NUCLEAR INNOVATION AND RESEARCH ADVISORY BOARD

Overview of Impact of the Nuclear Innovation Programme (2016 – 2022)

NIRAB-3-306

October 2022

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Executive Summary

The Nuclear Innovation and Research Advisory Board (NIRAB) has assessed the impact of the Nuclear Innovation Programme (NIP), funded by the department for Business Energy and Industrial Strategy (BEIS) between 2016 and 2022. The assessment has considered whether the NIP has changed the research landscape and the extent to which it has achieved the programme's high-level objectives. Our conclusion is that the programme has undoubtedly had a significant positive impact. The sustained loss of critically at risk-skills has been interrupted by the multi-pronged approach of the NIP and has enabled the UK to re-engage with international research bodies, restoring the status of the reputation of the UK as a valuable research partner. Some level of ongoing research and innovation funding will be required if the benefits to date are to be sustained, and a more ambitious programme for acceleration will be required to build on to progress. For example, advanced fuel cycle skills are no longer at immediate risk, but some level of work will be required to prevent the recurrence of that risk.

The programme has supported research relevant to High Temperature Gas Reactors (HTGR), which have recently been identified by BEIS as the preferred Advanced Modular Reactor (AMR) design. NIRAB advises that a follow-on research programme be commissioned as soon as possible covering the same or similar programme areas. Such a programme should be designed, as far as possible, to minimise any stop-start approach to funding and to provide the certainty and continuity of research that will maximise benefit. The programme should have dual objectives. The first is to develop engineered solutions towards licensable HTGR technology and associated infrastructure, opening the potential to deliver an HTGR fleet. The second is to maintain and extend broad strategic knowledge and technical capability to underpin future energy policy and support the future UK nuclear industry (fission and fusion), without prematurely foreclosing options.

Overview

This document provides Nuclear Innovation and Research Advisory Board (NIRAB) expert opinion on the impact that the Nuclear Innovation Programme (NIP), running from 2016-2022, has had on nuclear innovation in the UK, in response to a request from the Department for Business, Energy and Industrial Strategy (BEIS). BEIS also requested a NIRAB opinion on what research and development within the UK, if anything, could be stopped; what else needs prioritising and what R&D is needed in order to build an AMR demonstrator to the timescale necessary for a meaningful contribution to net zero emissions by 2050.

This report, validated at the September 2022 Board, presents NIRAB's view of the impact of the Nuclear Innovation Programme (NIP), where it has supported the Nuclear Industrial Strategy aspirations [1], and contributed to fulfilling its high-level objectives. NIRAB is aware that Government is in the process of commissioning a comprehensive evaluation of the NIP via a commercial process which is likely to report in late 2023, and will provide additional advice. NIRAB does not have access to detailed information such as project deliverables or Key Performance Indicator (KPI) data, and therefore the NIRAB advice contained herein has been developed from the open literature, principally information provided in the NIP summary brochure which summarises the scope and the key achievements of each of the contracts making up the NIP [2], alongside NIRAB members' own expertise and involvement in the various programmes.

Further advice is to follow on future RD&D needs and prioritisation.

Background

Scoping of the NIP began in 2016 and the first elements of the programme were commissioned in 2017. At that time, it was recognised that there were several areas of nuclear R&D skills, previously identified [3] that were critically at risk, to the extent that they could be lost within 5 years, and the UK was increasingly coming to be viewed as no longer amongst the top tier of nuclear nations. The Nuclear Industrial Strategy [2] set a number of objectives to address this, including:

- [continue] "to be a 'top table' nuclear nation, working in international partnerships leading the direction of future technology advances across the fuel cycle";
- "to be a key partner of choice in commercialising Generation III+, IV and Small Modular Reactor (SMR) technologies worldwide";
- "to be a respected partner contributing significantly to appropriate international research programmes undertaken with selected international collaborators";
- "to ensure the UK maintains energy security and affordability";
- "to ensure domestic and global commercial opportunities can be realised by companies in the UK, both in the short and long-term";
- "to maintain the UK's high technical skill base across the full fuel cycle, providing high value career opportunities at home and overseas";
- "to ensure the availability of qualified and suitably experienced nuclear regulators to ensure safety of nuclear at home and overseas through international cooperation".

The UK was falling well short of meeting these objectives. Even in areas where there was world leading expertise and competence, it was very much rooted in the past as a result of the recent lack of active programmes. In some areas this meant that expertise and knowledge primarily resided in relatively small number of experts, many of whom were approaching the end of their careers. Government acknowledged in the Nuclear Industrial Strategy [2] that a publicly funded programme of research and innovation would be required if these objectives were to be met.

In the last formal assessment published in 2020 [4], reporting 2018 figures, UK expenditure on nuclear R&D is still low relative to the USA, Japan & France. Compared to other OECD nuclear nations developing future nuclear reactor technologies, the UK *growth* in R&D spend since 2011 is proportionally the highest. In 2018, the UK had the 4th largest total civil nuclear R&D budget of the OECD countries including fusion (note the data above does not include the non-OECD nations Russia, China, and India, all of which have significant nuclear research budgets). NIRAB advises that the landscape survey is now relaunched to understand where the UK currently stands, as there have been many changes, including BREXIT, since this report was issued.

Nuclear Innovation Programme

The Nuclear Innovation Programme (NIP) formed part of a wider UK Government commitment to invest up to £505 million in an ambitious research and development programme named the Energy Innovation Programme (EIP,[6]) to bring technologies towards commercialisation. The EIP aimed to support innovation that would deliver cost-effective contributions to a decarbonised energy supply, economic growth, and jobs in the UK energy sector and its supply chain.

The high-level objectives of the NIP first set out in [7] were:

1. to deliver an ambitious nuclear R&D programme, including a process to identify and support modular reactor technology options that could offer significant value to the UK;
2. to reinvigorate the capability, capacity, and credibility of the UK Nuclear R&D landscape, focusing on key areas of historical strength and future opportunity;
3. to explore and develop the potential for innovation to reduce the cost of nuclear deployment and operation for both near and long-term technologies.

Nuclear Innovation Programme – Themes

The Nuclear Innovation Programme was made up of the following themes: 1) Advanced Fuels, 2) Advanced Manufacturing and Materials, 3) Advanced Modular Reactor Design and Regulation, 4) Advanced Reactors, 5) Strategic Toolkits, 6) Decommissioning & Robotics, 7) Thermal Hydraulics Facility.

Nuclear Innovation Programme – High-level observations

The Nuclear Innovation Programme has undoubtedly had a significant positive impact, addressing some of the problems faced by the sector at the outset of the programme and contributing to meeting some of the broad objectives agreed by Government and Industry. Initial observations can be made in several areas, as follows:

Skills

- The programme has secured the skills that were at greatest risk of loss, particularly in the advanced fuel cycle area. The loss of skills and capability has largely been averted for now and work has been funded which has developed or reinforced skills at all levels from technical apprentices and PhD students up to subject matter experts.
- Outside of the fuel cycle area there has been much good work in protecting key skills, but there also are some clear gaps.
    - In materials and manufacturing there has been an impressively broad range of activities that have started at low Technology Readiness Level (TRL) and been partially developed. The pathway to impact is not clear, and a focus on realising the benefit for the most promising areas is recommended.
    - The work in simulation science (reactor physics, thermal hydraulics, and digital twin) has brought together collaborative communities and has grown and developed skills.
    - NIP funding has improved the UK's Nuclear Thermal Hydraulics Computational Fluid Dynamic modelling capability for Advanced Modular Reactors, particularly

for liquid metals and molten salts technologies, but there is much to do to make this sustainable and provide supporting facilities.

- Funding for regulators has significantly improved their preparedness to regulate advanced rector systems and to engage with potential SMR and AMR developers to make clear the information required to underpin licensing and regulation. The regulators' adaptability and openness to innovation has also shifted during this period, with an increase in awareness and capability in this domain. This will be important to include within the AMR RD&D programme, as the regulators are unable to dedicate time to this engagement without Government funding, so this would need to continue in follow-on programmes.

However, it should be recognised that the root cause of the risk to key skills was the absence of publicly funded research in areas where commercial organisations have no short-term incentive to fund research. There is therefore a requirement for some proportionate level of public funding to sustain skills that are or will be needed to support an appropriate nuclear programme and maintain no less than an intelligent buyer capability relevant to a range of systems.

There is an emergent challenge to sustaining key generic and indigenous nuclear technical and operational skills as the Advanced Gas Reactors (AGRs) are shut down, but before HTGR reactors become established, particularly given the potential gap in time which might be 10 years or more. Key skills in structural integrity, thermal hydraulics, reactor physics, reactor chemistry, fuel manufacturing and materials science (especially graphite) will be required. NIRAB will need to do more work to assess the needs of a future skills maintenance and development programme, as current Nuclear Sector Strategy Group Nuclear Workforce Assessment is focussed on more practical construction related skills moving into operation and has yet to identify a full set of needs for the SMR and AMR programme. A developing future operator for the HTGR Demonstrator could make use of these skilled people and ensure transferable knowledge from the AGR programme is utilised.

International perception of the UK as a nuclear nation

NIRAB believes that the research and innovation funding from the NIP has gone some way to improve previous international perceptions of the UK as merely a niche player [3] in several ways:

- the very existence of the NIP has provided a signal to the international community and has improved the perception. Several components of the programme have also directly facilitated international engagement, further improving the situation;
- the UK has re-joined, and is fully integrated into, the Generation IV International Forum (GIF) and funding has been provided to enable representatives to provide a valuable input to discussions for the first time in more than a decade. Elements of the NIP have also provided important in-kind contributions for UK GIF representatives of interest to other nations in GIF. Funding has also enabled a UK representative to hold the role of GIF Policy Director as well as UK representatives on the Expert Group, Senior Industry Advisory Panel (SIAP), GIF Very High Temperature Reactor (VHTR) and GIF Sodium Fast Reactor (SFR) Programmes.

- NIP has funded engagement with OECD/NEA programmes and allowed UK participants to, for example, engage in international benchmarking exercises that impact on future policy decisions;
- NIP has also funded engagement with international initiatives exploring, for example, non-electric applications of nuclear heat;
- UK organisations have been a valuable partner in international collaboration on fuel development;
- NIP funding underpinned the establishment of the UK's first IAEA Collaboration Centre for 2020-2024 on the most important area, Advanced Fuel Cycle, led by NNL, that is an important building block for AMRs, SMRs and larger reactors;
- UK Regulators have begun to engage with other international regulators on a range of Advanced Nuclear Technologies (ANTs).
- Some of the research funded within the programme has directly fed into bi-lateral collaborations such as the US – UK Action Plan. Research in areas where the UK has a historic strength that is not available in the collaboration partner is particularly valuable. This also appears to be opening up interest and opportunities to collaborate on HTGR topics based upon a recent showcase of progress held in July 2022.

Continued participation in these international programmes is necessary if these benefits are to be sustained. Delivery of the HTGR programme to the timescales necessary will only be achieved through international collaboration

Cost Reduction / Job Creation

An objective of the NIP was to identify ways in which the cost of nuclear energy could be reduced. This objective applies equally to the future construction and operation of large and small reactors and to advanced reactors as well as light water reactors. The development and proving of advanced joining methods is one of the ways in which construction costs might be reduced, especially when combined with a modular construction approach. As a result of the NIP:

- a wide range of materials and manufacturing projects has been supported with the aim of developing novel approaches able to reduce costs, including innovative manufacturing and joining technologies, such as Hot Isostatic Pressing (HIP) additive manufacturing, and electron beam welding. Whilst lower TRL research has been supported, this needs to be followed up by considering a route-map to exploitation.
- At least one small to medium enterprise (SME) has developed a coating technology which will be deployed by a fuel vendor.

Nuclear Innovation Programme – Specific Impact per Sub-programme

This section provides an evaluation of each sub-theme with the focus on drawing out specific innovations or R&D that could have a significant impact in supporting the development of an AMR demonstrator, and subsequently an AMR fleet, to the timescales necessary for a meaningful contribution to net zero carbon emissions by 2050, whilst also considering how to maximise UK content. NIRAB noted that the sub-programme budgets varied enormously, ranging from <£2m (decommissioning and robotics and Strategic Toolkit, up to £46M for AMR

Feasibility and Development and £67M for the Advanced Fuel Cycle Programme, so direct comparison is not appropriate.

Advanced Fuels – Fuel and Recycle Overview

The Advanced Fuel Cycle Programme (AFCP) appears to have been well coordinated to achieve a specific set of goals and there has been considerable collaboration incorporating a wide range of industrial and academic organisations and national labs. The programme funded work on the development of several fuel types, exemplified below.

- Work on Advanced Technology Fuels more widely known as Accident Tolerant Fuels or (ATF) for current generation LWRs enabled UK organisations to engage with international partners with the goal of developing a commercially viable fuel product with significantly improved performance under accident conditions.
- Work on Coated Particle Fuel development, an important step towards HTGR fuel, supported a collaboration with the Japan Atomic Energy Agency
- Work on MOX fuels for fast reactors supported engagement with the Generation IV International Forum (GIF)

Vital work to keep capability open in recycling of fuel and other elements of the back end was also supported.

Work also supported participation in round-robin testing under the NEA OECD nuclear data programme. The positive impact of the programme to date will unravel in the absence of any ongoing programme.

However, NIRAB judges that further coated particle fuel development for HTGR from a UK source, if feasible, is on the critical path, and further development of pebble and prismatic fuels must be close to the critical path. Fuel is an area where significant international growth is expected, and where technology evolution is very significant. A NIRAB report will be published on this in due course. We noted that work to develop nuclear fuel for Advanced Nuclear Technologies has progressed internationally, and UK engagement has been important in the progression internationally and in the UK. The UK is close to the level of development internationally outside of China and Russia, and could develop a route capable of fuelling reactors at home and abroad. However, it is also expected that there will be options to procure fuel internationally in the future (outside of China and Russia). Demand vs supply may be an issue, and security of supply is a concern, as outlined in the British Energy Security Strategy [9]. There are also potential options to develop at an accelerated UK basis by technology transfer to the UK to then manufacture locally.

Recommendation 1: Nuclear fuels is an area where the UK has world leading expertise and associated R&D infrastructure and these should be used to progress the development of commercial scale enrichment and fuel manufacturing facilities, capabilities, and related tools that, as a minimum, could provide the fuel (TRISO) for a HTGR demonstrator. But more broadly could also provide fuel to international partners/markets.

Advanced Manufacturing and Materials Overview

The Advanced Manufacturing and Materials (AMM) programme held the promise of a significant potential decrease in the capital costs and risks of new nuclear power stations by offering a number of benefits, including off-site fabrication. It funded a wide range of projects although the technologies proposed tended to be low TRL, so it is unclear at this stage whether the work done will contribute to cost reduction or if it will be developed further with industrial support.

The NIP delivered several step changes in UK knowledge and capability in nuclear materials:

- The Industrialisation of Thick Section Electron Beam Welding Project delivered a full-scale component fabrication capability with substantial increase in TRL, providing an internationally relevant use case on nuclear sector agility in the UK.
- The U-Battery Advanced Modular Reactor HTGR: Full-Scale Demonstrator project demonstrated the full-scale modularised construction, transportation, and inspection of full-sized vessels (noting that the vessels were constructed with thinner walls than required for reactor operation, limiting its capacity to fully replicate reactor construction).
- The Automated Welding Equipment System Inspection and Monitoring (AWESIM) project developed the ability to both weld and undertake non-destructive testing in line, potentially saving significant time, and improving quality of welds in key nuclear components, which are often the weak point in components.
- The Nanostructured Steels to Extend Operational Performance Project was an outstanding example of industry, academia, and national laboratories (NNL and UKAEA) working together and has created a vital first step towards creep-resistant high temperature components to enable Generation IV and future fusion builds.

The Rolls Royce (RR) SMR project has (understandably) been concerned with low-risk and proven technology that can be rapidly implemented to support Generic Design Assessment (GDA) and First of a Kind (FOAK) timescales. The AMR RD&D programme and potential future AMR and SMR fleets have the possibility to utilise innovation beyond that of the RR SMR due to their longer lead time – but only if these can be delivered in a timely manner and are adequately demonstrated to meet operational and regulatory requirements. Crucially, the AMR programme also needs to take benefit from the improved deliverability designed into the SMR programme.

Significant progress has been made on codes and standards for HTGR reactors by international bodies such as American Society of Mechanical Engineers (ASME), and the NIP allowed the UK supply chain which has expertise in structural integrity to engage in this. The UK has some specific adaptations/procedures above such codes, providing additional substantiation to structural integrity safety cases for materials containing defects. Whilst this was developed for the current UK fleet, investment would allow it to be leveraged for HTGR materials assessments.

Recommendation 2: A vehicle or platform to enable accelerated commercialisation (i.e. rapid Technology Readiness Level progression and route to market) is needed, within an enabling regulatory framework if innovative materials and/or manufacturing techniques (as example technical areas of development) are to be implemented into future AMRs on the timescales needed to meet the 'early 2030s' Demonstrator timescale. Innovation must take second place to achieving the overall objective of a large economic HTGR programme.

Recommendation 3: Codes and Standards, Procedures and Guidance compliance of new reactor technology will be a requirement of the regulators (both in the UK and

internationally). The strong international reputation of the UK nuclear regulators could be used to encourage and influence the development of international design codes and standards for UK applications, where additional evidence may be required to support the UK claims, arguments, and evidence approach, and it will be important to fund this.

Advanced Modular Reactor (Feasibility and Development and Regulator Capacity) Overview

Funding within this theme included supporting regulators to prepare for regulating Advanced Nuclear Technologies. This significantly enhanced the ability of regulators to assess AMRs and has provided valuable feedback to potential reactor developers / vendors, as well as enabling regulators to engage with international colleagues to identify common issues, best practice and to influence international standards.

We noted that £30M was spent bringing forward three potentially promising reactor technologies (U-Battery HTGR, Westinghouse Lead-cooled Fast Reactor, and Tokamak fusion reactor). Since the AMR R&DD Programme is focussed on HTGRs two of these technologies will not currently be taken forward with BEIS innovation funding; however, they may be brought forward with private investment. We understand the balance of challenges. Whilst keeping options open has retained a level of competition and has supported capability more broadly, focus is now needed on technologies that are in a position to be able to make a significant contribution to net zero by 2050 timescales. Effort needs to be made to secure transferable material from the projects not taken forward and store that knowledge, in case options need to be explored in future, and to transfer lessons to the HTGR programme. Clear metrics are needed to ensure that money spent on the HTGR technology in Phase A of the AMR RD&D programme drives value and that further genuine progress is made and monitored to avoid "double-dipping" for work already funded.

NIRAB will develop further advice to support the transition to Phase B, where successful R&D needs to be transferring into commercial application.

NIRAB reviewed an example where this NIP funding stream supported other AMR reactor types beyond HTGR. It was noted that this work has improved design maturity and led to rig development that can be used more generically to benefit future trials. It is important to understand if these can be taken forward to benefit other programmes of work.

An interesting finding from NIP was a clear request from many stakeholders in a survey undertaken as part of the programme evaluation for funding for regulators to have innovation "sand pits" that enable innovative solutions to be considered in regulatory space prior to entering time consuming and expensive regulatory approval processes.

<u>Recommendation 4:</u> <u>Funding for regulators should continue at an appropriate level to meet HTGR programme needs.</u> NIP funding has enabled regulators to improve knowledge of AMRs significantly to enhance their ability to assess AMRs, and has provided both valuable feedback to potential reactor developers / vendors. It enabled the regulators to engage with international colleagues to identify common issues, best practice and to influence international standards. Funding should continue at an appropriate level to meet HTGR programme needs.

Recommendation 5: Further development of the GDA regulatory process for HTGRs that addresses both the reactor and the technology to extract the heat in the context of a real industrial setting is needed, including trialling innovation sandpits.

Recommendation 6: Ensure transparency in decision making, and that technology choices are made at the right time, with the right evidence, with money focussed as far as possible on the most promising technology.

Recommendation 7: A vehicle or platform to enable accelerated commercialisation (i.e. rapid Technology Readiness Level progression and route to market) is needed if novel control and protection strategies (as an example technical area) are to be implemented into future AMRs within the necessary timescales.

Advanced Reactors

Initial funding for advanced reactor thermal hydraulics model development enabled thermal hydraulics modelling skills to be nurtured[1]. The intent to support rig design, build and operation was not delivered, although that was in the original BEIS plan. If progressed this could have supported the RR SMR, but this opportunity is now likely to be missed, though it could still be an opportunity to support AMR development. This is discussed further in the Thermal Hydraulics theme section.

Digital innovation has a key role to play in enabling the deployment of advanced nuclear technologies in the UK. Digital twins have the potential to facilitate rapid design iteration, helping to shorten the design cycle, moving away from traditional timely and expensive experimental programmes. They could also enable improved operational efficiencies, helping to inform operational strategies and reduce risk, evolving alongside the physical reactor, continually incorporating operational data to further refine the digital twin throughout its entire life cycle. Work in this area is essential to enable the UK to drive reductions in cost of nuclear reactor design and build, and of supporting infrastructure (co-generation and other applications on terms of heat).

Recommendation 8: Build facilities, tools, and capability to undertake thermal hydraulics experiments through validation of high-fidelity computational fluid dynamics, multi-physics codes and similar tools. Continue to close a key gap in intelligent customer capability. Areas of focus should include fluid flow of helium, and validation of passive safety systems for post-shutdown heat removal.[1]

Recommendation 9: Digital innovation (including real-time monitoring, including remote / robotic in-service inspection), should be an integral component of the AMR RD&D programme, and specifically for HTGRs, which will help to validate supporting modelling activities [8], key to substantiating lifetime of a plant with components in a harsher environment.

[1] Note that this section deals with such thermal hydraulic skills generically, whereas the NIP workstream on thermal hydraulics was targeted at preparation for of strategy and specification for facility design and construction for a specific facility at a specific location.

Strategic Toolkits

NIP funding enabled coordination of UK input to international projects such as the OECD Halden project and the Jules Horowitz materials test reactor. It also supported capture of historic data and facilitated participation in the Generation IV International Forum and NEA-OECD membership. Potential for reputational loss and ability to leverage knowledge through collaboration is significant if this was stopped. BEIS also sponsored development of an online toolkit for Safety Cases (by Frazer Nash Consultancy), and this could be of value to future developers if they are provided access.

Recommendation 10: Continue funding membership and participation in international fora, including cost for UK representatives to travel, engage, and ultimately shape future direction. Delivery of the HTGR programme will be dependent on international engagement.

Recommendation 11: Ensure knowledge is captured and further promulgated from NIP to benefit GW, AMR and SMR programmes.

Decommissioning & Robotics

This was a broad-ranging programme, which provided the flexibility for bidders to include any technology they wanted to offer in order to drive innovation, to drive safer, faster, and cheaper decommissioning routes, but this is not an area that is a current target for this section of industry. NDA should be the lead sponsor of this research. There is relevant work in this area around robotics for in-service inspection and design for decommissioning that remain relevant.

Recommendation 12: This Decommissioning/Robotics programme approach proved successful in driving innovation in the nuclear sector, and in developing UK international reputation. The area of focus should be realigned to design for decommissioning.

UK Thermal Hydraulics Facility

Whilst the UK has retained a partial capability (skills and infrastructure) in thermal hydraulics there are currently no large-scale test facilities, and facilities and capabilities have been lost. A specific location was being considered. A lack of certainty, in relation to lack of funding through the last spending review, has stalled progress. Currently, without intervention, this appears to be leading to a missed opportunity to support UK skills and capability development in this area required by RR SMR, and creating risk. As many nuclear nations are looking to accelerate their nuclear deployment, this could put a premium on accessing international facilities for UK needs.

Recommendation 13: Undertake a review of programme to determine whether a UK facility could be put in place in time to support Rolls Royce SMR. If not, review the business case for buying into facility support internationally, short, and longer term. Compare with constructing facility targeted at supporting UK reactors in the future, including HTGR. Certainty and long-term funding commitment will enable this programme, which has the potential to still support other Advanced Nuclear Technologies, to progress.

Nuclear Innovation Programme – Concluding Comments

- The NIP has made a significant impact. Some level of ongoing research and innovation funding will be required if the benefits to date are to be sustained or built on. For example, advanced fuel cycle skills are no longer at immediate risk, but some level of work will be required to prevent the recurrence of that risk.
- The NIP has ensured that at least some improved intelligent customer capability has been secured across the full range of reactor systems, although capacity development is limited.
- Similarly, there is currently a good level of international engagement that ultimately drives future nuclear policy, but some level of funding will be required to sustain that engagement, by paying UK membership fees and funding the costs of travelling to meetings.
- Contracts have been let under the NIP in several programme areas and often in several phases within each programme. Whilst appropriate contracting processes need to be followed, the stop/start nature of funding has limited the progress that can be made in the programme as a whole. Continuity in any future funding should be maximised.
- The vision for experimental thermal hydraulics has not yet been delivered as a consequence of the thermal hydraulics facility being delayed.
- It is evident that a range of contracting strategies have been adopted. At one end of the spectrum, large contracts have been let to achieve a broad range of objectives across a whole programme area. This facilitated the delivery of programmes involving a wide range of organisations. At the other end of the spectrum, for example in the materials and manufacturing programme, numerous contracts were let to individual contractors. The route to deployment of the results of many of these contracts is not evident from the NIP summary brochure.
- There was limited collaboration within NIP project's sub-themes and across the themes more generally, and this could be facilitated in a future programme, through a delivery model/vehicle.
- NIRAB continues to work to develop recommendations for research priorities within a future innovation programme, which may need to be reactive to adapt to emerging outcomes from current programmes.

The NIP has contributed to the ability to develop and regulate an HTGR demonstration system. Just as importantly it has supported expertise relevant to a range of other advanced systems which may have a role to play further into the future. Without the NIP programme the 'HTGR Foundations' would surely have been much less firm.

NIRAB noted the importance of continuity. The stop/start nature of research contracts impacted both the momentum of projects (particularly for follow on phases of funding if delayed) and on the availability of technical resources to deliver the work, often meaning projects had to be delivered in shorter timeframes, and potentially impacting the quality of the final output.

<u>Recommendation 14</u>: It is recommended that multi-year goals are set and associated funding for future programmes to achieve those goals is committed to avoid stop/start issues.

Recommendations for future nuclear R&D funding

Recommendation 15: NIRAB supports continued and increased commitment to fund a broad range of future R&D, as we believe that many skills and facilities are, as yet, not resilient. We believe the future programmes should continue the same themes, with a focus on HTGRs.

Recommendation 16: Set up a future programme (following as quickly as possible on from NIP) comprising of parallel portfolios - for foundational research and applied research (innovation). We remain concerned that a broad range of skills and innovations will not be retained through current commercial routes and need further support. A thorough update to the Workforce Assessment to include a focussed update on SMR and AMR needs is recommended.

NIRAB suggests the following streams of work for such a future programme:

- Maintain and extend a broad strategic knowledge and technical capability to support the future UK nuclear industry (fission and fusion), without foreclosing options related to closed fuel cycle and limiting technologies. Focus will be on delivering sovereign security, intellectual property leadership and securing export benefits.
- Focus on engineered solutions towards licensable HTGR technology and associated infrastructure, opening the potential to deliver an HTGR fleet. Together, these dual streams should aim to continue to raise UK position on the international stage while growing the UK intelligent customer capability around fission and fusion energy of all types.
- There will need to be well managed coordination of the programmes for cross-fertilisation of ideas, and a clear set of expectations set at the start.

Challenges facing prioritisation of future R&D needs

The use case for the AMR RD&D will guide key decisions on our advice on innovation and R&D needs for delivering an AMR demonstrator to the timescales required, by the early 2030's. For example, power, outlet temperature and co-located facilities will all inform what R&D is required. NIRAB expects to undertake work later in 2022 to provide further advice in this area. The prioritisation criteria may need to be reactive to trends emerging both in Phase A of the programme, and as use cases become clearer.

NIRAB has debated the balance of implementing innovation (risk of failure in R&D) versus time to deploying an AMR RD&D project, and remains concerned about the tension between deployability of high levels of innovation and the requirement to demonstrate in the early 2030s.

In considering the benefits and risks of a very adaptable demonstration plant versus pushing for a demonstration plant very close to first of a kind and the planned fleet, an early active Demonstrator using proven high TRL components, heavily instrumented and with additional safety systems to allow trial of components up to much higher temperature ranges could be considered – with the capacity to switch in new novel material/manufactured components. However, NIRAB believes this is a significant risk to the schedule to deploy a fleet of HTGRs capable of making an impact on net zero. NIRAB believes that a demonstration plant needs to be close to a FOAK so that technical feasibility, regulatory compliance and investability are demonstrated.

Recommendation 17: The Demonstrator should look very like the FOAK, and should seek to demonstrate siting, construction, licensing, operation, and the full end use of the heat output; in other words, demonstrate the practical delivery of something useful to the UK based upon HTGR technology. This may restrict the extent to which the reactor can be used as an R&D/experimental facility.

Research and Development that has been directly relevant to UK HTGR AMR demonstration

Relevant R&D originally supported within NIP

HTGR technology was only identified as an AMR technology of particular interest towards the end of the NIP. Although the programme was not specifically designed to facilitate HTGR demonstration or deployment, it is still possible to take a retrospective look at the programme to identify where or how it might contribute to potential future HTGR deployment.

Examples of such relevance include:

- Work on coated particle fuels (CPF) is directly relevant to HTGR and supports the development of a strategically important indigenous UK capability. It has potential relevance to a number of other reactor types, including micro-reactors as well as power reactors supplying bulk industrial heat.
- The work undertaken to develop and couple reactor physics codes with fuel performance and thermal hydraulics is relevant to a range of reactor systems, including HTGR.
- Work starting to update nuclear codes and standards requirements for a range of advanced reactor systems is also relevant to HTGR.
- The substantial funding provided to regulators has significantly improved their preparedness to regulate advanced reactor systems. Regulators have engaged with developers of a range of reactor technologies, including HTGR. There are principles of passive safety design and regulatory response that will benefit from this work.
- Starting development of Thermal Hydraulics tools and capability.
- Development of innovative inspection tools for manufacturing will be particularly important if we move to modular, factory build programmes.

R&D within NIP that can stop

NIRAB has not identified any work from NIP that should be stopped at this stage.

R&D required above and beyond NIP

NIRAB is already starting to develop themes and sub-themes required for development beyond NIP which we understand would sit in AMR RD&D Phase B. NIRAB would welcome access to the AMR Phase A deliverables to support work in this area. These are likely to include the following development sub-themes (not a comprehensive list):

- fuel supply infrastructure for TRISO fuel including and beyond coated particle fuel to ensure a potential full UK fuel solution for the Demonstrator;
- materials, modelling, and systems for cogeneration / energy off-take;
- transferability of learning from fusion to fission and vice versa;
- low activation graphite, including potential UK supply solutions;
- passive safety validation;
- automation of control and protection;
- support for regulation and licensing [8]
- condition based monitoring.

NIRAB believes that a roadmap for HTGR deployment aligned to the R&D programme will be a major benefit to drive forward an HTGR programme.

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Appendix 1

<u>Key Questions to NIRAB – from BEIS</u>

- Has the NIP Programme made a positive impact on the nuclear innovation in the UK?
- What else needs prioritising?
- What R&D can we stop resourcing?
- What R&D is needed in terms of R&D in order to build an AMR demonstrator to the timescale necessary for a meaning contribution to net zero carbon emissions by 2050?
- How does the UK deliver an AMR demonstrator to the timescales required?
- NIRAB members to offer their expert opinions on how this can be achieved using innovative methods from their experience and knowledge to maximise UK content?
- Opportunities to further exploit the technology.