Initial considerations with respect to regulatory scope as part of AMR RD&D Programme, Phase A

July 2022

Overview

This document provides Nuclear Innovation and Research Advisory Board (NIRAB) advice to Regulators on regulation of the Department for Business, Energy and Industrial Strategy (BEIS) Advanced Modular Reactor Research, Development and Demonstration (AMR RD&D) programme, in response to a request from BEIS to undertake an assessment of a 'regulatory deliverable' produced by each of the suppliers. NIRAB advice to Regulators has been developed based upon a discussion paper presented to NIRAB and discussed at the Board meeting on Monday 4th July 2022. An overview of this document is provided in the cover letter from NIRAB to the Regulators.

Background

The UK government has announced its ambition to embark on an Advanced Modular Reactor (AMR) Research, Development and Demonstration (RD&D) programme that aims to demonstrate High Temperature Gas Reactor (HTGR) technology by the early 2030s, in time for any potential commercial AMRs to support net zero by 2050. As per the announcement (HMG, 2022): "This HTGR demonstration, which will be sited in the UK, should be shaped by end-user requirements, and should incentivise private investment in HTGRs by removing technical risk. It should have innovation at the centre of its design, build, and application." The AMR RD&D Phase A programme is split into two lots: one related to reactor demonstration; and the other on fuel demonstration. As part of the programme, the UK Regulators (Office for Nuclear Regulation, ONR and Environment Agency, EA) have been requested by BEIS to undertake an assessment of a 'regulatory deliverable' produced by each of the suppliers, which was defined in basic terms in the Invitation to Tender, and is expected to develop as part of the definition of a review programme and of the regulatory engagement process. ONR and EA have requested NIRAB to provide advice on the scope of the regulatory deliverable and assessment criteria. This discussion document therefore presents some key data and initial thoughts related to considerations with respect to regulatory scope as part of AMR RD&D Phase A. Noting that the **AMR RD&D programme is at an early stage and is focused on innovation and engagement with regulators throughout the programme**, it will be the case that not all challenges will be highlighted at the infancy of the programme and any discussions around regulatory scope will need to be within the limits of the vires of ONR and EA. Nevertheless, it is prudent to start identifying at least some of the likely challenges.

From the outset it is important to note that **in the absence of a specific design** (due to the fact the RD&D competition is open to different HTGR designs), **the pathway to effective, efficient and proportionate regulatory engagement and input is significantly curtailed**, as the safety of a particular system is heavily dependent on the exact implementation of that system. It is therefore suggested that every effort is made to identify as soon as possible the system or systems that are of interest for deployment in the UK. Nevertheless, drawing on openly available information, it is still possible to identify likely shared challenges for HTGR systems and new technical deployments that may differ from previous practice, such as energy storage systems directly coupled to the reactor.

Common challenges with HTGR systems and potential approaches to resolve these

It is suggested that common challenges amongst vendor designs are identified as early as possible, and expert group task forces established to help identify the most appropriate solutions. This approach would significantly accelerate technical progress and also demonstrate independent peer review and expert input to regulators which could compensate for the likely lack of Relevant Good Practice (RGP) for novel designs. Such an approach is already widely undertaken internationally and is actively encouraged in many fora, such as the Generation-IV International Forum. Another option would be to bring together the main stakeholders, as part of the AMR RD&D programme, to support key objectives, for example accelerated deployment and minimised investor risk whilst allowing UK regulators the independence to regulate. This is in some ways analogous to the 'G6' approach used to accelerate reduction of intolerable risks at Sellafield (ONR, 2021).

In the absence of specific information related to the reactor designs of interest for deployment in the UK at the time of writing, open literature information is an appropriate starting point. The broad topics (from the open literature) of interest related to regulatory approval challenges associated with HTGR technology are listed below, although this is unlikely to be a complete list and it is assumed that previous work undertaken in the UK on regulatory engagement (e.g. the AMR Feasibility and Development Programme etc.), would help identify additional common areas:

- **Verification and validation of the fuel route (e.g., fuel qualification)** (Petti, 2012; Demkowicz, 2020)
- **In-core inspection and instrumentation** (including fuel temperature determination, helium purity and ageing of materials) (Beck, 2011; Marsden, 2020; Mcdowell, 2011; Wright (2020)
- **Graphite dust** (impact on source term) (Areva, 2011)
- **Disposability of fuel/graphite and other waste streams** (IAEA, 2010)
- General points around **material performance under HTGR conditions**, which includes He-embrittlement (noting that the general challenges with respect to material

performance will depend on the temperature sought) (Marsden, 2020; MIT, 2018; Wright, 2020)

A key characteristic in any HTGR design is the ability of the fuel to fulfil its safety functions. This reactor type has a safety philosophy based on containment of fission products in the fuel so it will be critical to establish this aspect from the outset of the programme, given its key role in delivering safety benefits (and potentially associated siting flexibility). There is also the broader question of understanding the operating conditions of the fuel so the predictive qualities/accuracy of the computer codes, along with associated experimental validation, will also be important in any HTGR design. A range of fuel forms is considered for HTGR systems e.g. pebble vs prismatic and UO_2 fuel particles vs UCO (Demkowicz, 2020). The successful implementation of a HTGR fuel form will be dependent on factors including: 1) disciplined, controlled fabrication of the fuel form, with robust quality control and a specific quality assurance programme; and 2) understanding the operating conditions (normal and accident) for the exact fuel form chosen for a particular design (Demkowicz, 2020). There are also wider issues around the fuel route if fabrication takes place in the UK since there are criticality and chemical hazards unique to TRISO fuel manufacture (Brown, 2019; Demkowicz, 2020). This is particularly important as the enrichment for likely HTGRs moves significantly beyond 5 wt.% because safety margins are very sensitive to enrichment, entailing additional criticality controls. It is also important that the waste implications of out-of-specification manufactured material are also fully understood (noting the tight quality control associated with coated particle fuel (Demkowicz, 2020).

With respect to the topics above, there will be overlap with technical challenges associated with the legacy UK gas-cooled reactor systems so there may already be solutions to some challenges, for example, graphite dust in AGR systems and the disposability of waste from such systems. Hence, there is likely to be an onus on **vendors and regulators to focus on what is novel and what are the most pressing outstanding challenges with respect to the above topics**.

Additional wider challenges common with AMR systems

There are additional noteworthy topics covered in the literature associated with AMR systems, that will likely overlap with HTGR systems and have their own associated challenges (noting that the specific challenges will be dependent on the exact design(s) that are progressed). Three particular topics are: 1) **high assay low enriched uranium (HALEU) transport and management**; 2) **autonomous operation**; and 3) **broader challenges associated with limited data when trying to licence a new technology**.

HALEU

Commercial light water reactors currently employ fuel enriched up to 5 wt.% uranium-235 (U-235). Many AMR type systems, including HTGR systems, intend to use fuel enriched to between 5 wt.% and 20 wt.% U-235, so-called high assay low enriched uranium (ORNL, 2020; MIT, 2018). The successful deployment of systems that intend to use HALEU will be dependent on the ability to safely transport and manage large quantities of HALEU material (ORNL, 2020). However, with the **higher enrichment, this can create criticality challenges and there is uncertainty as to whether subcriticality requirements can be satisfied with existing, mature transport and management practices** (ORNL, 2020). There may also be novel wastes produced from generation and use of HALEU which will need to be managed.

NIRAB recommends that vendors and Regulators promptly develop a clear understanding of the safety and security aspects of the fuel route, particularly criticality implications of using HALEU fuel, fuel performance, recycle of out-of-specification fuel materials, and management of used fuel.

Autonomous operation

There has been a drive for autonomous operation for smaller reactor designs, and it is seen as a key enabling feature for smaller power systems to maximise their utility and minimise their cost (MIT-2018). Autonomous operation covers a spectrum of capabilities with how a control system responds to different states within the power plant from 1) rigid, pre-programmed responses to certain events but with the majority of important decision-making left to the human operator, to 2) full autonomy, whereby the system integrates control, diagnostic and decision capabilities, with no human intervention or oversight as part of response functions (Wood, 2017). Here, semi-autonomous is used to define a level of autonomous operation between the two extremes of rigid, pre-programmed responses and full autonomous operation.

A reason for the interest in autonomous operation for smaller power plants is that the most significant controllable element in day-to-day costs arises from operations and maintenance (O&M) activities, which heavily depends on staffing levels and the availability of the nuclear power plant (Wood, 2017). It is important to note that **whilst autonomous control been explored at a research level, it has never been implemented in any operating nuclear power plant** (Gomez, 2020; Wood, 2017) and many challenges arise from this, which are explored further in Appendix 1 of this document. Work underway to support the proposed ITER fusion reactor operation, inspection and maintenance philosophy should be leveraged. Nevertheless, effective autonomous operation could allow for reduced staffing levels and ensure high plant availability. **Without higher degrees of automation than is currently achieved in nuclear power plants, high staffing levels relative to unit power production would pose the threat of unsustainable O&M costs and hinder the deployment of both SMR and AMR systems, particularly those at power levels** below 300 MWe, noting that many AMR systems are targeting power levels below 25 MWe, which is far smaller than conventional power plants that output around 1 GWe/3 GWth (WNA, 2022).

It will be important for **any AMR concept that aims to employ autonomous control to establish early in the design the degree of automation and remote operation**

required/achievable. It is very unlikely that extreme autonomy will be achieved in first generation modular reactor systems and an iterative approach will be required, whereby the biggest gains with minimal implementation challenges are prioritised (Wood, 2017). This latter approach is potentially an item that regulators can enable via constructive discussions outlining the challenges foreseen with respect to different degrees of autonomous operation. An alternative approach to fully or semi-autonomous operation would be fast and accurate estimation for better informed decisions for operators (so called “human in the loop” (Gomez, 2020)); however, the benefits of this approach vs more highly autonomous approaches will be limited.

As per (Gomez, 2020), the use of research accelerators and task forces that allow for active discussion and collaboration in the area of autonomous operation is likely a very worthwhile goal. Finally, the technology gaps for autonomous control indicate research, development, and demonstration (RD&D) activities will be needed to fully realise the goal of autonomous control (Wood, 2017) and hence this could be a key aim of the AMR RD&D programme.

NIRAB recommends that the Regulators form an early understanding of the Instrumentation and Control Philosophy proposed, the approach to human-machine interface, passive safety focus, more extended operator intervention times, and cyber security of the plant and remote operation.

Broader challenges associated with limited data

The current worldwide light water reactor fleet benefits from over ten thousand reactor-years of operation and all of the associated data and knowledge this has brought. Any AMR system would only have a small fraction of comparable data under prototypic conditions, noting that few previously deployed advanced reactor systems (such as sodium-cooled fast reactors and HTGRs) have operated near commercial scale. In developing and licensing any reactor system it is important to have an understanding how key components will behave over time and this will be complicated by systems that aim to employ novel materials and manufacturing methods (Chevalier, 2020). There is also the broader question around how advanced modular manufacturing approaches that deviate from historical approaches could impact licensability.

One area that has received increasing attention relates to so-called digital twins, whereby (in general) a high-fidelity computational model of the system of interest is coupled to sensors on an operating system and both are used together to understand uncertainties and improve the performance of the system (Botin-Sanabria, 2022; Yang, 2022). Such an approach could help maximise the information and value from the AMR RD&D programme and support future licensing related activities. **NIRAB recommends that early focus for the demonstration should be around understanding the role of digital twins in on-line monitoring of the plant to support the safety case, and how that might develop with the operation of the demonstration facility.** In addition, an understanding of the rigour and security of the design process when using a digital twin, and how information captured from the digital twin would interface with manufacturing, including: 1) an understanding of the related manufacturing quality assurance and control regime; 2) the use of the digital twin as part of demonstration and confidence building activities and; 3) any regulatory implications associated with such activities.

Due to the fact that any Advanced Modular Reactor system by definition will have less experience than conventional light water reactors, there will also be important considerations around ensuring that the UK has Suitably Qualified and Experience Personnel (SQEP) resources to support any HTGR programme. Without sufficient SQEP resources this could also impact the ability of the regulatory to call on expertise to support independent assessment and therefore there is broader question around sufficient UK skills in the area of AMR technologies.

On the topic of lifetime of components, it is worth noting that the UK's base case associated with the Funded Decommissioning Programme (DECC, 2011) assumes a station operating for a minimum of 40 years. This is to at least allow for sufficient finance to accumulate to fund decommissioning activities. In the case of an AMR demonstrator or where shorter (e.g. 20 year) core lifetimes are proposed, it will be important both to define the system lifetime and establish how decommissioning will be financed from the outset. This may be problematic for some key components if there is not sufficient data to underpin their long-term operation, noting for instance that the target outlet temperatures from HTGR systems range from 600 to 950°C, which can greatly impact their expected material behaviour and the quality of data that underpins their targeted lifetime. In summary, **NIRAB recommends that it is worth regulators and vendors understanding what the barriers are likely to be with new methods/materials, the reasonable lifetime of key components given the quality of current data and how an AMR RD&D programme could be most effectively harnessed to address challenges in these areas for both the demonstration plant and any following plants**.

End-use application considerations

The vendor's plan for coupling the system to end-users is an important topic. Reactors are designed to minimise stresses put on their components (e.g. thermal stresses following changes in reactor power). The coupling of a use plant (e.g. for hydrogen production) may introduce transients in reactor power demand which could accelerate the ageing of components. The connection of the reactor to the use plant will require an intermediate circuit to allow the heat energy from the reactor's primary coolant to be transferred while avoiding potential contamination; it is possible there may be several loops, which could result in a reduction of energy transfer efficiency and therefore minimise the suitability of the plant for the end-uses it targets. Some advanced nuclear technology systems target co-generation whereby both electricity and heat are supplied to end-users (RS, 2020), and there are the added considerations that would need to be factored in if the power plant is located at an inland site with abstraction from water sources such as rivers. Whilst the cooling demands will be lower for smaller sized reactor systems than those of GWe-class reactor systems, for those employing abstraction and discharges to local rivers, assessments would need to be factored in for both the reactor and industrial end-users using the water coolant.

Some AMR designs, including HTGRs, intend to employ energy storage systems, in part to minimise the need for rapid changes in power by the nuclear reactor which can introduce ageing and damage to components through, for example, thermo-mechanical stresses (OECD, 2021). However, some HTGRs nominally propose the ability to undertake flexible operation, for instance via load-following (OECD, 2021). It would be useful to understand the extent to which flexible operation has been considered by vendors, end-user requirement and the data available to support licensing of flexible operation.

It is worth noting that whilst there is around 100 reactor years of operation of HTGR type systems, there is very little experience of coupling to an industrial end-user or energy storage medium. There are however international activities underway on this front (see for instance JAEA work on coupling of the Japanese HTTR system to hydrogen applications) and UK engagement in these respects may prove helpful for all parties involved.

A key general topic relates to the distance between the reactor and end-users, and therefore the external hazard from the end-user plants to the reactor, (including potentially hazardous industrial environments and energy vectors such as hydrogen which will have different associated hazards). From a safety perspective there will be benefit from separating certain end-users from the reactor to prevent any impact on the nuclear licensed site (or vice versa). However, the objective of many designers of advanced nuclear is to have smaller site footprints, lower on-site staffing, and optimised passive safety, which could drive closer co-location (MIT, 2018). There is a general point around the importance of understanding the strategy to achieve defence in depth and also outline the siting criteria assumptions at an early stage (i.e. including the impact of co-location away from remote, coastal locations which has tended to be the approach adopted for siting most nuclear power plants in the UK). In the case of hydrogen production co-location, preliminary work has been undertaken internationally on distances between the hydrogen production plant and nuclear power plant, indicating that distances of a few hundred metres would be sufficient (Verfondern, 2017). However, a UK specific study for the reactor and hydrogen process (including the amount of hydrogen produced and stored on site) would be required.

More generally most applications internationally of nuclear heat have focused on heat transportation to end-users; however, most of the literature on transporting heat from nuclear power plants is focused on low temperatures (around 80-120°C) (JRC, 2012; Axpo 2012; Jasserand, 2015), with some data on higher temperature heat (around 300°C) available. However, with respect to the latter, the information is highly contradictory with ranges varying from less than 5 km to 25 km (Ammar, 2012; Kavvadias & Quoilin, 2018; Ma, 2009; Gibbs, 2011). The challenge of transporting heat over long distances arises from heat losses which more readily occur with a higher temperature differential, so more effort / cost is required to insulate pipes to minimise these losses. The data on transporting heat above 300°C is very limited so very close co-location of the power plant to end-users may be necessary. Since distance is critical to safety and utility, and noting the diversity of applications and associated hazards, **NIRAB recommends that this matter is addressed as part of early regulatory engagement, accepting that, due to the large uncertainties and large combination of possibilities, there are limited benefits in trying to predict specific end-uses and hypothetical hazards**.

Additional items for consideration

Further to the points referenced above, it should be noted that there have recently been challenges in the UK around the separation of Control and Protection systems in nuclear power plants and on this point it would be useful for vendors and regulators to engage early to ensure lessons learnt can support the AMR RD&D programme.

Whilst we recognise that the AMR Demo regulatory input documentation will be very high level at this early stage, we would advise that it would be appropriate for the respondents to provide clarity about the Design strategy in a number of key areas e.g. adoption of the principles of Secure by Design, Safeguards by Design and Safe by Design concepts.

In addition to the synergies between autonomous operation in fission and fusion space, there are likely to be broader synergies with fusion. Hence it is important that AMR vendors and the fusion community work together to explore likely synergies and joined up R&D programmes that could provide enhanced value for money for UK investments in this area.

As part of initial confidence building measures around design integrity, we suggest that: 1) regulators form a high level understanding of the maturity level of the Responsible Designer (RD) and any action plans to develop that further; 2) the role that the RD has, and; 3) the future high level plan to support the development of the Intelligent Customer- Design Authority (DA) capability within the Demonstrator Licensee, in terms of transfer of knowledge and ownership of the design to the DA.

Given the importance of coated particle fuel for fission production retention, any claims to reduce the robustness of secondary containment will need to be examined carefully, noting that the secondary containment also acts as a protective system against external hazards. The passive safety philosophy may differ significantly from experience with LWR plants recently, and this will need a major focus. Finally, the ability to regulate addons over and above initial uses for the demonstrator, and potentially first of a kind, will need to be considered in the longer term and initial thoughts regarding how this can factored in from the outset may prove useful.

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Appendix 1

Additional information on autonomous operation

An autonomous control system for a modular reactor plant would need to provide continuous, remote and potentially unattended operation for an extended period with limited immediate human interaction, or limited local resource, supported by central operation. From the outset, the difficulty of achieving a fully autonomous operation should be noted. Although autonomous control has been explored at a research level, it has never been implemented in any operating nuclear power plant (Gomez, 2020; Wood, 2017). Autonomous control would need to be able to monitor, trend, detect, diagnose, decide, and self-adjust the power plant without any human intervention. Even to achieve a semi-autonomous system, significant technology development and demonstration would be required (Wood, 2017).

Important characteristics associated with autonomy include intelligence, robustness, optimisation, flexibility, and adaptability (Wood, 2017). Robustness would be a key concern, and understanding how the system would respond to events it has not been trained on (i.e. come across before) and ensure fault tolerance (including adaption in the case of sensor failures), fault avoidance and fault removal.

It is worth noting that under normal conditions, power operation can be relatively simple, with all reactor systems that have been licensed required to have inherent feedback effects serving to maintain stability. The response to off-normal events is where autonomy becomes more important and valuable (Wood, 2017). It is worth noting that any meaningful autonomous operating system would need to minimise reactor shutdowns (for instance not simply shutting down the system in the event an off-normal event taking place), with the primary objective of autonomous control being to limit the progression of off-normal events and minimise the need for shutdown (Wood, 2017).

Given the potential consequences associated with inappropriate action taken by an automated response system applied to a nuclear power plant, there will always be significant attention and caution regarding the implementation of such novel approaches (Gomez, 2020). Furthermore, there is the complication that much of the sophisticated learning methods that have become prominent in recent years (due to their enhanced performance) suffer from increased model complexity, turning such systems into effective “black box” techniques; thereby causing uncertainty with respect to how they operate and, ultimately, the way that they come to decisions (Linardatos, 2020). This uncertainty in how they operate and come to decisions may create barriers to implementing such approaches in autonomous operation given the risks associated with inappropriate actions. Nevertheless, varying degrees of autonomous systems have been deployed in high-risk applications such as surgical assistance, spacecraft, power grid stability, self-driving automobiles and unmanned aerial vehicles (Gomez, 2020).

It is worth noting that human operators have made mistakes in the past and exacerbated transient events; however, an important feature of human intelligence is the ability to learn and improve performance over time which human operators have demonstrated via thousands of reactor years of safe operation globally of nuclear power plants. Furthermore, human operators have demonstrated the expertise to ensure that trade-offs are fully understood before taking proper decisions (Gomez, 2020). This has set a high benchmark that any autonomous system will be assessed against.