CoRWM

Committee on Radioactive Waste Management

DEVELOPMENT OF SMALL MODULAR REACTORS AND ADVANCED MODULAR REACTORS – IMPLICATIONS FOR THE MANAGEMENT OF HIGHER ACTIVITY WASTES AND SPENT FUEL

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CORWM POSITION PAPER:

DEVELOPMENT OF SMALL MODULAR REACTORS AND ADVANCED MODULAR REACTORS – IMPLICATIONS FOR THE MANAGEMENT OF HIGHER ACTIVITY WASTES AND SPENT FUEL

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1 Executive Summary

- We are at the start of a new chapter in nuclear technology in England and Wales;
- There is considerable impetus for the development of Small Modular Reactor (SMR) and Advanced Modular Reactor (AMR) designs and their commercial deployment, both for energy security and for environmental reasons, particularly given the historic difficulties of deploying reactors at Gigawatt (GW) scale.
- The management of spent fuel and radioactive waste from these new reactors must also be considered when selecting technologies for investment, further development, construction and operation.
- This must involve addressing the uncertainties about such management at an early stage, to avoid costly mistakes which have been made in the past, by designing reactors without sufficient consideration of how spent fuel and wastes would be managed, and also to provide financial certainty for investors regarding lifetime costs of operation and decommissioning.
- It is essential to know:
    1) the nature and composition of the waste and, in particular, of the spent fuel;
    2) its likely heat generation and activity levels;
    3) how it could feasibly be packaged and its volume; and
    4) when it is likely to arise.
- So far there is little published material from the promoters and developers of new reactor types to demonstrate that they are devoting the necessary level of attention to the waste prospectively arising from SMR/AMRs, on which there has been Parliamentary criticism in respect of similar submarine reactors. The role of Great British Nuclear (GBN) in this respect will no doubt be clarified.

  We have noted however the Rolls-Royce SMR Generic Design Assessment (GDA) submission documents do helpfully include a discussion on optimisation through application of Best Available Techniques (BAT) to prevent the generation, and where this is not possible, minimise the volume and activity of wastes produced, disposed, and discharged and to minimise the consequent impact of such wastes on members of the public and the environment, which we commend.

- There are various mechanisms by which these questions could be addressed in the process of obtaining approval for the new reactors. These are principally:
    1) the process of Justification, which will be mandatory for all new reactor types,
    2) Generic Design Assessment which is optional and non-statutory,
    3) Nuclear site licensing, and
    4) Environmental permitting.

  The last two stages of control may in some cases come too late in the process to allow for effective optimisation of designs and the selection of materials that reduce waste.

  It remains to be seen how effective these mechanisms will be and whether they will occur sufficiently early in the decision-making process to ensure that radioactive waste management is fully and responsibly addressed.
- Clear guidance is needed from government to promoters, regulators, Nuclear Waste Services (NWS) and GBN on the necessity of addressing the cost, safety and environmental issues associated with radioactive waste management at an early stage.
- It is clear that different types of reactor, ranging from those which are very similar to current light water reactors (LWR), through to those using exotic fuels about which little is known, will present highly variable levels of confidence as to how the spent fuel and waste will be managed and ultimately disposed of.
- Even in the case of those reactor types about which most is known, there will still be important operating variables to be clarified. For example, how the reactor is constructed, operated and refuelled in practice will have potentially significant implications for radioactive waste management, including decommissioning wastes.
- In particular, it is not necessarily the case that all types of spent fuel and radioactive waste will be suitable for disposal in a geological disposal facility (GDF), at least without potentially difficult prior treatment processes. Some may simply not be able to achieve the necessary state of passive safety required in a GDF as currently planned, in which case other new options will have to be identified, which may involve treatment or conditioning and which could be expensive, complex and uncertain.
- The government and GBN should make this clear, so as to manage expectations of some vendors and provide clarity to potential investors and potential operators. We do not advocate saying that specific designs should be ruled out, as this is ultimately a question for the developer and investors, but it should be made clear what degree of certainty will be required regarding the proposed approach to and associated costs of the management and disposal of spent fuel and radioactive waste from operation and decommissioning.

- We note that it remains government policy that new nuclear development should only be supported if the government is satisfied that a safe disposal route for the wastes arising exists or will exist.
- Nuclear Waste Services (NWS), has a vital role to play in assessing disposability, as a provider of advice on disposability in Justification and GDA. Early discussion between developers and NWS is advisable but appears to be happening only to a very limited degree at present CoRWM believes that the role of NWS, at early stages of reactor design, should be formalised by clear advice, to encourage early engagement in the process. NWS will need the necessary resources for this task if a number of possible technologies are to be considered in a timely and effective fashion.
- It needs to be clear that it is for developers, not NWS, to present the necessary research findings to demonstrate that the waste can be disposed of safely, which may be extensive. NWS should be informed and consulted on such research and should have full access to the results for the purposes of GDF development and disposability advice.
- It is important that developers of new reactors have sufficient waste management capability and expertise to understand and assess the lifecycle and back-end issues, and to be an intelligent customer where they rely on outside expertise. Where the GDA process is pursued, this should form part of it.
- There is an important issue of timing that needs to be addressed between the emergence of the necessary information on spent fuel and waste from new types of reactor and the GDF development process as currently understood and underway.
- Plainly, this information is not going to be available to enable the implications for the scale and capacity and operating lifetime of the GDF to be made clear before any test of public support (ToPS) for a potential host facility. UK government and NWS need to address how this will be addressed in the ToPS, along with other uncertainties. It is for the government, working with NWS to manage the uncertainties in the inventory for disposal which these new technologies may give rise to.
- These questions will also impact upon the design and safety case of the GDF for the purposes of applying for a development consent order (DCO) as well as other environment and safety consents.
- NWS should consider how these uncertainties will be addressed, for example whether a GDF should be “future proofed” in its design so as to be able to take such wastes as may emerge (assuming they are disposable) or whether a second disposal route for these wastes must be contemplated. These are important questions which will impact the consenting processes and also the financial provision to be made by developers and investors.

2 Introduction

This paper is a consideration of the back-end operations that will be necessary to support small modular reactors (SMRs) and advanced modular reactors (AMRs). The distinction between these two categories is made by the generation and maturity of technology: SMRs are Generation III (Gen III) reactors, while AMRs are Gen IV. By back-end operations, we mean the management and disposal of the spent fuel (SF) and radioactive waste (RW) that will be produced from the operation and decommissioning of SMRs and AMRs, including how that material will be characterised, packaged, made safe through various processing operations such as cementation or vitrification, and stored, whether on site or elsewhere.

There is considerable impetus both internationally and in the UK for the development of SMR and AMR designs and their commercial deployment, both for energy security and environmental reasons, particularly given the difficulties of deploying reactors at GW scale. In many cases this will involve government financial and practical support through Great British Nuclear (GBN) which was put onto a statutory footing by the Energy Act 2023. However, it is crucially important that in the process of supporting and developing these technologies adequate consideration is paid to these back-end operations, to avoid potentially very costly mistakes ad future risks, the consequences of which may fall on UK taxpayers to deal with far into the future. An example is the pursuit of reactor technologies (Magnox and AGR)[1] which resulted in a large stockpile of irradiated graphite in the UK, presenting significant problems of management due to its large volumes and complex and long-lived radionuclides. [2] For example, successful deployment of graphite in 21st century reactors will require careful consideration if such problems are not to be [3]

We note that the conclusions of the Department for Business, Energy and Industrial Strategy (BEIS), now the Department for Energy Security and Net Zero (DESNZ)) public dialogue on advanced nuclear technologies, which found that public support for new nuclear was based on several important provisos, including the necessity for there to be credible solutions to nuclear waste storage and disposal before progressing with the deployment of advanced nuclear.[4]

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[1] For a useful discussion of the issues around the UK's pursuit of these technologies, see Professor Sir Roger Williams, *UK Civil Nuclear Energy: What Lessons?* British Academy Review, Issue 13 (June 2009). See also Martin Forwood, The Legacy of Reprocessing in the UK (International Panel on Fissile Materials, July 2008).

[2] Kun Fu, Meiqian Chen, Shuhong Wei, Xiangbin Zhong, *A comprehensive review on decontamination of irradiated graphite waste.* Journal of Nuclear Materials, Vol 559 (February 2022) 153475

[3] Makuteswara Srinivasam, *Design and manufacture of graphite components for 21st century small modular reactors* Nuclear Engineering and Design Vol 386 (January 2022) 111568.

[4] See https://www.gov.uk/government/publications/public-dialogue-on-advanced-nuclear-technologies-ants

That means exploring six issues which are critical in this regard:

1) establishing the fundamental chemical, physical and radiological properties of the spent fuel (SF) and radioactive waste (RW) that will be produced, and especially the nature of the SF, including its likely physical dimensions, heat generation, fissile properties, radioactivity levels; and chemical composition;
2) establishing the volume of the waste that is likely to be produced and when;
3) how this waste will be conditioned and packaged;
4) clarity on how and where this conditioned and packaged waste will be stored before final disposal;
5) annualised costs of these operations; and
6) how these back-end operations will be financed.

The first three questions are crucial to establishing whether the waste will be disposable within a GDF, and how this will impact upon the design of the GDF.

In turn, numerous important subsidiary questions will arise, such as the role and responsibilities of the Nuclear Decommissioning Authority (NDA) and NWS and the regulators, and subsequent legal requirements of various kinds, such as the relevant planning regulations governing siting. Many of these questions are explored in this paper.

The government's 24 GW(e) nuclear new build ambition has also been supplemented by the announcement of the recent GBN competition for small and advanced modular reactors. A number of consequences arise from this, one of the most important is the inevitable production of RW including Higher Activity Waste (HAW) in greater quantities relative to the presently assessed Inventory for Geological Disposal (IGD).

This waste issue is one that appears, with some exceptions as mentioned in this paper, to have been largely ignored or at least downplayed up to now, in terms of both minimising RW and SF, and creating certainty as to the matters listed above. CoRWM's view is that this needs to change, and that waste management needs to have a significantly greater prominence in the process of bringing forward and developing new designs of SMR and AMR. In particular it needs to be recognised and appreciated that in the case of AMRs, there is a high level of uncertainty regarding whether some wastes and spent fuels will be disposable in a GDF, either at all, or without very costly and complex prior processing. . There are some encouraging signs that this may be changing, and the need to address the issue seems well in the minds of regulators and NWS as the developer of the future GDF. However, in our view, more still needs to be done to give the issue the prominence required.

The government's ambition of 24 GW(e) nuclear capacity raises numerous RW and SF management issues. These include arrangements for interim storage, whether this waste is suitable for currently planned disposal routes and when it might be disposed. This is a wider issue than waste from SMR and AMR and is not addressed specifically in this Paper, but it is an important theme to which CoRWM will be returning, raising as it does the question of capacity for interim storage at Sellafield and elsewhere.

There are many questions to be answered concerning the RW and SF management aspects of the design and operation of SMRs and AMRs. This Paper begins the process of raising them, with the caveat that our knowledge of the reactor designs and their fuel requirements is relatively immature compared with large GW reactors. This induces a high level of uncertainty about the resultant disposability case for some of the fuels that are being proposed (and their waste products). This is not a new problem: in June 1953, Admiral Hyman G. Rickover, of the Reactor Development Division of the US Atomic Energy Commission pointed out the enormous gulf between the theoretical design of reactors and how they are built and operated in practice. Regardless of this high level of uncertainty, CoRWM believes that early consideration of the waste management and disposal aspects of new nuclear technologies is essential. It is a necessary and important step for the process of developing and ultimately approving these new reactor designs to be placed on to a sound basis.

CoRWM also notes that this is a topic which is attracting international interest. The Nuclear Energy Agency (NEA) has recently (October 2023) launched a joint project on Waste Integration for Small and Advanced Reactor Designs (WISARD) which will focus on exploring how front-end and design phase decisions impact back-end strategies to support sustainable future nuclear systems.[5] The project is responding to global interest in innovative fuels, SMRs and AMRs for sustainable nuclear energy. It aims at integration of a sustainable spent fuel and waste management strategy from the very beginning of advanced reactor lifecycles. This is entirely in line with CoRWM's own view and the conclusions expressed in this paper. We also note that Euratom's partnership programme for research and development, the European Joint Programme on Radioactive Waste Management or EURAD-2, includes work on wastes from SMR and AMR. There is an opportunity for the government and GBN to take a leading role in this field and to maximise the prospects of long term societal, economic and environmental benefits that the new technologies could offer.

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[5] https://www.oecd-nea.org/jcms/pl_86832/joint-project-on-waste-integration-for-small-and-advanced-reactor-designs-wisard

3 Acknowledgements

CoRWM shared a final draft of this paper with a number of important stakeholders, all of whom responded with very helpful comments, which greatly assisted in the comprehensiveness and accuracy of the final version, and which strengthened our provisional conclusions.

We are most grateful in that regard to DESNZ, the national devolved administrations, the Office for Nuclear Regulation (ONR), the Environment Agency (EA), Natural Resources Wales (NRW), NWS, the NDA, GBN and Rolls-Royce SMR (RR SMR).

The views expressed are of course our own, as are any errors or omissions.

4 Note

Where in this paper and its recommendations we refer to “government”, we mean His Majesty’s Government of the UK, unless the term is qualified.

This is because new nuclear development is a function reserved to the UK government and GBN is a public body of the UK government, though of course waste management is a devolved matter and devolved administrations have an important role in that regard.

Where we refer to government in the sense of devolved administrations we say so expressly.

5 Policy and Regulation

The prospect of significant new nuclear generating capacity, in the form not only of large-scale reactors (such as those under construction at Hinkley Point C, where the twin unit UK European pressurised water reactor (EPR) will be capable of generating 3,260 MW(e)), but also SMR and possibly AMR, raises the question of whether current regulatory regimes as they stand are entirely suitable for that new programme.

In particular, CoRWM is concerned to avoid the recurrence of decisions which have been made over the long history of nuclear energy in the UK that have resulted in waste streams which pose difficulties of both management and disposal, resulting in significant expenditure and risk which could have been avoided with greater forethought. (see Section 2 above) Experience of the only SMRs in active use in the UK, in the submarine fleet, is not reassuring - with criticism from the Public Accounts Committee of delays in managing radioactive material after end of active service[6] (though we wish to make clear for the avoidance of doubt that currently proposed SMRs are not akin to submarine reactor technology)

CoRWM notes that while policy, as described below, means that the future costs of RW and SF management should be borne by the operator rather than the taxpayer, ultimately those costs are passed through to the utility's customers. There is therefore a public interest in avoiding decisions which would have the effect of increasing costs. In addition, if in future there are issues with higher activity waste (HAW) which were unforeseen and require substantial additional expenditure, perhaps many decades in the future, the reality is that there is a significant risk that such costs would end up being borne by the taxpayer. The probable financial models for some SMR and AMR development, involving private equity for example, may not necessarily lend themselves to long term financial stability.

5.1 Current policy

The draft policy set out in the Policy Consultation on *Managing Radioactive Substances and Nuclear Decommissioning* published in 2023 recognises a difference between SMR, where it seems likely that HAW will be suitable for disposal in a GDF, and AMR, for which some highly active waste streams are known to exist that do not yet have a current treatment, conditioning and disposal route.

This distinction can be summarised as broadly categorising such wastes and spent fuels in a threefold way, more fully described in the technical section which follows:

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[6] "The Ministry of Defence committed to handling its retired nuclear powered liabilities responsibly, disposing of them "as soon as reasonably practicable". This includes removing the irradiated nuclear fuel (defueling), storing the submarines safely, taking out the radioactive parts (dismantling), and then recycling the boat. By 2020, the Department had not yet disposed of any of its 20 submarines retired since 1980, with nine still containing irradiated fuel." (House of Commons Committee of Public Accounts: Submarine defueling and dismantling. (One Hundredth and First Report of Session 2017–19))

1) those which are essentially similar to existing wastes from light water reactors (LWR), where there is a good, but not complete, level of knowledge and confidence as to the properties of the waste;
2) an intermediate category where there are some common features with existing waste, but which may present some novel challenges in terms of disposability; and

those where at present little is known about the waste and its characteristics and where some wastes may well not be disposable in a GDF, or only with great technical difficulty and at great cost and involving a protracted R&D programme to address the uncertainties, perhaps involving decades of research.

In relation to the GDF, the Draft Policy states:

> *54. An important issue that will need to be communicated to the [Host] community will be the inventory for disposal. As set out in chapter 8, paragraph 8.81 the inventory for disposal comprises a number of categories of waste and material. It is not anticipated that those categories of waste and material will change significantly. If, however, the list of waste and materials were to change significantly it would need to be discussed with the Potential Host Community. A process for agreeing any future material changes to the categories of waste to be disposed of in a GDF would need to be agreed before the Test of Public Support.*
>
> *55. In April 2022 the UK Government set out an ambition in its British Energy Security Strategy to increase its plans for deployment of nuclear power to up to 24 gigawatts through large-scale nuclear power stations, small modular reactors (SMRs) and advanced modular reactors (AMRs).*
>
> *56. The waste from a new build programme of large-scale nuclear power stations and SMRs, comprising spent fuel (yet to be declared waste) and ILW not suitable for disposal in near surface facilities will be disposed of in a GDF. Waste from any future AMRs will also be disposed of in a GDF if it is suitable to do so. It would need to undergo an Assessment of Disposability by RWM [now NWS] in support of the regulatory and permitting processes of the ONR and relevant environment agency before a final decision can be taken on whether it will be disposed of in a GDF.*

This important distinction between waste and spent fuel from SMR and AMR accords with CoRWM's own view. The uncertainties noted in the Draft Policy have potentially important implications for the process of taking forward the GDF, in terms of permitting, cost and public acceptance.

5.2 Underlying principles

There are a number of general principles of waste management which are well understood, and which must be applied to the development of new SMR and AMR:

- *Justification*: the benefits from the technology must outweigh the radiological detriment (including that from decommissioning and from managing RW and SF during and after the life of the installation);

- *Optimisation*: the waste should be in such a form as to facilitate disposal and minimise radiological dose, applying principles of Best Available Techniques (BAT) and As Low as Reasonably Practicable (ALARP); and
- *Polluter pays*: the full costs of managing spent fuel and waste, including that arising from decommissioning of the installation, should be borne by the operator (or operators) of the installation. As a corollary, the waste should be in such a form as to allow for reliable and robust provision to be made and to minimise the risk of public funds having to pay the costs. The more exotic or difficult the waste, the more likely this eventuality may be (for example if SF does not meet criteria for passive safety and requires processing to render it suitable for disposal, which itself may lead to residues which present problems regarding disposability).

We should stress that justification and optimisation are not discrete watertight processes and that optimisation should form part of the justification process, as well as underpinning other stages of regulatory oversight.

5.2.1 Justification

This is required by the Justification of Practices Involving Ionising Radiation Regulations 2004. (JoPIIRRs) Guidance on these Regulations (revised in 2023) states:

> *"10. The process of justification requires that before a practice is introduced, it should be shown to give an overall benefit. It is also implicit that all aspects of the practice should be considered. For example, where a practice generates radioactive wastes, the detriments arising from their management need to be taken into account in the justification of the practice."*

The Guidance refers to when new types of nuclear power plant may require separate justification:

> *"26. In the context of the nuclear industry, nuclear power generation represents a very broad generic class or type of practice. However, the benefits and detriments arising from the operation of different designs of nuclear power plants could differ substantially. Where there are such substantial differences, it is unlikely that a single Justification decision could be made. Rather, a decision may need to be made in respect of a particular type of nuclear power plant and the conditions attached to the justification decision would ensure that it applied only to plants of similar designs and having broadly similar benefits and detriments. However, it may be possible to make a single decision in relation to a number of similar reactor designs, each employing particular processes, provided the evidence indicates that the technical differences do not result in major disparities between the scale and balance of the benefits and detriments."*

In line with the Guidance, it is likely that separate justification decisions will be needed for different types of SMR and AMR if the evidence indicates that there are substantial differences in their impacts, arising from their different designs, types of fuels, coolants and technologies. This seems likely to be the case for SMRs and AMRs, which are quite different technologically from previously assessed reactor types, though it may be argued for example that the Westinghouse AP300 SMR design is essentially a smaller version of the AP1000, using much the same technologies, which may make the process more straightforward in being able to rely on findings in relation to the AP1000 design.

It is instructive to consider how the issue of waste has been treated in respect of decisions under the JoPIIRRs of types of large new reactors. There have been three justification decisions for nuclear reactor types; these being the AP1000, the UK EPR and the UK ABWR.

In each decision document there was a chapter dealing with radioactive waste. The decisions note that:

> *"The guidance for Regulatory Justification applications for new nuclear power stations said that applicants should provide information explaining how decommissioning and waste management and disposal would be dealt with, and that an application could cover:*
>
> *• the nature and volume of radioactive waste that could be expected to be produced;*
>
> *• features of the design that facilitate decommissioning; and*
>
> *• mitigation strategies, regulatory arrangements and related assurance to address detriments and risks."*

In the case of the AP1000[7] the decision summarised what the application said about waste as follows:

> *7.13 The Application stated that the operation and eventual decommissioning of new nuclear power stations would add a relatively small volume of radioactive waste to that already requiring management and disposal in the UK.*
>
> *7.14 Higher activity waste and spent fuel would be disposed of in a geological disposal facility (GDF). The Application stated that the impact on the size of such a facility would be determined principally by the quantity of additional spent fuel requiring disposal. It stated that using reasonable assumptions, a programme of 10 gigawatts (electrical) (GW(e)) of new generation could require an increase in the below ground "footprint" of a GDF of the order of 50% based on 60 years' operation of new nuclear power stations.*
>
> *7.15 The Application stated that the types of waste created by the class or type of practice are similar to those already existing and for which management, storage and disposal measures already exist and have either been demonstrated or are in the course of being implemented under Government led processes. The Application stated that there is also considerable and growing international experience to build on. The Application stated that radioactive waste and spent fuel from new nuclear power stations could, if necessary, be stored safely for long periods until a disposal facility became available.*

The government's position on reprocessing of spent fuel from AP1000 reactors was:[8]

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[7] Essentially the same reasoning was given for the EPR.

[8] We note that the position on reprocessing is currently subject to the consultation as part of the draft policy paper Managing Radioactive Substances and Nuclear Decommissioning (DESNZ, 2023). The current draft (para. 7.6) makes clear that proposals for new reactors should proceed on the basis of no

> *7.54 The Government's position is that any new nuclear power stations that might be built in the UK should proceed on the basis that spent fuel will not be reprocessed and that plans for, and financing of, waste management should also proceed on this basis. The Secretary of State has therefore not considered high level waste (HLW), which arises from fuel reprocessing, in this decision document.*
>
> *7.56 The Government's view is that any new nuclear power stations that might be built in the UK should proceed on the basis that spent fuel will not be reprocessed. Therefore the spent fuel from new nuclear power stations would be treated as waste and disposed of in a GDF.*

We would query whether the same assumption as to no reprocessing could be made for all types of AMR which may come forward for justification, some of which as we describe in section 4 below have fuel cycles that *require* reprocessing. This would add an important new dimension to the process.

Ultimately the Justification decision was grounded on the degree of similarity between waste from the AP1000 and that already destined for a GDF:

> *7.62 Based on scientific consensus and international experience, the Secretary of State considers that despite some differences in characteristics, waste and spent fuel from new nuclear power stations would not raise such different technical issues compared with nuclear waste from legacy programmes as to require a different technical solution.*
>
> *7.63 The disposability assessment for the AP1000 conducted by the Nuclear Decommissioning Authority's Radioactive Waste Management Directorate (NDA RWMD) on behalf of Requesting Parties as part of the GDA process supports that conclusion and has concluded that, compared with legacy wastes and existing spent fuel, no new issues arise that challenge the fundamental disposability of the spent fuel expected to arise from operation of the AP1000. This conclusion is supported by the similarity of the wastes to those expected to arise from the existing PWR at Sizewell B. Given a disposal site with suitable characteristics, the spent fuel from the AP1000 is expected to be disposable.*

An assessment of disposability from NWS is therefore crucial to the Justification process:

> *7.64 The Secretary of State has taken note of the Disposability Reports prepared by NDA, and believes it is appropriate to place weight on their conclusions, together with the regulatory work of the EA and HSE through the GDA process. NDA is the organisation tasked with implementing geological disposal in the UK and is also responsible for issuing Letters of Compliance confirming that proposals for conditioning and packaging of higher activity wastes will lead to compliant packages for transport and disposal as currently understood. As such, NDA is an expert in the field of radioactive waste management and the Secretary of State accepts its conclusions as being the most thorough and up-to-date analysis regarding waste from new nuclear power stations in the UK, available at the time of making this decision.*

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reprocessing and that plans, and financing should reflect this. However, reprocessing is not entirely ruled out for new technologies as they are developed to support AMR and it will be for developers to make the case on this, to be considered on the merits.

It is also important to note the scrutiny given to interim storage as part of the justification process. Again, this rested on precedent as to safe storage for the necessary cooling period and until a GDF was ready, and the likelihood of robust arrangements for dry cask storage being developed:

> *7.85 Modern nuclear power stations that are developed internationally include robust spent fuel storage arrangements. Following discharge from the reactor the fuel is required to be cooled, initially in a water-filled pool, as is the case currently at Sizewell B and internationally. The minimum period for storing spent fuel under water is 9 to 12 months, after which dry storage can be considered and internationally the storage of spent fuel in dry casks has become increasingly practised. Common practice for modern PWR designs is for fuel to reside in pool storage only for the period when it is hottest and then for it to be transferred to a dry cask storage system for the remainder of the time required to be stored on site.*
>
> *7.86 Although there are currently no dry fuel stores for PWR spent fuel in the UK, there is considerable international experience which gives confidence that similar stores can be constructed and licensed for operation in the UK. Moreover, British Energy submitted an application in February 2010 for planning consent to construct and operate a dry fuel store at Sizewell B.*[9]

It can be said therefore that justification of a new SMR and AMR reactor type may rest critically on the following issues, such that a very low level of health detriment can be predicted:

1) Absence of need for reprocessing of spent fuel;
2) Compatibility with disposal in a GDF; and there being sufficient capacity within a planned GDF.
3) Robust arrangements for interim storage.

5.2.2 Optimisation

As pointed out above, optimisation is a general principle which should underpin all stages from initial design development, through justification, into the GDA process (if followed) and through to nuclear site licensing and environmental permitting. Apart from justification which has already been discussed, there would appear to be three means by which the design of new reactors can be potentially regulated, so as to optimise the RW and SF produced in terms of their risk and disposability. There is however an issue as to whether their scope and timing will be fully conducive to optimisation. The processes are:

1) through the GDA process;
2) through environmental permitting (EP) for a radioactive substances activity; and
3) through the nuclear site licensing (NSL) process.

Stages 2 and 3 are mandatory statutory processes, whereas GDA is a voluntary process on the part of the promoter of the technology or “requesting party” and the ONR and EA/NRW as

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[9] This has since been built and is in operation.

prospective future regulators. As discussed below, whilst RR SMR is currently going through the GDA process, this is not mandatory and some developers of new reactors many well choose to follow the GDA process only for the first steps, and then proceed to direct licensing and permitting, or not to make use of the GDA process at all.

Whilst the statutory NSL process does undoubtedly allow ONR to exert some control over optimisation in respect of SF and RW, it happens late in the design process when designs are or should be finalised and sites identified. Controls can be exerted through site licence conditions on the generation of waste, in particular LC33 on disposal of waste and LC35 on decommissioning, but we would question whether these in themselves do provide the necessary and sufficient degree of control to ensure that installations are designed and built so as to optimise SF and RW produced, at least in cases where the design has reached an advanced stage.

Similarly, the statutory EP process can contribute to the optimisation process, requiring the application of Radioactive Substances Regulation (RSR) principles which include optimisation and demonstration of BAT by way of the requirements of Schedule 23 of the Environmental Permitting (England and Wales) Regulations 2016 and associated Regulatory Guidance. Techniques in the context of BAT include both the technology used and how it is operated. The difficulty is that whilst an application for EP may be made early before construction begins and a final investment decision is made, timing is a matter for the operator, and unless the design of the reactor has previously been subject to optimisation, the techniques available at the EP stage may be constrained.

The GDA process would appear on the face of it, to provide an earlier stage of regulatory oversight, but it is a voluntary, non-statutory process and whilst it is in principle open to all developers, it is by no means clear that all types of new reactor would be subject to it. The process does include waste management, but the full level of detail necessary is unlikely to be provided until the final GDA stage of detailed assessment (Step 3), though fundamental matters affecting acceptability of the design should be identified during Step 2 and it is encouraging that revised guidance on GDA for requesting parties issued in October 2023 makes clear that even at Step 1 there must be a plan as to how to engage with NWS in preparation for the expert review process in Step 2. The government guidance on Entry to GDA for Advanced Nuclear Technologies (December 2022, revised July 2023) states:

> *"The modernised GDA has 3 Steps for ONR and EA to conduct the assessment. The scope and content for each step is detailed in the Regulators' guidance. The 3 steps are:*
>
> *• Step 1 initiates GDA and is where matters such as the scope and timescales are agreed, and ONR's and the Environment Agency's knowledge of the design and the RP's safety, security and environment cases increase. Importantly this step includes the RP identifying any immediate gaps in meeting regulatory expectations and proposing how these will be subsequently resolved. The outcome of Step 1 is a Step 1 Statement which sets out the agreed scope and expectations for the subsequent GDA steps.*

> *• Step 2 is the fundamental assessment of the generic safety, security, and environment protection cases, to identify any potential 'show-stoppers' that may preclude deployment of the design. The outcome of Step 2 is a formal statement of the Regulators' findings – the GDA Step 2 Statement.*
>
> *• Step 3 is the detailed assessment of the generic safety, security, and environment protection cases on a sampling basis. The outcome of Step 3 can be either DAC & SoDA as available in previous GDAs for NPPs, or a Step 3 Statement of Regulators' findings depending upon the GDA scope agreed in Step 1, or an interim DAC and interim SoDA."*

However, notably that Guidance contains no reference to the issue of waste.

Guidance from the Environment Agency (EA) to requesting parties, as revised in October 2023, more helpfully makes clear that the environmental case submitted for GDA must include information on waste arisings, in terms of quantity, nature and disposal route, and must address the use of best available techniques (BAT) for optimisation of waste:

> *"The optimisation process for BAT should take account of:*
>
> - *the technology to be used and the way the facility is designed and will be built, maintained, operated and dismantled*
> - *the wastes arising throughout the lifetime of the facility, including more challenging wastes*
> - *the potential radiological impact of wastes on people and the environment and how this is used to prioritise optimisation of design*
> - *preventing and minimising (in terms of radioactivity) the creation of radioactive waste*
> - *minimising (in terms of radioactivity) discharges of gaseous and aqueous radioactive wastes*
> - *minimising the impact of those discharges on people, and adequately protecting other species*
> - *minimising (in terms of mass and volume) solid and non-aqueous liquid radioactive wastes and spent fuel*
> - *selecting optimal disposal routes (taking account of the waste hierarchy and the proximity principle) for those wastes*
> - *the suitability for disposal of any wastes and spent fuel for which there is no currently available disposal route and how they will be managed in the interim so as not to prejudice their ultimate disposal (this should take account of the view of NWS on the disposability of such wastes and spent fuel)*
> - *the full range of anticipated feeds into the radioactive waste management system consistent with the Source Term* [10]

The EA will apply the RSR objective and principles to the process: Principles 2 (Optimisation), 7 (Lifetime Planning for Radioactive Substances), 8 (BAT) and 10 (Polluter Pays) are all relevant.

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[10] Source term refers to the magnitude and mix of the radionuclides released from the fuel, expressed as fractions of the fission product inventory in the fuel, as well as their physical and chemical form, and the timing of their release.

Also relevant are the Radioactive Substances Management Developed Principles (RSMDP) in particular on BAT to minimise waste and to minimise environmental risk and impact. There is accordingly no shortage of guidance.

Similarly, the Office for Nuclear Regulation (ONR) Technical Guidance on the GDA process (para. 429) emphasises the importance of waste management issues in the process:

> *Demonstration of safe management of radioactive wastes (including HAW) and of long-term interim storage of spent fuel, including suitable and sufficient design features to support management:*
>
> - *Minimisation of generation (including the wastes arising from decommissioning).*
> - *Application of the waste management hierarchy.*
> - *Minimisation of accumulation.*
> - *Control and containment (including prevention of leakage and escape).*
> - *Characterisation and segregation.*
> - *Storage.*
> - *Condition monitoring and inspection.*
> - *Disposal using available and planned disposal routes ("disposability").*

The RR SMR entered Step 2 in April 2023, which will be when the first technical assessment takes place, and the EA (with NRW as partner regulator) and ONR as regulators focus on what features and arrangements are in place to protect people and the environment. This includes looking at how the design can be optimised to reduce the amount of radioactive waste and spent fuel produced and how that waste and spent fuel is managed and disposed of. This process may therefore be regarded as setting a benchmark for future reactor types, and will, we hope, be rigorous.

It appears, from discussions we have had with the regulators and RR SMR, that the issue of SF and RW is being treated seriously. It is notable that the RR SMR is the first reactor to go through GDA where the design is developing in parallel with the GDA process and significant optioneering is taking place, for example on design and materials selection. Other SMR or AMR developers may not of course be in the same position if a design has already been finalised and commercialised overseas.

We have noted that RR SMR has already sent an initial disposability case to the EA and that feedback from EA is at the time of writing awaited. We have also noted that the GDA submission documents by RR SMR do helpfully include a discussion on optimisation through application of BAT to prevent the generation, and where this is not possible, minimise the volume and activity of wastes produced, disposed, and discharged and to minimise the consequent impact of such wastes on members of the public and the environment, an approach which we commend. The Executive Summary reads:

> *"Application of Best Available Techniques (BAT) to prevent the generation, and where this is not possible, minimise the volume and activity of wastes produced, disposed, and discharged and to minimise the consequent impact of such wastes on members of the public and the environment, is a fundamental objective of the Rolls-Royce Small Modular Reactor (RR SMR) and a UK regulatory requirement for all industrial processes. This*

> *document describes a methodology for the optimisation of the RR SMR through the application of BAT during the design stage and describes a proportionate approach for the subsequent demonstration of BAT in the RR SMR design. It draws upon relevant guidance and establishes good practice on the application of BAT within the nuclear industry. The methodology for gathering and evaluating BAT options has been aligned with, and integrated, into the design decision process for the RR SMR to allow a holistic consideration and optimisation of all the key factors influencing design decisions and the approach to demonstrating the application of BAT is structured upon the claims-arguments-evidence model. The RR SMR key design principles and assessment criteria, explicitly incorporate criterion on environment, safety and security alongside technical feasibility, cost, and market factors. These criteria are aligned with The United Nations Sustainable Development Goals (SDGs) and the goals of the Wellbeing of Future Generations (Wales) Act and have been incorporated into the RR SMR design process through the Decision Record Template. Development of the RR SMR from an early concept design to a fully developed power station design presents a unique opportunity to develop a design that embeds the principles of ALARP, BAT and Secure-by-Design at a fundamental level from the outset. These principles are consistent with global good practice and incorporating them into the RR SMR design will improve its compliance with regulatory requirements across different jurisdictions around the globe."*

Another important issue for GDA is operator competency. We note from the EA's Statement of Findings at the end of Step 1 of the Rolls Royce SMR that competency in fuel management is a necessary issue to be addressed at Step 2 (emphasis added):

> *"We noted that some organisational and management arrangements were still being implemented, and the working arrangements are still evolving, for example, in relation to:*
>
> - *arrangements for managing changes to the design and E3S case*
> - *record-keeping in relation to design development, governance and review*
> - *a formal risk management process within the IMS [Integrated Management System]*
> - *<u>intelligent customer capabilities for specifying and managing technical service contracts supporting GDA activities</u>*
> - *<u>full implementation of competency and capacity arrangements (noting that the Requesting Party's use of 'skills assured' for its competency management framework appears to us to represent good practice)</u>*
>
> *Rolls-Royce SMR Ltd plans to address these gaps during the early stages of Step 2."*

This seems important to CoRWM because there is a potentially serious skills shortage in respect of back-end and waste management technologies in the context of new reactors as we discuss below.

It is vital in our view that those developing the technologies be incentivised to invest in the development of the expertise and knowledge base required and it is encouraging that RR SMR are doing so. Including the issue within the GDA process could be one way of doing this, though of course the process is not statutory.

5.3 Funding / Polluter Pays

It is clear government policy that the full costs of disposing of radioactive waste and spent fuel from new nuclear power stations is to be borne by the operator, including both interim storage and disposal in a GDF, or other final disposal facility. The same goes for the cost of decommissioning the facility itself and dealing with the wastes arising. This is in contrast to nuclear power stations developed by the state, such as the Magnox fleet, where the cost falls on public funds. The principle remains that "the polluter pays".

Indeed, there is in place a legal framework to ensure the adequacy of financial provision by operators via the funded decommissioning programme (FDP) under the Energy Act 2008. An FDP approved by the Secretary of State must be in place before construction of a new nuclear power station begins, and must be complied with thereafter. NDA provide reassurance to the SoS as part of that process. Failure by the operator or by an associated Company which has obligations under the FDP to comply with the FDP is a criminal offence.

Para. 1.2 of the government's guidance on FDP reads:

> *"Any Operator of a nuclear power station is responsible for dealing with any waste that it produces and ensuring that the site is decommissioned and remediated in accordance with relevant legal and licensing requirements. The purpose of Chapter 1 of Part 3 of the Energy Act is to establish a regime whereby Operators of new nuclear power stations have in place plans for decommissioning their stations, and managing and disposing of the waste that they produce. They must also make prudent provision to meet the full cost of their decommissioning and their full share of waste management and waste disposal costs (i.e. the Designated Technical Matters)."*

Applying the same principle to operators of the new reactors, whether SMR or AMR, seems clearly appropriate. However, there are issues which need to be considered and addressed before the SMR, and more particularly the AMR, programmes proceed to actual development:

1) The obligations apply in cases where a person applies for a nuclear site licence in respect of a site on which the person intends to construct a nuclear installation for a purpose for which a generating licence under section 6(1)(a) of the Electricity Act 1989 is required, i.e. a licence authorising a person to generate electricity for the purpose of giving a supply to any premises. They also apply where the installation has already been built and is now intended to be operated for such a purpose and a nuclear site licence is applied for to do so. Therefore, they would not apply to an installation not supplying electricity to premises, for example providing steam or heat. This may well be relevant to some AMR.

2) These obligations apply to the person applying for the nuclear site licence, i.e. the operator. The enforcement provisions apply to the site operator, or a company associated with a site operator (i.e. a parent or subsidiary), to fail to comply with an obligation imposed by an approved funded decommissioning programme in respect of the site. Whereas it is clear for conventional large nuclear reactors how these provisions work, the arrangements as to who will operate AMRs and SMRs may be different and

are not clear at present. However, it will remain the case that a nuclear site licence will only be granted to a company with a sufficient demonstrable degree of control over the site and with the necessary competence and capability to comply with SLC and other requirements.

The point we wish to stress is that back-end issues – spent fuel management, interim storage and disposal in particular, but also reactor decommissioning – must be seen as an integral and important part of assessing the viability and acceptability of new reactor designs and should be considered at all stages, not just at the stage of licensing. For the avoidance of doubt:

- Decisions by government and GBN as to which technologies to support
- Justification, as required by law
- GDA under the current process involving all relevant parties
- Final investment decisions (FID) by investors and funders.

In making that consideration, clarity and sufficient certainty as to the waste and spent fuel which will be generated in operation, fuel management and disposal and decommissioning will have to be provided. There is no guarantee that all types of waste will necessarily be disposable to a GDF. In our view this needs to be made clear by the government as part of a road map for prospective technology promoters before the process gets much further.

5.4 Development Consent Order (DCO) for SMR and AMR

The DCO process applies to generating stations with a capacity of over 50 MW. SMRs or AMRs will also have to obtain a DCO, unless they are either not generating electricity for the grid (in which case they are not deemed to be generating stations) or have a capacity less than 50 MW.

The current National Policy Statement (NPS) for nuclear, EN-6, applies in a legal sense only to stations deployable by 2025. However, according to a Ministerial statement of 2017, EN-6 will continue to be an important and relevant consideration for nuclear power stations deploying after 2025, subject to any new or revised NPS being produced. The test in the 2008 White Paper on Nuclear Power is that the Secretary of State will need to be satisfied that *"effective arrangements exist or will exist to manage and dispose of the waste they will produce"*. Annex B of EN-6 sets out how the government has satisfied itself on that issue.

For HAW this is predicated on a GDF being technically achievable. In particular, based on disposability assessments, no new issues arise with the fuel from the reactor designs then being assessed (EPR and AP1000), compared with legacy wastes and existing spent fuel. This was strengthened by the similarity of the expected wastes from the Sizewell B PWR (see Annex B, para. B.2.4).

No such formal assessment has yet been made for any SMR or AMR, and for the reasons discussed in this Paper, there is significant uncertainty as to whether all types of wastes and spent fuel from SMR, and particularly AMR, will be suitable for disposable in a GDF; certainly, some will raise quite different issues from existing PWR fuel.

This issue will clearly need to be resolved, if it can be, before DCO applications are made for new reactors. This needs to be clearly understood Otherwise, the DCO process will be unable to advise the Secretary of State as required.

5.5 Resources

One theme we have noted recurring in our interaction with stakeholders is that in order to address the back-end issues relating to an expansion of nuclear capacity and new types of reactors, a significant increase in expertise will be needed within developers, regulators, and NWS.

RR-SMR, for example, have currently four dedicated regulators from EA and ONR with whom they liaise on average every two weeks. Also, RR-SMR have a framework agreement with NWS to address disposability.

If a number of SMR and AMR designs are going through the GDA or licensing/permitting processes at the same time and also NWS is being asked to address disposability, the human resource requirements from what is currently a limited pool of relevant expertise (for which there is international competition) will be very significant.

The skills gap in nuclear energy has been highlighted by the Government's Nuclear Skills Taskforce, although the emphasis appears to be on the growth of skills in the front-end of civil and military nuclear programmes.

6 Wastes from SMRs & AMRs

6.1 Introduction

The development of new SMR and AMR technologies offers a unique opportunity to consider waste treatment, SF management, conditioning, storage and disposal, as well as decommissioning, during the conceptual design phase. This could help realise, upfront, reduced lifetime operational and decommissioning costs.

It cannot be assumed that all new SMR and AMR technologies will be able to use the same well-developed radioactive waste management and disposal practices and infrastructure that have been implemented for the UK's past and current fleet of nuclear reactors because the designs and their operating conditions may not be the same. It is important to note that this is a sliding scale, with some reactor designs offering more certainty in terms of radioactive waste management and disposal than others.

Figure 1 summarises CoRWM's assessment of the "technology readiness level (TRL)"[11] of new reactor technologies, with specific regard to radioactive waste management and disposability assessment. On this scale, large PWRs are just below a TRL of 9, which will be attained when spent fuel from these reactors is first emplaced within a GDF (anticipated to be in the Finnish Onkalo facility within the next decade).

A TRL of 1 – 2, where we place waste from molten salt (MSR) and fast reactors, both for the case in which novel fuel and coolant types will be used (rather than where existing fast reactor spent fuel legacies exist, for example), indicates technologies that are at a level of basic technology research with respect to radioactive waste and disposability.

A TRL of 3 – 4, where we place high temperature gas-cooled reactors (HTGRs), such as those anticipating use of TRISO fuel, indicates technologies that have proven feasibility at the laboratory scale and have taken steps to proof of concept of waste management and disposal, but not yet full-scale demonstration.

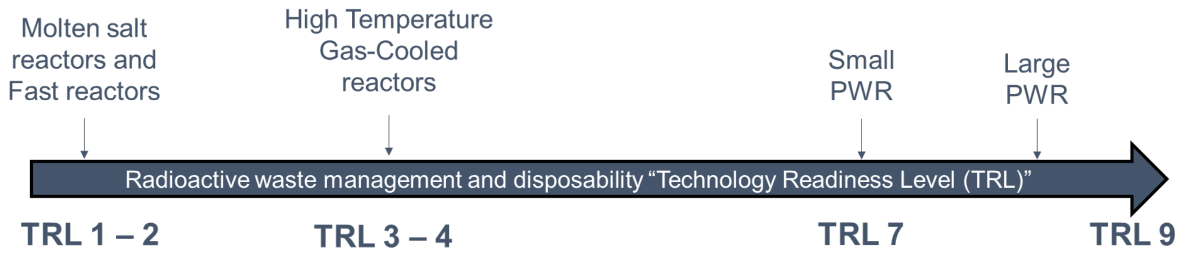

Figure 1. CoRWM's assessment of the waste and disposability technology readiness level (TRL) of new generic types of nuclear reactor. A TRL of 1 is defined as the basic principles having been observed, while a TRL of 9 is a technology proven in an operational environment.

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[11] TRLs are a 9-point scale ranging from basic science (1) through lab demonstration (4) and prototype (6) to validated final product (9).

Small PWRs, depending on design, are estimated to reside at a TRL of around 7, given that their spent fuel and decommissioning wastes are likely to be similar to those from a large PWR.

According to the IAEA, for countries with established nuclear power programmes, management of SF arising from SMRs should not pose a challenge, particularly if SMRs based on current technologies are deployed.[12]. Proposed technologies that do not deviate significantly from current light water reactor (LWR) designs are likely to be able to utilise waste management, storage and disposal routes currently in use, albeit potentially with some modifications to accommodate subtle differences in the characteristics and volume of waste.

There are, for some reactor types, considerable differences in the proposed technologies that necessitate radically different approaches to spent fuel management and that impact upon the type and volume of wastes generated during operation and decommissioning. For example, for reasons of chemical reactivity, the SF from many proposed AMRs will not be compatible with geological disposal without processing and subsequent treatment and conditioning. Further, this must be performed using processing techniques that have never been utilised on an industrial scale, or in a nuclear context.

Here we consider some of the main factors that are known to influence the waste type and volume anticipated from SMR and AMR technologies. This draws upon the technical knowledge of the CoRWM committee members, their own experiences in radioactive waste and spent fuel management research and development, as well as from discussion with relevant organisations with a stake holding in radioactive waste management. We also take into consideration of the recent peer-reviewed literature on the subject.

It is important to note that, in making this assessment, it was necessary to make several assumptions since detailed designs for all the approximately 80 new SMR and AMR technologies currently proposed are not available. During the preparation of this report the six designs selected for the GBN SMR competition in the UK were announced and hence the discussion draws on these examples, where required.

These assumptions, and the uncertainty in radioactive waste management and disposal that they induce, are detailed in Section 6.3.

6.2 Summary of current understanding

The following factors influence the amount and type of radioactive waste generated from a nuclear reactor:

- Fuel type: while PWRs use ceramic-based oxide fuels (e.g., UO_2, MOX), AMR designs propose a range of novel and exotic fuel types such as metallic or salt-based fuels. Some of these chemically reactive materials will require treatment prior to disposal, to

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[12] https://www.iaea.org/newscenter/news/small-modular-reactors-a-challenge-for-spent-fuel-management

transform them into 'passively safe' materials. The choice of treatment route will influence the volume and type of waste generated;

- Fuel enrichment: the higher the enrichment of the fuel, the greater the quantity of depleted uranium (DU) generated in its fabrication, with higher enrichments implying the potential for higher burnup (see below);
- Burnup: spent nuclear fuels (SNF) with higher levels of burnup can, overall, exhibit higher levels of radiotoxicity, which may have implications for the GDF post-closure safety case, and may require longer cooling times prior to disposal than spent fuel with lower burnup. Such cooling could influence required storage times for SNF on-site post de-fuelling, as well as the design and footprint of a GDF;
- Refuel cycle: aside from those SMR and AMR designs espousing a single core load without the need for refuelling, most SMR and AMR designs will be refuelled, typically at intervals of 18-24 months. This process usually involves the removal (or discharge) of fuel that is deemed spent and the redistribution of fuel fit to remain in the core to more advantageous positions. A high rate of refuelling can enable very efficient fuel use whilst minimising spent fuel arisings, but incurs greater lost generating revenues; conversely, longer periods between refuelling can necessitate the removal of larger quantities of spent fuel having higher decay heat etc. because of the longer time spent in the reactor;
- Reactor size: smaller reactors tend to experience more 'neutron leakage' than larger reactors and, therefore, may potentially generate a greater proportion of neutron activated reactor parts / furniture, unless neutron reflectors are used, the nature of the flux, i.e., spectrum, and the isotopic composition of these materials notwithstanding. Having a greater proportion of neutron-activated reactor furniture and neutron reflectors will increase the quantity (and possibly also activity) of long-lived ILW when compared with a large PWR; this can be minimised via the careful selection of materials having a reduced susceptibility to neutron activation, but the presence of some isotopes can be unavoidable due to the role they play, e.g., silver-based alloys in control rods etc.[13];
- Coolant / moderator choice: some novel coolants (e.g., liquid metal or salt) and moderators (e.g., graphite) may require additional waste management at the decommissioning stage. For example, for a liquid lead-cooled fast reactor, there is currently no treatment route for large volumes of radioactively contaminated lead; and
- Open or closed fuel cycle: some types of AMR *require* reprocessing as part of their fuel cycle. Reprocessing operations necessarily generate secondary waste streams that increase the overall volume of waste compared to that of spent fuel alone. Reprocessing may also generate additional wastes during decommissioning of the reprocessing facility.

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[13] 'Long-lived activation products in reactor materials', J. C. Evans et al., NUREG/CR-3474, August 1984.

These factors are generalisations, and it is challenging to compare, like-for-like, specific reactor technologies of different designs in terms of their radioactive waste generation because detailed designs and operating strategies are not yet available. Relatively few comparisons have been attempted, with three such studies detailed in the following.

The National Nuclear Laboratory (NNL) report *UK Nuclear Horizons* (March 2011)[14] considers 5 separate, reference new-build scenarios, from no new nuclear build and phase-out of existing plant through to a rather extraordinary maximum growth case relative to current forecasts, equivalent to 138 GW(e) capacity (86 EPRs).

Whilst the NNL study predates discussion on SMRs, with the focus being on forecasts of large reference PWRs only (i.e., AP1000 and EPR), it highlights the distinction in the UK that SF baseline estimates for disposal based on the Magnox fleet are smaller than they would have been in the absence of reprocessing r. Consequently, estimates of spent fuel for a nuclear renaissance, whilst small, show significant additionality to the spent fuel inventory from current UK operating capacity. More detail as to how these estimates have been derived would benefit the interpretation of this work, as they appear to be based on a constant scaling factor between forecast number of reactors and quantity of discharged fuel, suggesting the implications for the GDF could be defined better.

The recent US Department of Energy (DoE) study by Kim et al. (2022)[15] attempts a detailed comparison between specific reactor types, evaluating the radioactive waste attributes of SMRs and AMRs anticipated for deployment in the next decade, in comparison with a large 'reference' PWR with a specific power output, thermal efficiency and using a defined fuel element (1175 MWe, 50 GWd/t, η_{th}=34%, 4.5% $^{235}UO_2$)[16].

A range of SMR/AMR designs were evaluated, including those selected by the US DoE for near-term deployment, assuming a 60-year lifetime and 90% capacity factor. Designs involving liquid metal, molten salt or gas coolants were considered, alongside a small LWR. These included the Terrapower Natrium™ sodium-cooled fast reactor, based on metal alloy fuel, and the Xe-100 reactor design from X-energy, which is a gas (helium)-cooled high temperature reactor (HTGR) using TRISO (tri-structural isotropic) fuel (akin to the HTGR being considered in the UK). The small LWR example was the NuScale power VOYGR™ (77 MWe, 49.5 GWd/t, η_{th}=31%, 4.95% $^{235}UO_2$). The report considered waste in terms of that which is front-end, back-end and end-of-life, as defined in more detail in Section 6.4.

For front-end wastes (fuel fabrication), it was determined that the VOYGR™ small LWR would generate 23% greater DU mass per GWe-year than would a large reference PWR. This is because DU arisings escalate with enrichment and fall with higher burnup and/or higher thermal

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[14] https://www.nnl.co.uk/wp-content/uploads/2019/01/nnl__1315903177_position_paper_from_nnl_-_uk_n.pdf

[15] https://fuelcycleoptions.inl.gov/SiteAssets/SitePages/Home/SMR_Waste_Attributes_Report_Final.pdf

[16] The four figures represent, in order, reactor output, fuel burnup, thermal efficiency, fuel enrichment percentage.

efficiencies. The challenge of a greater mass of DU on the IGD is subject to commercial factors and does not necessarily correlate with a greater mass for disposal.

Less spent fuel is produced with increasing burnup, so in the case of the VOYGR^{TM} LWR, the lower burn-up and thermal efficiency η_{th} when compared with a large PWR result in ~10% increases in spent fuel volume, mass, activity and decay heat. It was further estimated that 10% less end-of-life waste (wastes arising from decommissioning) would arise, but a large uncertainty in this value was highlighted due to uncertainty over the technologies that would be used in decommissioning and, for example, whether neutron reflectors used to minimise activation would be replaced regularly or left *in-situ*.

In comparison, the DU arisings for the Natrium^{TM} and Xe-100 reactors were forecast to be lower than VOYGR^{TM} (17% higher and 3% lower than the corresponding reference large PWR, respectively) because, despite the higher enrichments in these cases, the burnup and thermal efficiencies are higher too. Similarly, the higher burnup and thermal efficiency results in less SF volume, mass and decay heat but higher long-term activity and radiotoxicity due to the elevated plutonium content: lower normalised activity is expected with respect to decay heat, due to significantly higher thermal efficiencies relative to the reference PWR. The situation is reversed for Xe-100 with reduced spent fuel mass, decay heat, activity, and radiotoxicity, but the spent fuel volume is greater due to the low-density, spherical TRISO fuel design.

Krall et al. (2022)[17], also considered three candidate SMR designs against a large reference PWR: the NuScale integral pressurised water reactor (iPWR) (60 MWe, >30 GWd/t, 5% $^{235}UO_2$); the Terrestrial Energy IMSR-400 (400 MWe, 3% $^{235}UO_2$ dissolved in a molten salt for start-up) and the Toshiba 4S-30 sodium-cooled fast reactor (30 MWe, 19% ^{235}U-Zr alloy fuel) - the latter two might be considered AMRs in the present context. The reference PWR in this case was the 3.4 GWth AP1000, not unlike the reference used by Kim et al.

Given the paucity of information in the public domain about each design, Krall et al. made several assumptions about the reactors evaluated in their study, including the neutron reflectors used and their configuration in the designs (some reflector options, i.e., beryllium, could present significant near-term non-radioactive, waste management challenges) and the conclusions must be considered with this in mind. Moreover, neither reprocessing nor the very different fuel cycles proposed for AMRs were considered. As such, some findings of the work are only tenuously relevant to AMRs in the absence of further consideration (this notwithstanding, the chemical form of exotic fuels and coolants associated with the AMR designs will add to the complexity of radioactive waste management and disposal). Nonetheless, all reactor types were considered to produce more, and in some cases, significantly more, radioactive waste than the reference PWR.

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[17] L. M. Krall, A. M. Macfarlane and R. C. Ewing. Nuclear waste from small modular reactors, PNAS, 119 (23), e2111833119 (2022). https://www.pnas.org/doi/10.1073/pnas.2111833119

6.3 Uncertainties that necessitate assumptions

CoRWM understands that the difficulty in assessing the volume and type of RW and SF arising from any given new nuclear technology arises from a lack of detail in published reactor designs, operating strategies and decommissioning plans. Further complication arises in assessing the disposability of such material in a GDF, since the specific form of the waste and the disposal concept that must be tailored to it, are also unknown.

The technical details for SMR and AMR designs currently available do not allow for detailed quantitative analysis of radioactive (and non-radioactive) wastes/spent fuel arising for management and disposal; therefore, there is a great deal of uncertainty regarding the information necessary to make suitable, and financially sound, plans for radioactive waste/spent fuel management and disposal. This is exemplified by the studies described in Section 4.2, for which numerous assumptions were required to reach their conclusions. Such a high level of uncertainty at this stage is concerning, unless such information is being guarded for proprietary reasons and will be forthcoming during the GDA process.

There are several important factors that must be understood for a reasonable waste/spent fuel management strategy to be developed. Firstly, the specific design of a nuclear reactor and the way in which it is operated, i.e., reload cycle, has direct implications for the volume and type of radioactive waste generated in the life cycle of that technology as described above.

Modifications deemed necessary in a more complete design consideration, and particularly increases in enrichment and inventory, could have significant implications for forecasts of waste arisings. Further, specifications tend to refer to core averages in terms of enrichment and burnup at discharge, as do the recent published studies described above, whereas greater granularity is needed to appreciate the range of likely spent fuel characteristics (see below) which might define the range of acceptability for storage and disposal.

Secondly, the characteristics of the spent fuel should be understood, since the burnup, decay heat and radionuclide inventory, as well as size of the spent nuclear fuel assemblies and their packaging, are all important factors regarding the requirements for cooling time, dry-storage and disposal.

Other factors not related to spent fuel are also important; for example, the potential for undesirable material combinations likely to exacerbate the treatment and disposal of end-of-life wastes, is unknown. This might include, for example, fuel assembly and infrastructure components (i.e., 'reactor furniture', being predominantly metals) with a particular susceptibility to activation (and especially ^{60}Co as discussed below). Similarly, any special coolant requirements or systems may bring about a greater use of ion exchange resins. These are just two examples of where reactor design will influence the volume and nature of ILW.

Moreover, undertaking calculations based on absolute waste quantities, particularly mass and volume, is complicated by uncertainty in the full extent of the roll-out in terms of a fleet, i.e., the number of reactors. As such, an estimate normalised to power (GWe-year), as is adopted in the limited literature on the subject to date (c.f., see Krall et al. and Kim et al.), might result in unrealistically modest volume estimates relative to MAGNOX, AGR and forecast EPR norms.

Quantitative estimates that suggest ‘more of the same’, particularly with respect to SF, are only part of the picture; the potential exists for relatively small volumes of exotic wastes to arise for which disposal routes do not exist (particularly for some AMRs) due to incompatibility with a GDF, for example, due to exception with post-closure safety cases in terms of decay heat and radionuclide inventory.

6.4 Currently shortlisted technologies

An element of clarity has been provided through the recent announcement (6th October 2023) of the six companies shortlisted by GBN into the next stage of the UK’s SMR competition for nuclear technologies, i.e., EDF, GE Hitachi, Holtec Britain, NuScale Power, Rolls-Royce SMR and Westinghouse Electric, since it carries with it six candidate designs.

These six all have the following in common:

- All are LWRs and all (except the GE Hitachi boiling water reactor (BWR)) are PWRs;
- Using a maximum ^{235}U enrichment in uranium dioxide (UO_2) fuel of 5%; with:
- inlet/outlet temperature ranges of 229-296°C and 287-327°C respectively;
- operating lifetimes of 60 years (except Holtec who claim 80 years); and
- refuelling cycles of 12-24 months.

The announcement cited above suggests that, in the UK, SMR designs will be distinct from AMR, with the former being LWRs operating at temperatures consistent with current LWR operation.

CoRWM understand that in terms of AMR, the HTGR design is the likely design of choice, i.e., an inherently safe, helium (He) cooled design based on TRISO fuel, producing <300 MWth with a gas outlet temperature not requiring use of new materials (i.e., maximum ca. 650°C).

The potential for further substantiation of new and existing materials at higher temperatures is to be anticipated for alternative use cases.

Some AMR designs advocate the use of metal fuels. Given that the UK already has a significant legacy resulting from the use of metal fuels, that will itself be complicated to dispose of permanently, primarily due to their chemical reactivity relative to ceramic fuel forms, CoRWM considers that it would be very challenging to embark upon a programme of waste management and disposal of metal spent fuels arising from advanced reactors. Adding such a challenging legacy should be avoided.

Similarly, some AMR designs (particularly some liquid-metal-cooled fast reactors) espouse a single core load fuel cycle, without refuelling, implying the final disposal of whole, spent cores. This is considered by CoRWM to be very difficult, as this form of spent fuel is likely to be incompatible with a GDF scoped to accept a limited variety of relatively low-burnup fuel elements, due to physical size and the potential for defence-in-depth measures to be less easy to implement.

6.5 Assessment of the key challenges for SMR / AMR radioactive waste management and disposal

6.5.1 Front-end wastes

Front-end wastes are those generated by fuel manufacture and are expressed in terms of depleted uranium produced (DU).

Increased fuel enrichment will result in increased DU arisings from fuel manufacture. Due to increased neutron leakage per GW(e) from the smaller cores in SMRs, relative to a large reference PWR, the use of higher ^{235}U enrichments is proposed for many SMRs (albeit most specifications are still quoting levels < 5%), to offset the effect of this on neutron economy. Whilst such leakage is anticipated to be a small effect, and one potentially offset by improved core design; for example, using reflectors, increased enrichment will also result in increased DU arisings from fuel manufacture. Thermal efficiencies lower than the reference PWR could further exacerbate this effect.

This should be considered with reference to the recent CoRWM report[18] on the management of depleted, natural and low-enriched uranium. Relatively little detail is available currently on the use of reflectors in upcoming reactor designs; for example, the use of beryllium to reduce neutron leakage and thus the need for higher enrichments and hence DU arisings, could impact adversely end-of-life toxic waste arisings and the ease of decommissioning. This may also be the case for other reflector materials that become radioactive via neutron activation.

AMR designs (c.f., molten salt and high-temperature, TRISO-fuelled designs) often specify higher enrichments (typically in the range of 5% to 19.75% ^{235}U, excepting those designs concerning thorium or plutonium) and hence there is the potential for greater arisings of DU. However, the higher burnup (in part due to the higher enrichments) and thermal efficiencies (due to higher temperature operation) characteristic of these designs have the potential to offset this effect on front-end waste, due to reduced overall fuel consumption.

6.5.2 Back-end wastes

Back-end wastes are those arising from reactor operation producing SF, and are usually quantified in terms of volume, mass, decay heat, and long-term activity and radiotoxicity.

Burnup estimates for PWR-type SMRs, comparable to a large reference PWR but with lower thermal efficiencies, suggest an increase in spent fuel arisings per GW(e), across mass, volume, activity and decay heat. Estimates of mass and volume currently vary within the limited research published to date, but importantly, increases in activity and decay heat could mandate

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[18] https://www.gov.uk/government/publications/uk-uranium-inventory-management-and-disposal-options-corwm-position-paper

longer cooling times, with the potential that this will result in longer SF residency on reactor sites. This may, therefore, influence the time envelope within which SMRs are anticipated to be built, operated and decommissioned, given that the spent fuel will need to be compatible in terms of decay heat and activity with receipt at a GDF.

However, the detail of a given reactor fuel reload cycle is also important in this regard. For fuelling strategies that allow for a relatively small proportion of fuel in a core to be replaced frequently, reduced volumes of SF with only modest cooling requirements will be generated. In contrast, a strategy where a greater proportion of fuel is replaced less frequently, could create more SF requiring longer cooling times. The more frequent outages necessary in the former scenario would incur greater lost generating revenues. Consequently, a techno-economic balance would need to be struck.

CoRWM believe that it is important that accurate forecasts of burnup and enrichment at discharge must include details of the frequency and batch approach to reload and should reflect that burn-up and enrichment vary across a core.

SF stored at the site of the reactor can be an emotive issue with local communities; conversely, longer periods to allow for decay, prior to disposal, may not align with the closure schedule of the GDF. This issue could potentially be managed by ensuring burn-up and efficiencies are comparable to a reference PWR and by avoiding exotic alternative fuels. The question of the need for long term cooling and storage of SF at centralised facilities raises issues which are beyond the scope of this paper, but to which CoRWM intends to return.

6.5.3 AMRs

For molten salt (MSR) based AMRs, the combination of higher burnup and thermal efficiencies is expected to result in less SF volume, mass and decay heat, but higher long-term activity and radiotoxicity. The exotic chemical nature of this spent fuel, relative to national and international experience, is likely to present significant challenges associated with both interim storage, conditioning and disposal.

The situation is somewhat reversed for high-temperature, gas-cooled AMRs, which should generate spent fuel with reduced mass, decay heat, activity and radiotoxicity; however, the volume of SF is likely to be increased due to the TRISO fuel design and potentially by structural graphite components in some designs. TRISO fuel particles are spherical, which can reduce packing efficiency, and it is less dense than UO_2 spent fuel, on account of the layers of pyrolytic carbon that surround it. As such, on the basis of energy output, estimates suggest that 8 times as many SF containers would be generated for TRISO fuel when compared to a large PWR.[19] This estimate does not account for the additional graphite used as a moderator in prism or pebble-bed high temperature gas-cooled designs.

Less concern exists, aside from its volume, in terms of disposal of TRISO SF (excepting uncertainty over co-disposal of its graphite moderator), but more confidence might be had if post-irradiation examination studies of extant TRISO samples (c.f., building on experience from the DRAGON test reactor and other international HTGR test programmes) were performed to test assumptions concerning storage and disposal suitability. Opportunities to undertake testing on irradiated TRISO fuel could, if appropriate fuel particles could be identified, give useful insight to the characteristics of such material and their behaviour within a disposal environment.

6.5.4 End-of-life wastes

End-of-life wastes are those arising from decommissioning operations, expressed in terms of a combined volume of LLW and ILW.

The increase in neutron leakage from smaller SMR cores, relative to reference large PWRs, could have a deleterious effect on end-of-life waste arisings. These might include higher levels of activation of reactor furniture resulting in greater quantities of intermediate level waste (ILW) / LLW at end-of-life, higher activities and associated complications associated with access for decommissioning, and potentially longer periods of decay prior to decommissioning.

The significance of this, or otherwise, will depend on the success of mitigations for neutron leakage in the reactor designs, the detail of which is not yet available. Indeed, the choice of materials used in the reactor design more generally, will impact upon the volume and activity of decommissioning wastes.

Whilst otherwise largely a geometric effect, the neutron spectrum may also be important in terms of the likelihood of activation, but again more design detail is needed to understand this fully.

As is noted in the scant published research on this topic, the specific nature of the technologies used in decommissioning will have a significant influence on the absolute waste quantities produced. The potential to replicate activity in terms of modular deconstruction is likely to aid the minimisation of these wastes and could accelerate decommissioning programmes (see the importance of consistency point below).

Of note, concerning MSR-based AMRs, is that an integral reprocessing facility is often implicit in these designs. If feasible, reprocessing might reduce overall spent fuel volumes, but is likely to increase the volume of end-of-life wastes significantly, due to the requirement to decommission

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[19] K. Dungan, R. W. H. Gregg, K. Morris, F. R. Liven and G. Butler. Assessment of the disposability of radioactive waste inventories for a range of nuclear fuel cycles: Inventory and evolution over time. Energy, 221, 119826 (2021)

the necessary reprocessing facilities. Government policy is clear that such reprocessing – if it occurs at all – must be at the operator's expense, not the taxpayers.

6.5.5 Disposal of wastes.

Currently, any waste produced from an SMR or AMR must be compatible with disposal in a GDF, to comply with UK policy.

Upfront consideration of whether any given waste is compatible with disposal in a GDF, and which treatment and conditioning route is suitable (if required), should inform vendors, their investors and those responsible for implementing decommissioning and disposal, and ultimately the public, of the long-term financial implications of that technology.

While SF from PWR-type SMRs has similarities with that arising from large PWR equivalents, there are subtle differences that may influence the transport, operational and post-closure safety cases for geological disposal. Only when detailed information about the characteristics of the SF is known will sufficient information regarding compatibility with a GDF be known to demonstrate that wastes and spent fuel are expected to be disposable through GDA or permit application.

The key characteristics of SF that must be understood with a high level of certainty prior to disposal include:

1) decay heat, as this will influence the number of fuel assemblies that can be loaded into a package, and their spacing in the GDF – both could significantly increase the footprint of the GDF;
2) burnup, as this will influence the decay heat and the radionuclide inventory (important to understand for post-closure and criticality safety cases);
3) the chemical form of the waste, which must be non-reactive in water (i.e., passively safe); and
4) the size of the waste packages, which may influence physical handling of the fuel during transport and emplacement.

It should not be assumed that all RW and SF is compatible with disposal in a GDF until detailed discussions have been held with the geological disposal facility implementers, NWS and associated regulators.

The impact of decay heat on a GDF is highly likely to be geology specific. Until a GDF site has been selected, site-specific thermal limits will remain unknown, which as a result increases the uncertainty whether that SF from any given technology could be disposed of in a GDF and whether sufficient suitable rock is available to accommodate a higher thermal load.

Some types of novel fuels under consideration; for example, metallic fuels and salt-based fuels considered in AMR designs, may not meet the GDF safety case requirement for passive safety, i.e., they are chemically reactive and, therefore, would not meet GDF requirements without appropriate treatment and conditioning. Such processes will likely generate a large volume of secondary ILW waste, which may also require treatment and, as a result, these must also be considered as part of the decommissioning and disposal planning.

While the UK currently possesses a complex legacy of waste, including some metallic fuels, CoRWM believes new reactors should not be permitted to increase significantly the challenge of dealing with such complex legacy wastes.

The disposal system (e.g. underground tunnel layout, container type, backfill material, post-closure safety assessment) for PWR-type spent fuel is well constrained and understood, with many examples of designs underpinned by over 40 years of science and engineering R&D, developed through cooperation across a range of countries (e.g. through the EU Euratom research programmes). For any spent fuel type that deviates significantly from PWR fuel, a new disposal system will need to be developed, which will require a programme of significant R&D. Based on examples from the current inventory for disposal, the R&D required to formulate disposal solutions for new fuels and materials could take years and cost tens of millions of pounds per new type of spent fuel or material. For AMR spent fuel, it is unclear from where the funding for such R&D, necessarily performed in universities and the wider nuclear supply chain, will be resourced.

Given that some types of fuel (e.g., MOX) require long cooling times prior to meeting disposability decay heat requirements, it is possible that the operational lifetime of a GDF may need to be extended beyond current plans. Conversely, if a suitable long-term storage solution is not available for nuclear technologies that require rapid re-fuelling, there may be a necessity to dispose of new build waste in a GDF earlier than currently planned.

CoRWM believes that the role of NWS, prior to the GDA process, should be formalised, to encourage early engagement. Such engagement might foster development of systems-level scenario planning that considers the whole lifecycle of a particular nuclear technology, which may assist decision makers with technology selection. Clarity around the financial incentives of planning for waste management and disposal is essential.

6.6 Other Key Factors

Consistency across SMR designs, specifications and operation schedules could play a role in reducing uncertainty with respect to waste management and disposal. Waste of a similar inventory and physical form across a fleet is likely to be managed more easily prior to disposal and disposed of more easily.

Targeting consistency of design(s) across a fleet could have important benefits. Whilst diversity of vendor might favour market resilience and healthy competition, nuclear fuels spanning a variety of enrichments, physical forms and operational characteristics could impact adversely on the costs of future management, by affecting the nature and quantity of the waste produced, and whether it is compatible with the GDF. In the reactor designs associated with the vendors selected recently for the UK SMR competition, none plan to utilise High Assay Low Enriched Uranium (HALEU). If this were chosen as a fuel type, e.g., following a more detailed assessment of the desired neutronic characteristics of a given core design, then this could influence the discussion in this paper significantly. Having an inconsistent mix of low enriched uranium (LEU) and HALEU in nuclear technologies would add complexity and additional challenges to those already discussed. The same might be the case of claims made with respect to burnup and thermal efficiency, i.e., reductions in these could influence back-end waste arisings, recognising the importance of reload schedules in the context of these parameters described earlier.

While it is currently envisaged that spent fuel generated from new build reactors will be stored on-site until disposal, consistency in reactor design could make a central storage facility more feasible than if multiple different types of fuel and decommissioning waste were to be generated from a fleet of reactors of different designs. As stated above, dealing with the associated issues of timing, cost, siting and public acceptability are beyond the scope of this paper, but will need to be grasped.

As already noted, the demands for skilled and expert personnel to address these issues is formidable. The UK is currently deficient in the skills necessary to support the R&D required to underpin the treatment, conditioning and disposal of novel radioactive wastes arising from advanced nuclear fuel cycles, and those skills necessary to optimise the operation of a new fleet of reactors to minimise its waste burden. In our experience, the current nuclear skills shortage is impacting upon there being enough suitably qualified personnel to plan for, and advise upon, these important issues.

7 Conclusions and Recommendations

7.1 Conclusions

7.1.1. The management of SF and RW from these new reactors must be considered when selecting technologies for investment, government support, further development, construction and operation.

7.1.2. This must involve addressing the uncertainties about such management at an early stage, to avoid the costly mistakes which have been made in the past, and also to provide financial certainty for investors regarding lifetime costs of operation and decommissioning.

7.1.3. It is essential to know:

- the nature and composition of the waste and, in particular, of the spent fuel;
- its likely heat generation and activity levels;
- how it is to be packaged and its volume; and
- when it is likely to arise.

7.1.4. It is clear that different types of reactor, ranging from those which are very similar to current pressurised water reactors (PWR) through to those using exotic fuels about which little is known, will present highly variable levels of confidence as to how the spent fuel and waste will be managed and ultimately disposed of.

7.1.5. Even those reactor types about which most is known will still have important operating variables to be clarified. For example, how the reactor is operated and refuelled in practice will have potentially significant implications for interim radioactive waste management and disposal.

7.1.6. In particular, it is not necessarily the case that all types of SF and RW will be suitable for disposal in a GDF as currently envisaged, at least without difficult prior treatment processes. Some materials may simply not be able to achieve the necessary state of passive safety required, without substantial processing and maybe not even then. There are important questions on SF and RW from these new reactor types, which may possibly impact the consenting processes for the GDF and will also affect the financial provision to be made by developers and investors for decommissioning and the transfer of waste and spent fuel to any GDF. In which they are disposable. Clearly, seeking to make a GDF suitable for receiving future and as yet indeterminate forms of waste and spent fuel would most likely involve substantial additional cost and complexity.

7.1.7. Government and GBN should make this clear, so as to manage expectations of some vendors and provide clarity to potential investors. We do not advocate saying that specific designs should be ruled out, as this is ultimately a question for the developer and investors, but clear guidance is required.

7.1.8. NDA and NWS in particular, have a vital role to play in assessing disposability, as a consultee in Justification and GDA. Early discussion between developers and NWS is clearly advisable but with some exceptions, such as RR SMR, this appears to be happening only to a very limited degree.

7.1.9. It needs to be clear that it is for developers, not the NDA / NWS, to fund and undertake the necessary research, which may be extensive. NWS must be consulted about such research and NWS will need to have full access to it for use in support of its disposability assessment and development of the GDF.

7.1.10. There is an important issue of timing that needs to be addressed between the emergence of the necessary information on spent fuel and waste from new types of reactor and the GDF development process as currently understood and underway

7.1.11. Plainly, this information is not going to be available to enable the implications for the scale and capacity and operating lifetime of the GDF to be made clear before any test of public support (ToPS) for a potential host facility. NWS needs to address how this will be addressed in the ToPS.

7.1.12. These questions will also impact upon the design and safety case of the GDF for the purposes of applying for a development consent order (DCO) as well as other environment and safety consents.

7.2 Recommendations

7.2.1 Clear guidance is needed from government to promoters, regulators and GBN on the necessity of addressing the cost, safety and environmental issues associated with radioactive waste management at an early stage.

7.2.2 Government should make clear what degree of certainty will be required regarding the “back end” of the nuclear fuel cycle. That is, the proposed approach to and associated costs of the management of spent fuel and radioactive waste from operation and decommissioning.

7.2.3 The role of NWS, should be emphasised, so as to encourage early engagement in the process. NWS will need the necessary resources for this task if a number of possible technologies are to be considered.

7.2.4 It is important that developers of new reactors have sufficient management capability and expertise to understand and assess the back-end issues, and to be an intelligent customer where they rely on outside expertise. Where the GDA process is pursued, this should be an important aspect of it. The required growth in skills to meet these challenges must be addressed.

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9 Glossary

Abbreviation	Definition
AMR	advanced modular reactor
AGR	advanced gas cooled reactor
ALARP	as low as reasonably practicable
AP1000	advanced passive 1000 - Westinghouse pressurised water reactor
BAT	best available techniques
BEIS	Department for Business, Energy and Industrial Strategy
BWR	boiling water reactor
CoRWM	Committee on Radioactive Waste Management
DCO	development consent order
DESNZ	Department for Energy Security and Net Zero
DU	depleted uranium
EA	Environment Agency
EN-6	national policy statement for nuclear power generation
EP	environmental permitting
EPR	UK European pressurised water reactor
FDP	funded decommissioning programme
GBN	Great British Nuclear
GDA	generic design assessment
GDF	geological disposal facility
GWd/t	Gigawatt days per metric tonne
GW(e)	Gigawatt electrical
GTCC	greater than class C LLW
HALEU	high assay low enriched uranium
HAW	higher activity waste
HLW	high level waste
HTGR	high temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
IGD	inventory for geological disposal
iPWR	integral pressurised water reactor
ILW	intermediate level waste
IMS	integrated management system
JoPIIR	justification of practices involving ionising radiation
LEU	low enriched uranium
LLW	low level waste
LWR	light water reactor
MAGNOX	Magnesium non-oxidising reactor
MOX	mixed oxide fuel
MSR	molten salt reactor
MW(th)	mega watt thermal

Abbreviation	Definition
NDA	Nuclear Decommissioning Authority
NNL	National Nuclear Laboratory
NSL	nuclear site licensing
NWS	Nuclear Waste Services
NRW	Natural Resources Wales
ONR	Office for Nuclear Regulation
PWR	pressurised water reactor
RR-SMR	Rolls-Royce small modular reactor
REP	radioactive environmental principles
RSMDP	radioactive substances management developed principles
RSR	radioactive substances regulation
RW	radioactive waste
SMR	small modular reactor
SNF	spent nuclear fuel
SF	spent fuel
TBq	terra becquerels
ToPS	test of public support
TRISO	tri-structural isotropic fuel
TRL	technology readiness level
U	uranium
UO_2	uranium dioxide
UK	United Kingdom
UK EPR	United Kingdom European pressurised water reactor
US DoE	United States Department of Energy