for the physical forms of fissile materials in the fuel cycle. Illustrations of levels of challenge are:

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

NO - An LWR fuel cycle with low enriched uranium (LEU) and a once-through fuel cycle

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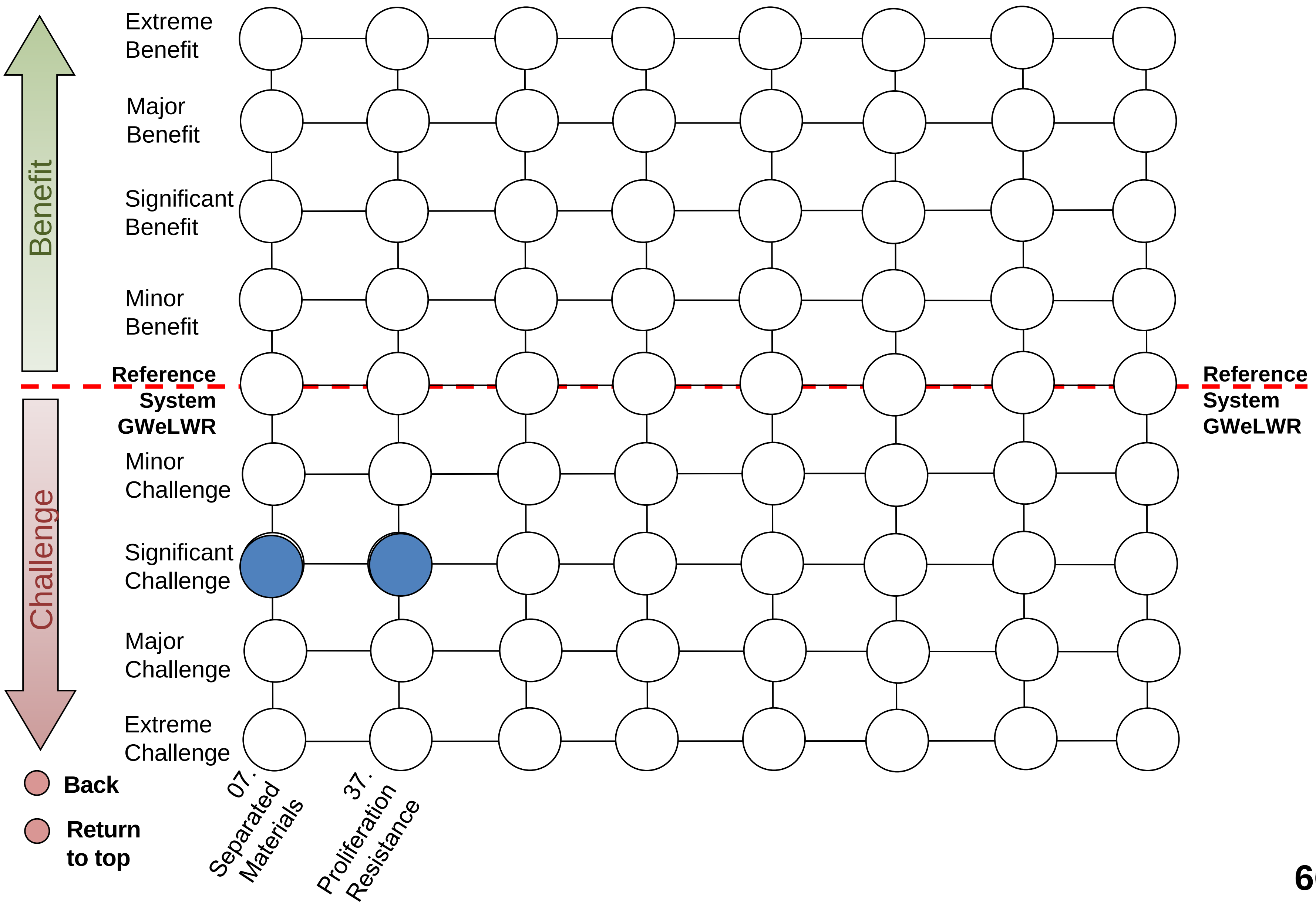
1c.1 Does the fuel cycle involve the production of high grade fissile materials at any stage



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07. Separated Materials

GIF MSFR will perform significantly differently to LWRs in respect of separated materials. For the once-through LWR system, there are essentially no separated nuclear materials. For a GIF MSFR with a Th-232 breeder blanket, there is the potential to separate U-233. This is a fissile nuclide with considerable attractiveness for a potential proliferator. U-233 is classified by IAEA in the same category as high enriched uranium (HEU). Unlike plutonium, the fissile fraction of U-233 does not change significantly with irradiation, which is adverse in this context. The presence of ppm concentrations of U-232 is a potential complicating factor for a proliferator, but because work-rounds can be postulated it may not be possible to take full credit for U-232.

07. Separated Materials

One of the goals of GIF is that the nuclear systems should avoid producing at any stage nuclear materials such as high enriched uranium (HEU), weapons-grade plutonium (WG-Pu) or reactor-grade plutonium (RG-Pu) that could be used (with minimal processing) as the fissile material for a nuclear weapon.

A definitive analysis of the proliferation resistance impact of different separation flowsheets has yet to be carried out, but NNL's judgement is that the discriminating power is likely to be moderate, hence the medium designation against this parameter. Nevertheless, it should be acknowledged that proliferation resistance is a very important political consideration and it is likely that any decision on future UK reactor systems and reprocessing plants will need to address the political sensitivities and this is why relevance to the UK has been assigned high.

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07. Separated Materials - references

Insert here

37. Proliferation Resistance

GIF MSFR will perform significantly differently to LWRs in respect of separated materials. For the once-through LWR system, there are essentially no separated nuclear materials. For a GIF MSFR with a Th-232 breeder blanket, there is the potential to separate U-233. This is a fissile nuclide with considerable attractiveness for a potential proliferator. U-233 is classified by IAEA in the same category as high enriched uranium (HEU). Unlike plutonium, the fissile fraction of U-233 does not change significantly with irradiation, which is adverse in this context. The presence of ppm concentrations of U-232 is a potential complicating factor for a proliferator, but because work-rounds can be postulated it may not be possible to take full credit for U-232.

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37. Proliferation Resistance

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

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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

Commentary required

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Description

08. Spent Fuel Characteristics

09. Sabotage Resistance

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:

YES – Applies to, for example, a once-through fuel cycle with uranium oxide fuel in which there are multiple inherent barriers to accessing fissile material.

NO – Applies to 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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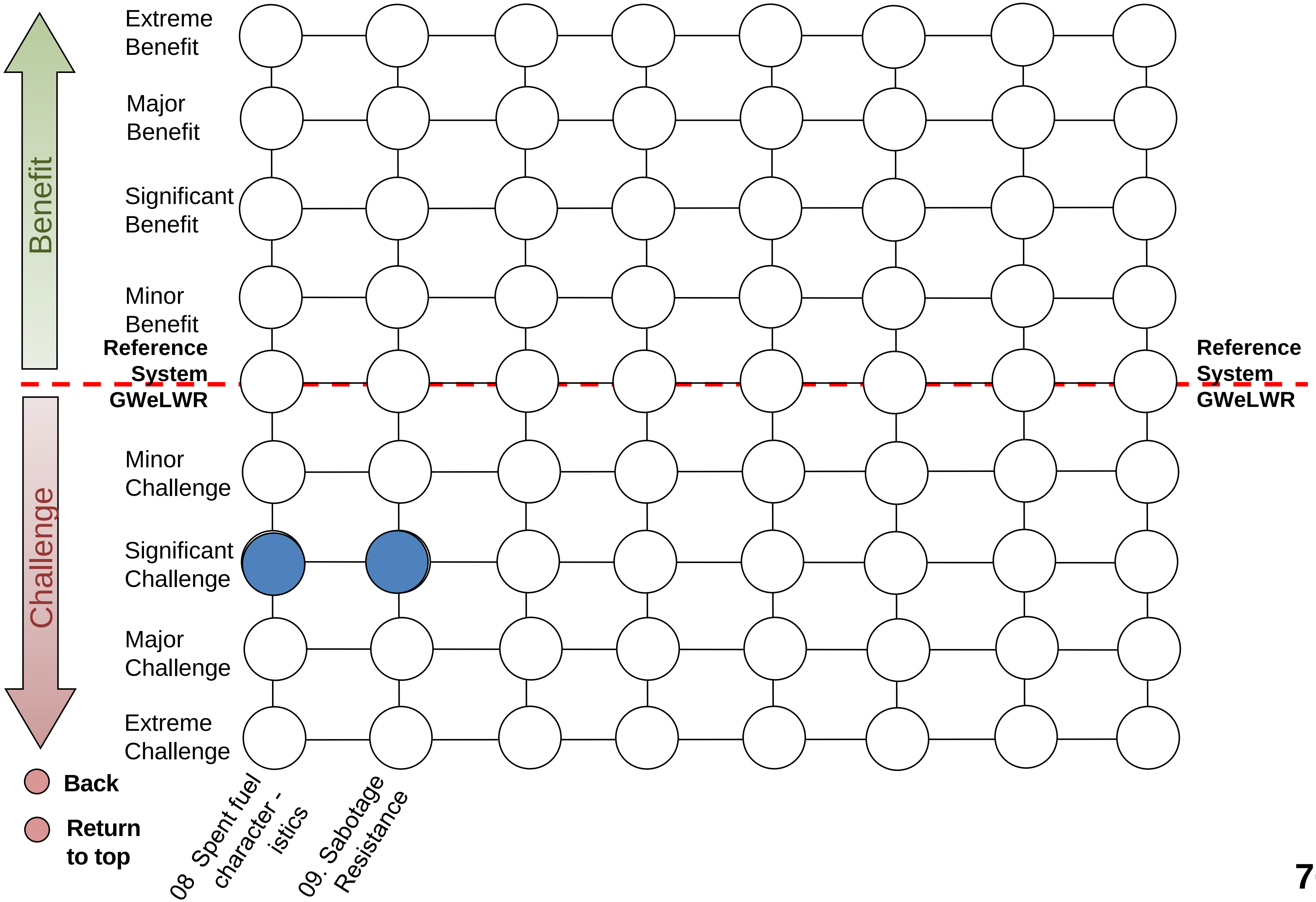
GFA Assessment GIF MSFR versus GWe LWR as Reference System – *Work in Progress*

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



08. Spent fuel characteristics

The is no spent fuel as such in GIF MSFR. The fuel salt is continually processed to remove fission products and is continuously topped up with Th-232. The fuel salt would remain at final shutdown and unless recycled into a follow-on GIF MSFR. If not recycled, the fuel salt would need to be managed in some way, perhaps to remove residual fission products and heavy metals or possibly storage/immobilisation.

The gas and solid fission product separation plants would produce heat producing high level waste that would need to be managed by some means. This might entail long term on-site storage, followed in the longer term by immobilisation and geological disposal.

Engineering design work on fuel salt management and gaseous/solid waste management has not yet been carried out. Significant challenges could be expected.

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References

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.

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

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

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

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

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08. Spent fuel characteristics - references

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09. Sabotage resistance

It is difficult to evaluate in the absence of a detailed engineering design for GIF MSFR. The presence of molten salt containing fission products could be interpreted to be less passively safe than irradiated solid fuel. Multiple levels of containment may be required to demonstrate adequate protection against sabotage, aircraft impact or missile attack.

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 and the discriminating potential between most of the designs would be expected to be low. However, in some of the systems considered (small modular LWRs and Hyperion) the nuclear island is largely sited underground and therefore exceptionally well protected. This is why the discriminating power is set to medium.
Vulnerability to external attack is an area which has come under close scrutiny in the UK and this is why its relevance is set to high.

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09. Sabotage resistance - references

Insert here

2a. Economic Competitiveness

Summary

In the absence of fully engineered designs, it is difficult to comment on the economics of GIF MSFR. The conceptual design emphasises engineering simplicity, but the risk is that the designs will become more complicated as they are developed.

- 2a.1 Overnight construction cost
- 2a.2 Operating and Maintenance cost
- 2a.3 Fuel cycle cost – front and back end combined
- 2a.4 Decommissioning cost
- 2a.5 R&D cost – feed from HLD1

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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.

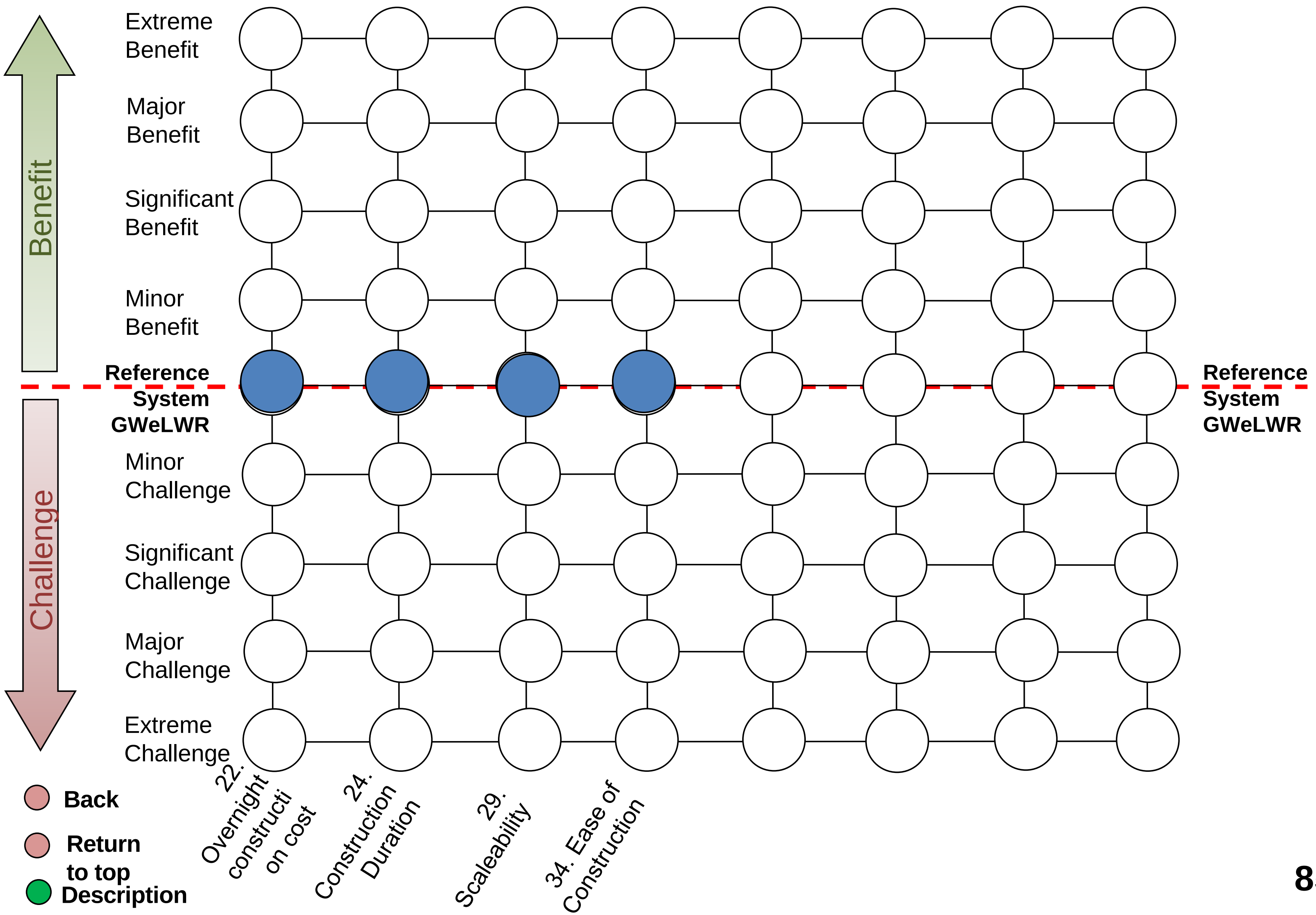
Fuel cycle cost: This criterion is intended to capture the cost of operating the fuel cycle, both procuring new fuel and all the back-end costs associated with spent fuel management or reprocessing/recycle, usually expressed as a levelised cost in £/MWh.

Decommissioning cost: This is the actual cost of decommissioning <u>*without*</u> 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.

GFA Assessment GIF MSFR versus GWe LWR as Reference System – *Work in Progress*

2a.1 Overnight construction cost



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Description

22. Overnight construction cost

To be cost effective compared with conventional reactors, the installed cost per MWe for GIF MSFR should be comparable. Also, the reactor operating lifetime should be comparable and certainly no less than 30 years. With no detailed engineering design available, capital cost projections are best regarded as working targets and credible cost estimates are unlikely to be available for 20 least 20 years.

Considerations such as primary component lifetime will be more important for GIF MSFR because of the difficult of component replacement in high active environment.

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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:

LOW – Plants with a high degree of modularisation and short construction times.

MEDIUM – Plants with a limited degree of modularisation and moderate construction times. This might apply to current large LWRs operating a once-through fuel cycle, for example.

HIGH - 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

For all nuclear plants the detailed breakdown of construction costs is regarded by the reactor vendor as commercially sensitive and must be assumed not available for the GFA. This applies to the projected costs of a reactor that is yet to be built as well as for any reactor that has recently been completed. The best that GFA can achieve is to identify what the generic challenges are.

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24. Construction duration

Not possible to comment in the absence of a detailed engineering design.

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

29. Scaleability

GIF MSFR is a large output plant comparable to current LWR and assumed equivalent in this respect.

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. The discriminating power is not considered high between the different systems and has been set to medium. The potential relevance to the UK is considered medium.

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29. Scaleability - references

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34. Ease of Construction

Not possible to comment in the absence of a detailed engineering design for GIF MSFR.

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.

The SFR, GFR and MSR designs are likely to require large size pressure vessels that may not be compatible with factory construction and modular assembly and are therefore distinguished from the other six designs considered, all of which would be factory built. On this bases the discriminating potential and UK relevance are set to high

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34. Ease of Construction - references

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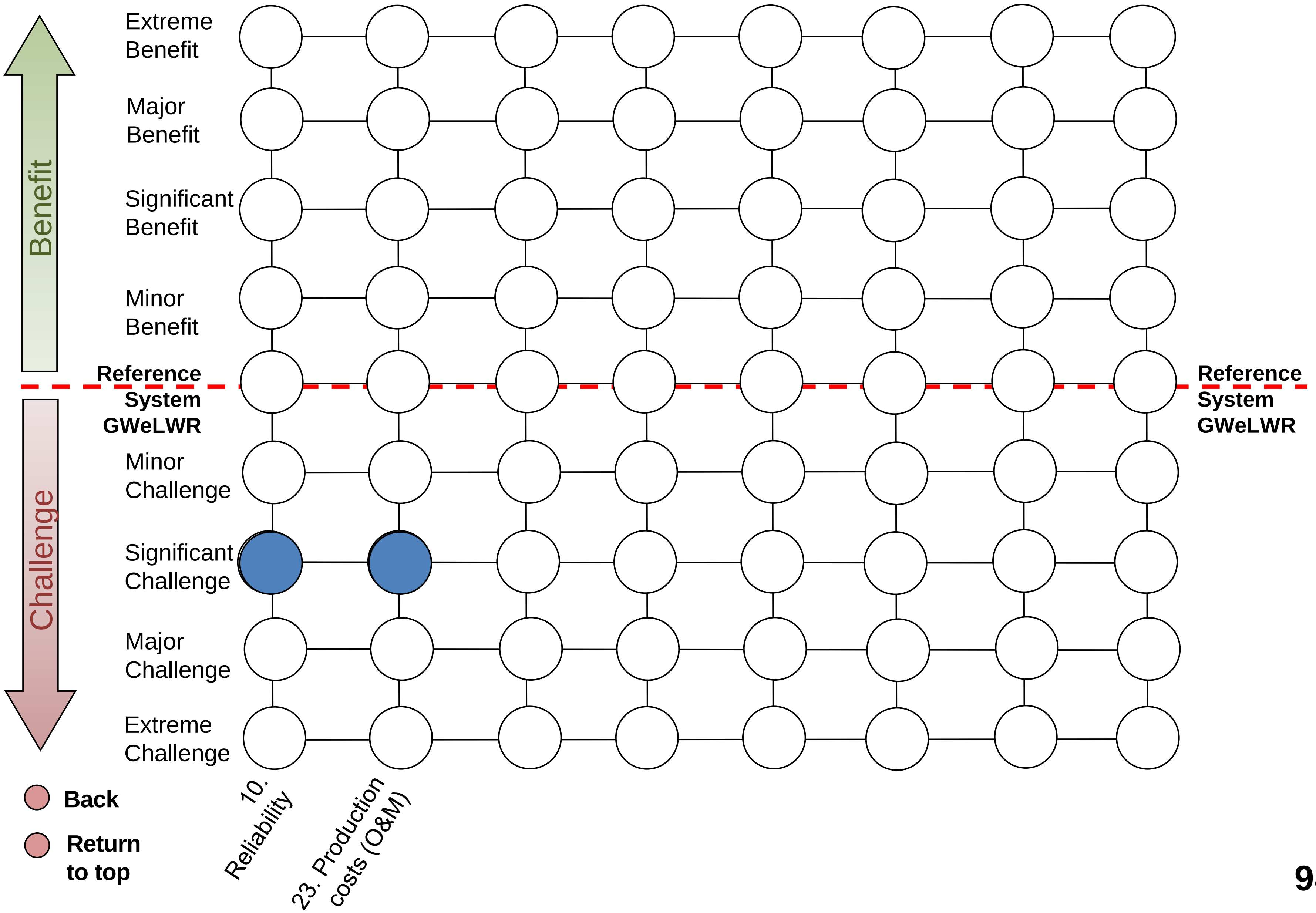
2a.2 Operating and maintenance cost



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10. Reliability

Potential issues for long term reliability of GIF MSFR associated with maintenance/replacement of primary circuit components.

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Description

References

10. Reliability

This is the forced outage rate, which should be very low. It is classified in GIF as an operational safety and reliability issue, but it is also important for economics. Best operational practice at modern LWRs gives spurious reactor trip frequencies considerably less than 1 per year. Forced outages due to equipment failures are rare. For example, in Sizewell B there has only been one significant forced outage in 15 years of operation.

Any new nuclear plant built in the UK would need to be able to demonstrate very low forced outage rates in order to be economically competitive.

All of the systems considered in this report are designed to offer high reliability, though because some are not demonstrated the discriminating power of reliability is rated medium. It is assumed that the UK would only adopt reactor systems that are already mature and proven to be reliable.

The importance of reliability for best operational practice and economics makes its relevance to the UK high.

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10. Reliability - references

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23. Production costs (O&M)

Production costs difficult to comment on in the absence of detailed engineering design for GIF MSFR. Critically dependent on primary circuit component reliability and reliability of solid and gaseous fission product processing plants.

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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. Therefore, there O&M costs have high discriminating power. The economics of nuclear power is key to its deployment in the UK’s competitive electricity market and therefore it is assigned high relevance.

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23. Production costs (O&M) - references

Insert here

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

Difficult to comment on GIF MSFR fuel cycle costs in the absence of engineered designs for the reactor and fission product processing plants. It appears that little thought has been given so far to the management of fission products post-extraction and how these would impact fuel cycle costs. The theoretical advantages of no requirement for fuel fabrication, no uranium ore or enrichment needs to be balanced with the complex requirements to manage fuel salt and fission products.

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 levels of challenge are:

LOW – For example, the once-through LWR fuel cycle

MEDIUM – For example, the closed LWR fuel, cycle (i.e. thermal recycle)

HIGH – For example, a fast reactor system with recycle, especially if there was recycle of minor actinides.

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

Insert here

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2a.4 Decommissioning costs

41. Decommissioning costs

Difficult to comment in the absence of a detailed engineering design for GIF MSFR. Decommissioning of the primary circuit would entail removal of the fuel salt, followed by decontamination and removal of the primary circuit components. The potential for extensive contamination of the primary circuit and its components with fission products and actinides might be expected to severely complicate decommissioning compared with LWR.

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References

2a.4 Decommissioning costs

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

LOW - A nuclear system with small, modular components compatible with disposal as self-contained units.

MEDIUM - Current LWRs where, after defueling, there are only medium active components that need to be decommissioned in the core.

HIGH - Systems with graphite moderation, such as the UK's legacy gas cooled reactors, due to the need to deal with large masses of material.

41. Decommissioning costs

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

2a.4 Decommissioning costs - references

41. Decommissioning costs

MSRE still awaits decommissioning more than 40 years after it ceased operating. The fuel salt remains in place in two drain tanks awaiting immobilisation and final disposal. The fuel salt is solid, but is periodically heated (without melting) to avoid the build-up of fluorine produced by radiolysis. The fuel salt can be considered to be in interim storage, but with active intervention in the form of re-heating, monitoring and inspection. A detailed account can be found in: K J Notz, Decommissioning of the Molten Salt Reactor Experiment – a Techical Evaluation, ORNL/RAP-17, Jan 1988

Decommissioning MSRE is posing a difficult challenge, despite it having had nominal full power output of 8 MWth and accumulated just 1.5 full power years over its lifetime.

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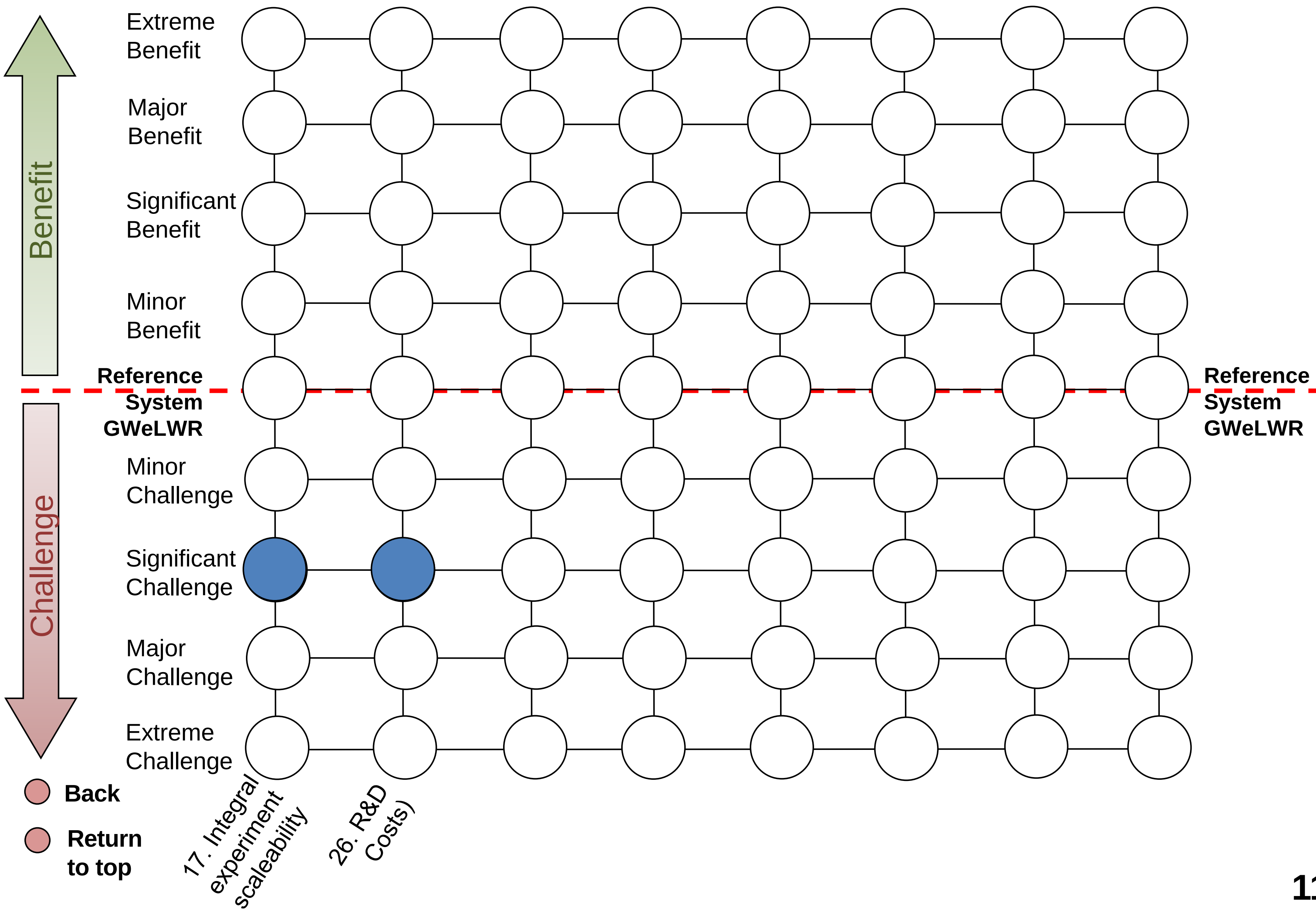
2a.5 R&D cost



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17. Integral experiment scaleability

A comprehensive experimental programme will be required to support the design and licensing of a commercial GIF MSFR. The MSRE experience is a valuable first step, but has limited relevance to a commercial GIF MSFR because it had a small power output, a low power density and only ran for the equivalent of 1.5 full power years.

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References

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.

Integral experiment scalability is important only during the R&D phase and any mature system ready for deployment in the UK would be expected to have already completed this development phase and already be at a High Technology Readiness Level (TRL).

Integral experiment scalability is a very detailed technical consideration that would not be expected to be a prominent issue in high level assessments such as these.

It is assumed that the UK would only adopt reactor systems that are already mature, for which this metric would no longer be relevant. Therefore integral experiment scalability has low discriminating power and low relevance to the UK.

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17. Integral experiment scaleability - references

Insert here

26. R&D costs

GIF MSFR development will incur considerable R&D costs over a long period of time. Government investment will be necessary, since industry is unlikely to be able to bear the expense and risk.

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. In this case the R&D cost would be of low relevance to the UK and low discrimination power.
However, if the UK was to buy into technology that was not being developed elsewhere (such as ADSR), the UK would incur the R&D costs and risks and therefore the discriminating power and UK relevance would be high. To allow for this possibility, this is how the metrics have been assigned.

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26. R&D costs - references

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3a. Fuel Security

Summary

Extreme benefit compared with reference once-through LWR, since in principle GIF MSFR can operate a fuel cycle self-sufficient in fissile material, requiring only a feed of fertile 232Th.

3a.1 Ability to deploy – fissile material availability

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

3a.3 Uranium dependence

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Description

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

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3a.1 Ability to deploy – fissile material availability

In equilibrium operation, a thorium fuelled GIF MSFR breeder would not require any external fissile material and would therefore be self-sustaining, requiring only a feed of fertile 232Th. Compared with the LWR reference system, this is an extreme benefit. External fissile material is needed to start up GIF MSFR and support its operation until it reaches equilibrium. This could be in the form of plutonium or enriched uranium.

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 solid and gaseous fission product waste streams accumulated during operation will need to be immobilised for transport and storage/disposal. The form that these waste streams would take does not appear to be discussed in the literature.

At the end of the life of an GIF MSFR, it is usually assumed that the fuel salt will be recycled into a follow-on generation of GIF MSFRs. Even in this eventuality, the fuel salt will need to be disposed of eventually and the most prudent assumption is that the fuel salt will need to be disposed of at the end of the lifetime of the first generation of GIF MSFRs. The fuel salt would not fit with existing reprocessing or waste management methods and would require a new process route to be developed. No assessment has been made of the compatibility of the final waste form with the GDF.

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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.

YES - Applies for example to conventional spent oxide or metallic fuel, irrespective of whether the main fissile material is uranium or plutonium, because both fuel types are compatible with existing reprocessing technologies.

NO – Applies to unconventional fuels, such as fuels based on thorium matrix or coated particle TRISO fuels (used in high temperature gas reactors) which are incompatible with established reprocessing methods. Fuel which is not straightforward to reprocess represents an intrinsic barrier to accessing fissile material.

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

Extreme benefit compared with reference LWR once a thorium cycle self-sustaining in fissile material is established.

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01. Fuel utilisation
39. Sustainability
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:

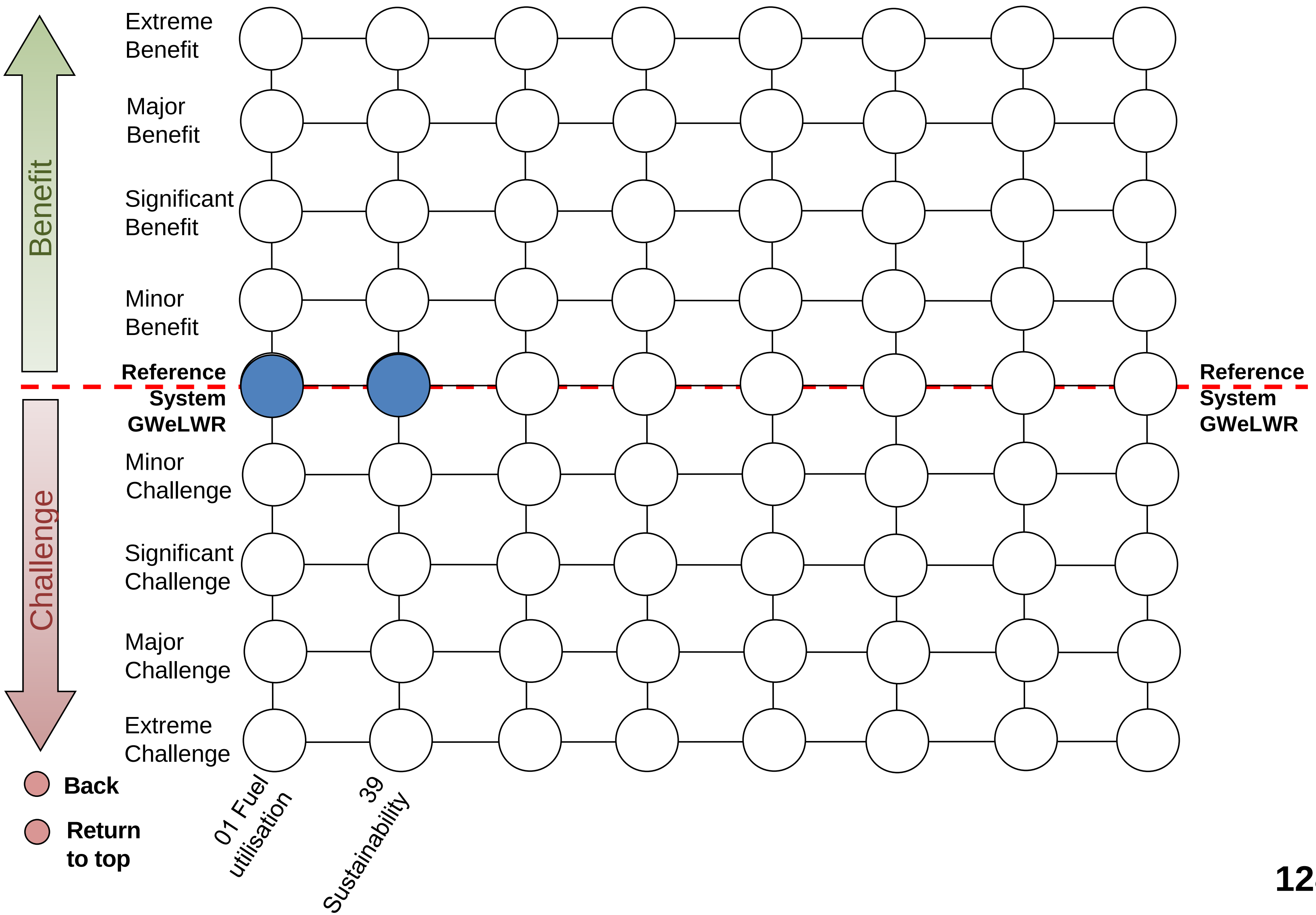
HIGH - LWRs have a specific uranium requirement of approximately 200 tU/GWye. CANDU reactors have a lower specific uranium requirement of approximately 160 tU/GWye.

MEDIUM - 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.

LOW - 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. The upper threshold of 20 tU/GWye is designed to capture systems which are only marginally capable of breeding but that nevertheless would improve by a factor of 10 or more on current LWR and CANDU reactors.

GFA Assessment GIF MSFR versus GWe LWR as Reference System – *Work in Progress*

3a.3 Uranium Dependence



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01. Fuel utilisation

Extreme benefit compared with reference LWR once a thorium cycle self-sustaining in fissile material is established.

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 capable of a self-sustaining (breeding) fuel cycle, with a virtually zero uranium requirement. The discriminating power is high because it is a strong distinguishing factor between the thermal and fast reactor options.

Although fuel utilisation is not considered an important consideration for UK new build in the immediate future, there are scenarios of high world nuclear capacity where it may become a significant issue. This applies particularly to UK scenarios with high nuclear dependence, such as the Level 4 nuclear trajectory postulated in the recent 2050 Pathways Analysis Report published by DECC.

The relevance to the UK is therefore considered high, on account of its potential impact in the medium to long term future.

01. Fuel utilisation - references

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39. Sustainability

Extreme benefit compared with reference LWR once a thorium cycle self-sustaining in fissile material is established.

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References

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. Sustainability is therefore a high discriminator that may at some future date be of high relevance to the UK.

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39. Sustainability - references

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3b. Waste storage and disposability

Summary

Waste storage and disposability are very different from the reference LWR and will require an entirely new fuel cycle infrastructure. Compatibility of the waste forms with the GDF has not been assessed.

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

3b.2 GDF disposal impact – waste incorporation rate

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

3b.4 GDF disposal impact – long term radiotoxicity

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

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Description

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 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.

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

The wastes from GIF MSFR need to assessed for compatibility with current reprocessing technology.

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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. Therefore the attribute has a simple YES/NO allocation:

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

YES – Applies to current reactor technologies that are deployed commercially or evolutionary developments thereof.

NO – Applies to any innovative systems that generate waste forms that are not proven to be compatible with current storage or repository specifications.

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

Insert here

3b.2 GDF disposal impact – waste incorporation rate

Insert here

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.

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

Insert here

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References

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

Waste form volumes from GIF MSFR have not been assessed. The total activity of fission products produced per GWye will be comparable to that of the reference LWR, the main dependence being on thermal efficiency of GIF MSFR.

Solid and gaseous fission products will need to be immobilised for storage and transport. A particular feature of GIF MSFR is that the fission products will need to be processed at virtually zero cooling time and this has implications for short term heat load in the immobilised waste form. There appears to be no discussion in the literature of the waste forms and how they would be managed. The presumption is that the time for which fission products are stored before immobilisation should be minimised to limit the potential hazard. Balancing cooling time and time to immobilisation is likely to pose a major 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.

Back

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

Insert here

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

GIF MSFR will have a lower long term decay heat output than the reference LWR in equilibrium operation due to smaller transuranic inventory. Possible benefits for GDA capacity.

Back
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Description

GDF disposal – long term decay heat

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

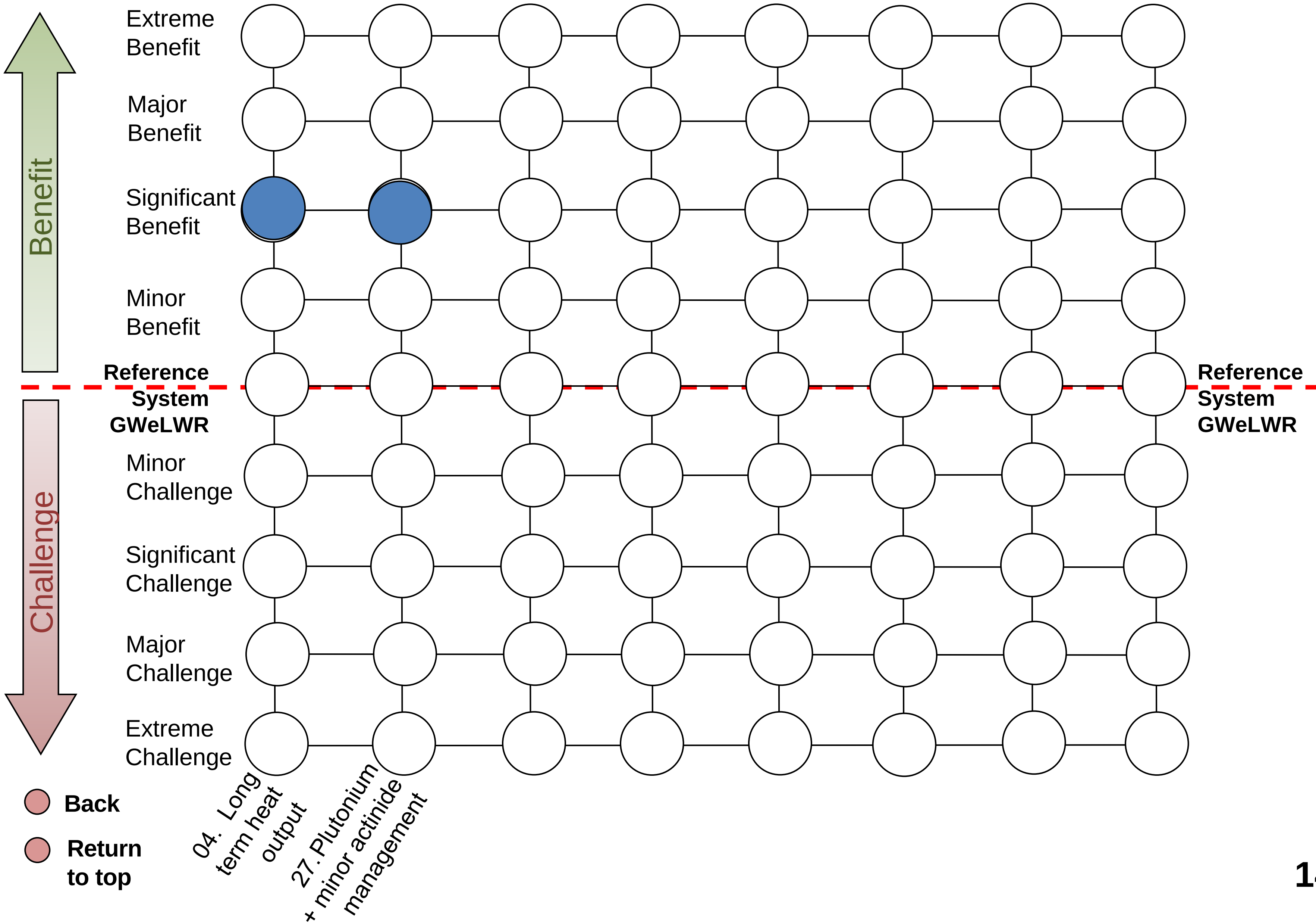
This is a measure of the long term decay heat of spent fuel or high level waste in interim storage pending disposal and in the GDF. Decay heat is important, because it determines how long spent fuel or immobilised high level waste will need to be held in interim storage prior to final disposal. Also, 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.

Back

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



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04. Long term heat output

GIF MSFR will have a lower long term decay heat output than the reference LWR in equilibrium operation due to smaller transuranic inventory. Possible benefits for GDA capacity.

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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.
Because the capacity of the geological disposal for heat generating waste is limited by the heat output, this makes both the discriminating power and relevance to the UK high.
Consideration of long term heat outputs is a complex technical issue and great care is needed to ensure that comparisons between different reactors and fuel cycles are fair and meaningful. Long term heat output will be a major determining factor in the design and justification of a geological disposal facility, which is why the discriminating power and relevance have been set to high.

04. Long term heat output - references

Insert here

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27. Plutonium and minor actinide management

GIF MSFR has the potential to be deployed to irradiate plutonium and minor actinides. The neutron spectrum in GIF MSFR is especially suited for transuranic transmutation. GIF MSFR avoids the need for fuel fabrication and this represents an extreme advantage for GIF MSFR over conventional reactor systems.

27. Plutonium and minor actinide management

Most of the systems considered here are capable in principle of recycling plutonium and some would also be capable of destroying minor actinides (principally neptunium and americium).

Plutonium recycle is potentially very important for UK given the large stock of separated plutonium from historic fuel cycle operations and a capability to irradiate the plutonium and effectively disposition it as spent fuel is of high relevance to the UK. The capabilities of the various systems in this respect are expected to be very similar and only have moderate discriminating power.

There is no immediate interest in the UK in minor actinide management and this situation is not expected to change in the foreseeable future. However, it should not be dismissed as irrelevant to the UK because there is considerable interest internationally and the UK needs to be aware of developments that could potentially result in minor actinide management eventually becoming established as best international practice for sustainable nuclear energy. At the very least, the UK may need to assess minor actinide management as part of the justification process and in would need to be fully informed.

27. Plutonium and minor actinide management - references

Insert here

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3b.4 GDF Disposal Impact – Long Term Radiotoxicity

Insert here

GDF disposal – long term radiotoxicity

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:

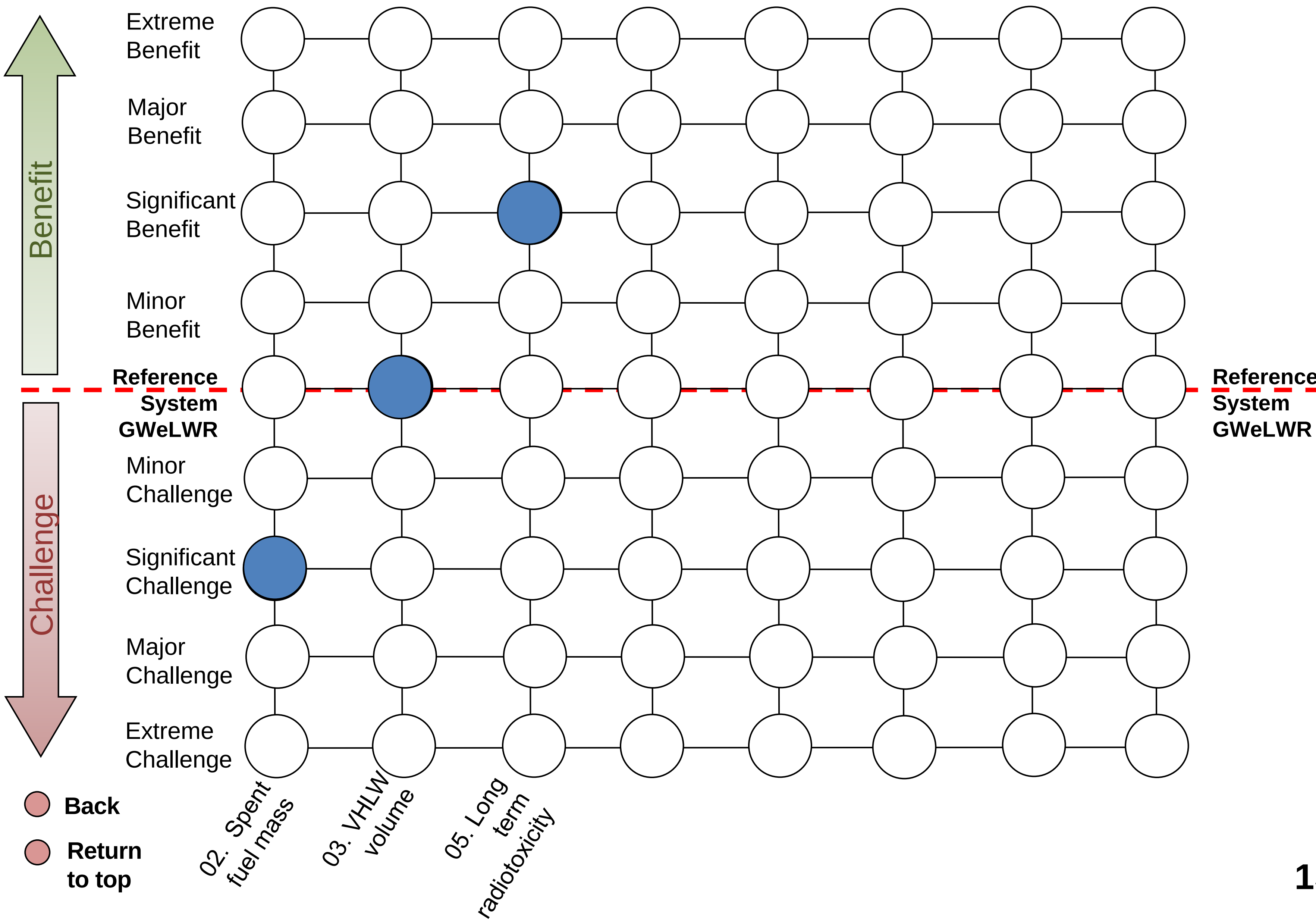
HIGH – Covers uranium or uranium/plutonium fuel assemblies or immobilised high level wastes from thermal reactors such as LWRs.

MEDIUM – Covers 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. Also covers a high converter Th-232/U-233 fuel cycle and possibly the once-through Th-232/U-233 fuel cycle.

LOW – Covers 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.

GFA Assessment GIF MSFR versus GWe LWR as Reference System *– Work in Progress*

3b.4 GDF disposal impact – long term radiotoxicity



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02. Spent fuel mass

There are no spent fuel arisings from GIF MSFR during operation, only gaseous and solid fission product waste streams. At the end of reactor lifetime there will be fuel salt for immobilisation and disposal that takes the place of spent fuel. The mass of fuel salt is essentially just the normal core inventory and this will be divided over the number of years the reactor has operated, so that the volume per GWye will be quite small.

With no spent fuel arisings, GIF MSFR is similar to a conventional reactor in which all the spent fuel is reprocessed and the fission products immobilised. However, this attribute has been assigned to "Significant Challenge" because of the significant differences in fuel cycle plant design requirements compared with current experience.

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).
The spent fuel arising has only low discriminating power for the once-through options, because it is determined by the fuel discharge burnup and the system thermal efficiency and these do not vary greatly.
For the recycle options the spent fuel arising is important only in that it determines the throughput and capacity of reprocessing plants, which again is only a low discriminator.
In the UK, the mass of spent fuel for disposal is not the limiting factors in waste management. The overall relevance to the UK is therefore classified low.

02. Spent fuel mass - references

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03. VHLW volume

The solid waste form volume from GIF MSFR is unknown.

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.

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03. VHLW volume - references

Insert here

05. Long term radiotoxicity

The long term radiotoxicity of GIF MSFR operating a thorium cycle in equilibrium is significantly reduced compared with the reference LWR. This applies for cooling times between approximately 500 years and 1E5 years, when the radiotoxicity of the LWR reference is controlled by the plutonium decay chains. For timescales in excess of 1E5 years, the radiotoxicity of GIF MSFR increases to above the LWR reference, due to the in-growth from the U-233 decay chain.

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Description

References

05. Long term radiotoxicity

The radiotoxicity is a measure of the hazard potential of radioactive material. The most logical units to measure radiotoxicity are in Sieverts (Sv) per GWye, the Sievert being the unit of biological dose, which accounts for energy deposition in biological tissue, weighted by biological damage factors for different tissues, different types of radiation and depending on the retention of different radionuclides in the body.

There are potentially significant differences in radiotoxicity per GWye between the once-through and recycle options, depending on the reactor systems and the specific scenarios considered.

Radiotoxicity is a complex technical issue and great care is needed to ensure that comparisons between different reactors and fuel cycles are fair and meaningful.

Although radiotoxicity is often cited as an important discrimination parameter, its relevance to a geological disposal facility is questionable. The more important consideration for a geological disposal facility is the combination of the radiotoxicities of the different nuclides and their mobilities in the immediate vicinity of the facility and the surrounding geology. The design of a geological repository is influenced primarily by heat load and not radiotoxicity and therefore radiotoxicity is not likely to be a major determining factor in the design of a geological disposal facility

However, in the absence of a specific site for the geological disposal facility, radiotoxicity is often cited as the best available measure and indeed has been used in UK reactor and fuel cycle options studies.

On balance, radiotoxicity is assigned medium discriminating power and medium relevance to the UK

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05. Long term radiotoxicity - references

Insert here

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

A new suggested attribute – as GDF safety cases are generally driven by long-lived mobile fission and activation products rather than by radiotoxicity per se.

Analysis depends on establishing a reference repository.

To be developed

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

A new suggested attribute – as GDF safety cases are generally driven by long-lived mobile fission and activation products rather than by radiotoxicity per se.

Analysis depends on establishing a reference repository.

To be developed

References

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

Insert here

3c. Siting

Summary

Depends on electrical output. GIF MSFR is approximately 1 GWe, so essentially equivalent to reference GWe LWR.

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

3c.2 Siting – associated fuel cycle plants

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Description

3c. Siting

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

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

Insert here

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

SMALL MODULAR – Small modular unit size with possibility of location at sites which would not be suitable for large units.

LARGE UNIT SIZE – Large unit size plants with siting requirements similar to those of current UK power stations.

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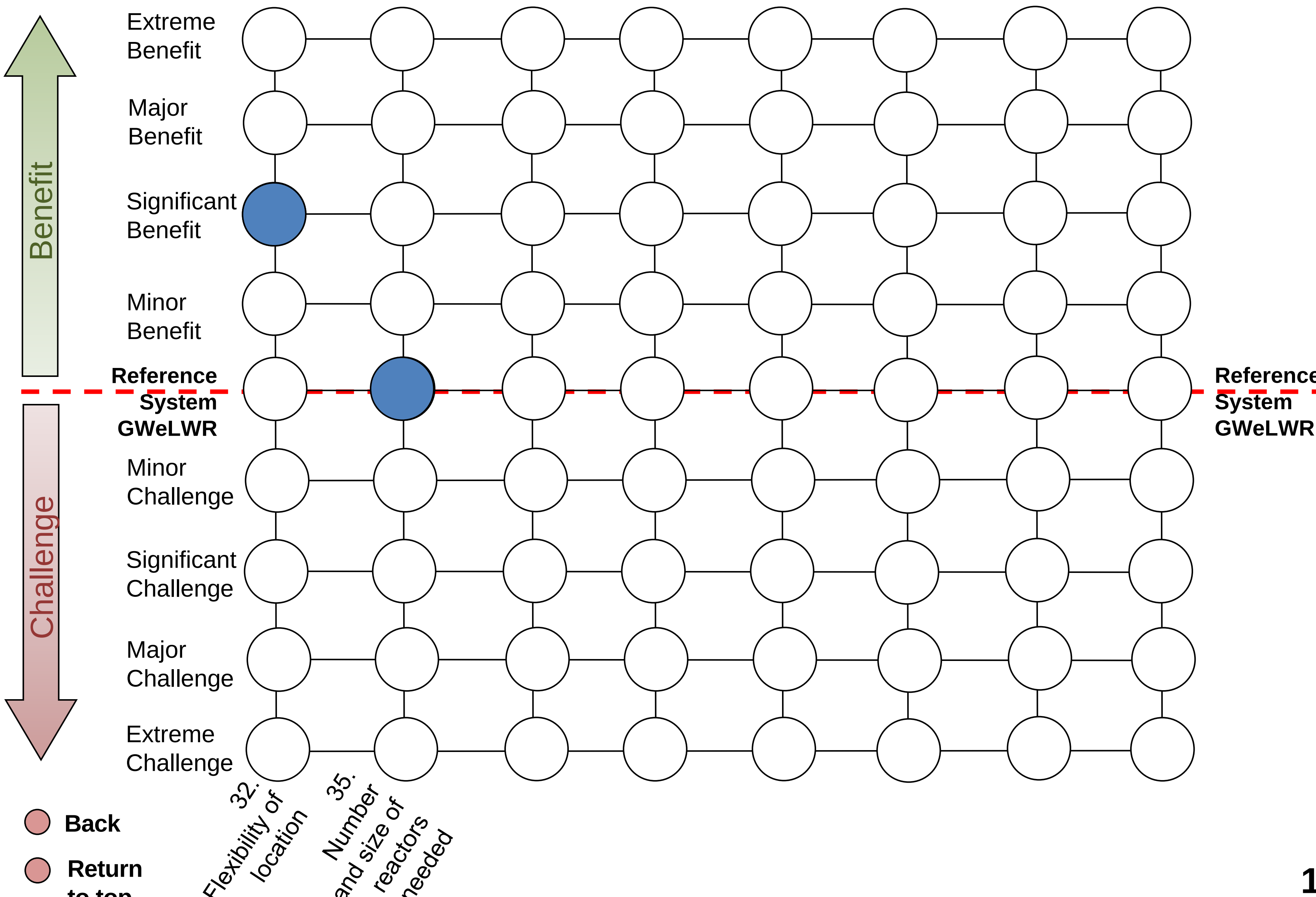
3c.1 Siting – number and size of reactors - references

Insert here

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



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32. Flexibility of location

Depends on electrical output. GIF MSFR is approximately 1 GWe, so essentially equivalent to reference LWR with respect to grid connectivity requirements for electrical production. GIF MSFR has a higher thermal efficiency than the reference and also has the potential to use a Brayton or a supercritical conversion system. These features would reduce cooling water requirements, thereby widening the potential sites.

GIF MSFR is also potentially capable of being used for high temperature process heat applications which is not possible with the reference system, so this is assessed as a "Significant Advantage".

32. Flexibility of location

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

32. Flexibility of location - references

Insert here

35. Number and size of reactors needed

Depends on electrical output. GIF MSFR is approximately 1 GWe, so essentially equivalent to reference LWR.

35. Number and size of reactors needed

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

35. Number and size of reactors needed - references

Insert here

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3c.2 Siting – associated fuel cycle plants

GIF MSFR will require an entirely new fuel cycle infrastructure.

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. Assessments under 3c.2 would examine this siting challenge.

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

Insert here

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36. Fuel cycle plants

GIF MSFR will require an entirely new fuel cycle infrastructure.

36. Fuel cycle plants

The fuel cycle plants needed for the various reactor system options are potentially very different and therefore the associated fuel cycle is potentially a strong discriminator. The requirements of the fuel cycle plants are of high relevance to the UK.

36. Fuel cycle plants - references

Insert here

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4a. Access to international programmes

Strong potential for international collaboration on GIF MSFR through Gen IV or France.

4a.1 Re-engagement in international programmes

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Description

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.1 Re-engagement in international programmes

Insert here

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References

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

Insert here

4b. Time and Cost to Deployment

Summary

GIF MSFR is still at the conceptual stage of development and at a low Technology Readiness Level. Thermal spectrum MSR assessed to be at TRL5, fast spectrum MSR at TRL 2.

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

4b.2 Technology Readiness level

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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.

4b. Time and Cost to Deployment - references

Insert here

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4b.1 Commercial availability – Deployment Time

Estimated minimum 25 years for GIF MSFR. This timescale estimate assumes that GIF MSFR would be developed by a well funded international consortium.

25. Development Costs

30. Timescales to Deployment

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Description

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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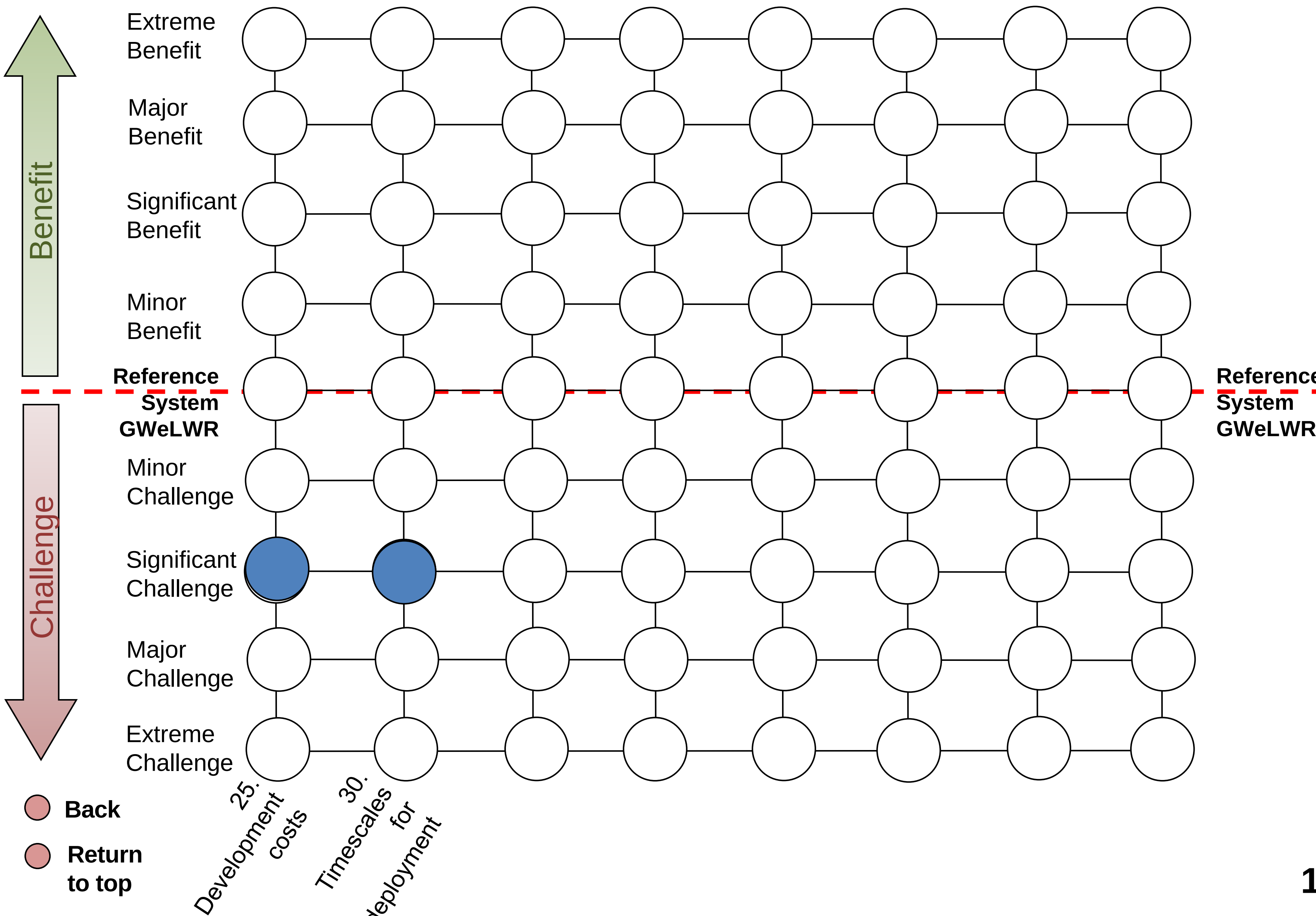
4b.1 Commercial availability



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25. Development costs

Development costs for GIF MSFR will be significant. There would be a requirement for R&D spend sufficient to prepare for a prototype reactor and the costs of designing, building, oeprating and decommissioning the prototype. The prototype could be a small scale version of the eventual commercial design or it could be scaled at the same level as the commercial plant, the decision being governed by the level of exposure to financial risk that was deemed acceptable.

Beyond reach for reactor vendors without help from governments and/or consortia. Would probably demand international collaboration.

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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. In this case the development cost would be of low relevance to the UK and low discrimination power.
However, if the UK was to buy into technology that was not being developed elsewhere (such as ADSR), the UK would incur the developments costs and risks and therefore the discriminating power and UK relevance would be high. To allow for this possibility, this is how the metrics have been assigned.

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25. Development costs - references

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30. Timescales to deployment

Estimated minimum 25 years for GIF MSFR. This timescale estimate assumes that GIF MSFR would be developed by a well funded international consortium.

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Description

References

30. Timescales to deployment

The timescales at which new reactor systems could realistically be deployed is a strong discriminator between the different systems, with some requiring more development than others.
The timescale at which any new system could be deployed would be of high relevance to strategic planning in the UK.

30. Timescales to deployment - references

Insert here

4b.2 Technology Readiness Level

According to the Dalton report (Technology Readiness Level & Technology Readiness Assessment of Gen IV & SMR Systems, NNL (12) 12415 Issue 2 March 2013), Thermal spectrum MSR is assessed to be at TRL 5, while fast spectrum MSR is assessed to be at TRL 2.

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. Example timescales are:

SHORT TERM – applies to systems which are already commercially available and therefore at Technology Readiness Level 9 (TRL 9). Earliest start-up date 7-17 years from today.

MEDIUM TERM – applies to systems which are at a late stage of development (TRL 7-8). Earliest start-up date 17-37 years from today.

LONG TERM – applies to systems which are at an early stage of development (TRL 6 or lower). Earliest start-up date >37 years from today.

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.

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31. Technology Readiness Level

According to the Dalton report (Technology Readiness Level & Technology Readiness Assessment of Gen IV & SMR Systems, NNL (12) 12415 Issue 2 March 2013), Thermal spectrum MSR is assessed to be at TRL 5, while fast spectrum MSR is assessed to be at TRL 2.

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

Back

4b.2 Technology Readiness Level - references

31. Technology Readiness Level

Technology Readiness Level & Technology Readiness Assessment of Gen IV & SMR Systems, NNL (12) 12415 Issue 2 March 2013

4c. Meet and enable UK supply chain

Summary

GIF MSFR presents increased opportunity for UK involvement in the supply chain. Immature designs 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. The UK has experience of laboratory molten salt reprocessing technology, but this experience is of very limited relevance there remain significant challenges for the UK to realise the potential of this technology.

4c.1 Market Failure (to be developed)

4c.2 Supply chain opportunities

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Description

References

4c. Meet and enable UK supply chain

Summary

This Strategic Attribute simply accounts for systems which mitigate against market failure and provide increased opportunities for the UK supply chain. This would provide an incentive for UK involvement in any particular reactor system.

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4c. Meet and enable UK supply chain - references

Insert here

4c.2 Supply chain opportunities

Insert here

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Description

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

Enter here

5a Meets Energy Requirements - load follow capability

The absence of solid fuel with performance limitations is advantageous for GIF MSFR. Whether this advantage is deliverable depends whether there are any other constraints on power cycling. In the reference LWR, fuel and core limitations are the prime determinant of load-follow response and it is likely that a fully engineered GIF MSFR design would provide a significant advantage in this respect.

5a.1 Flexibility – load follow capability

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Description

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.

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5a.1 Flexibility – load follow capability

Insert here

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Description

28 Load follow capability

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.

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28. Load follow capability

Insert here

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

Insert here

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Description

5b. Meets energy requirements – Process Heat

Not relevant to current UK market, but potential for future market to develop. GIF MSFR has a higher temperature output than LWRs and has increased potential for industrial heat processes so is provisionally classified as a significant benefit.

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Description

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

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.

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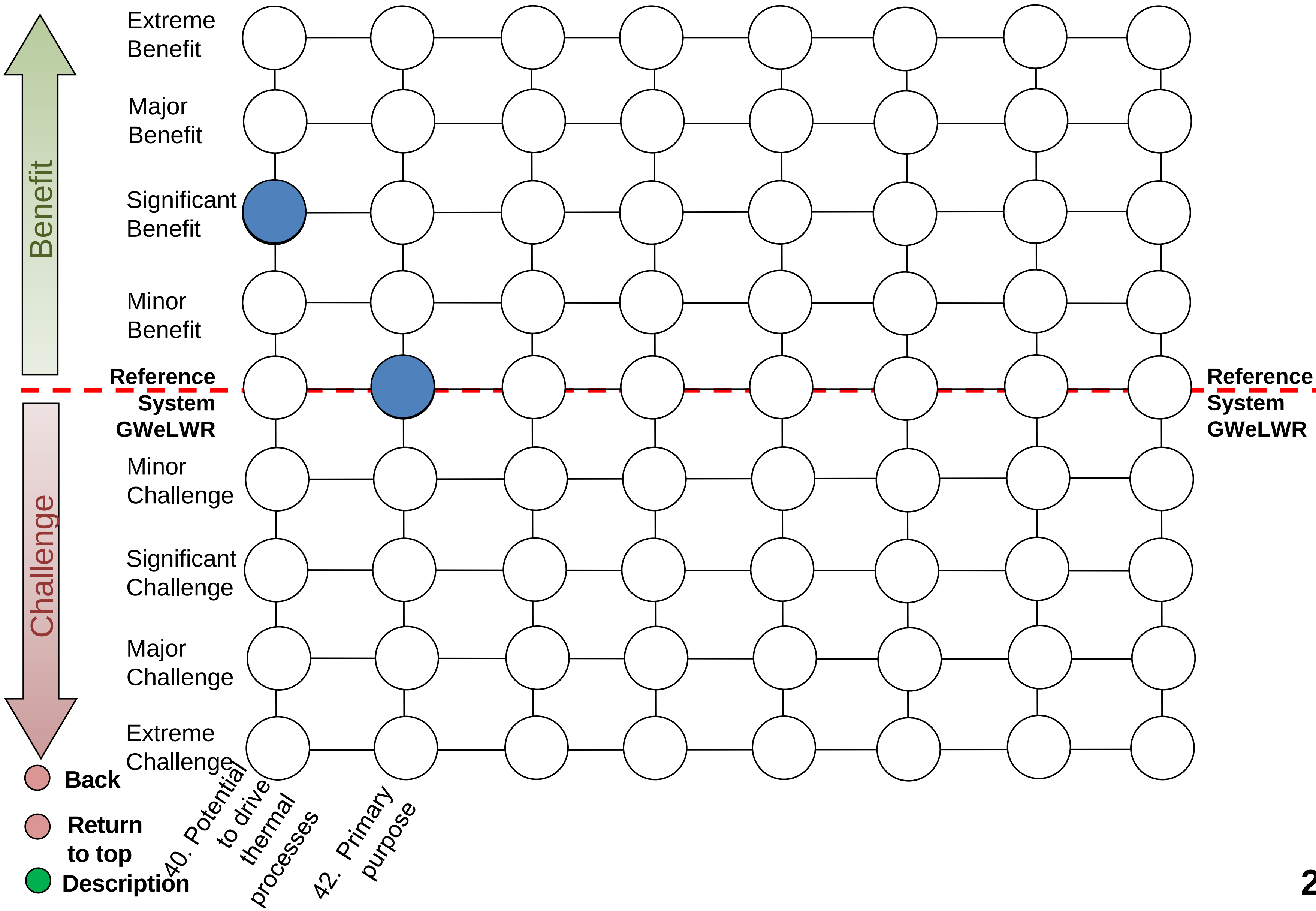
5b.1 Industrial process heat – potential to drive thermal processes



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Description

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.

40. Potential to drive thermal processes

Not relevant to current UK market, but potential for future market to develop. GIF MSFR hasa higher temperature output than LWRs and has increased potential for industrial heat processes so is provisionally classified as a significant 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 of the systems considered (eg GFR, MSR and VHTR) have very primary circuit operating temperatures compatible with high temperature process heat applications. On this basis the discriminating power and UK relevance are set high.

40. Potential to drive thermal processes - references

Insert here

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.

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 that might be relevant in the UK. It is conceivable that if the UK opts to burn its plutonium stocks in reactors that the optimum system choice may be different to the systems chosen for large scale electricity production. On this basis the discriminating power and UK relevance are set high.

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42. Primary purpose - references

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