NUCLEAR INNOVATION AND RESEARCH ADVISORY BOARD

Research, Development and Innovation required for a High Temperature Gas Reactor Demonstrator

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Report

Technical Appendices

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Edition 1

Our sponsors in the Department for Energy Security and Net Zero (DESNZ) have asked us an interesting but challenging question. “What Research, Development and Innovation (RD&I) is needed for the UK to deliver a High Temperature Gas Reactor (HTGR) Demonstrator by the early 2030s?”

Amidst the intensifying climate crisis, and in a shifting energy landscape, the importance of energy resilience, stability of supply and energy security is apparent. The UK has made a legally binding commitment to be a Net Zero nation by 2050 so there is an urgency in addressing the UK’s energy requirements through clean, reliable, environmentally sustainable sources.

Nuclear energy’s emission-free characteristics make it an important component of a compelling climate change solution for various industrial applications and advanced reactor designs offer opportunities to abate ‘hard to decarbonise’ sectors through higher temperature heat and efficient hydrogen generation.

2024 will be critical in setting the direction of the UK’s future nuclear programme. To have significant impact on the net zero targets there must be clarity on the role different nuclear technologies will contribute and the timescales associated with their delivery.

There is a clear need to build momentum behind existing programmes to realise the wider socio-economic benefits of nuclear power and to that aim, what role advanced nuclear technologies can play in the future nuclear energy mix.

It has been a privilege to Chair the Nuclear Innovation and Research Advisory Board (NIRAB) as we have set out to answer this question.

Professor Francis Livens
Chair of the Nuclear Innovation and Research Advisory Board (NIRAB)

Executive Summary

The third iteration of the Nuclear Innovation and Research Advisory Board (NIRAB III) was convened in 2021 comprising of industrial, academic and independent experts with diverse backgrounds. The group was tasked by the Department for Energy Security and Net Zero (DESNZ) with the question: 'What RD&I would be required to deliver a High Temperature Gas Reactor (HTGR) Demonstrator by the early 2030s?'

At present the specific reactor design, size, use-case, the developer, and role of HMG (including Great British Nuclear (GBN)), licensee, operator, siting, cost and precise schedule have not been determined. Hence, NIRAB looked to answer this question through a technology agnostic lens, without access to design details, level of maturity or RD&I programmes of specific advanced reactors.

NIRAB has interpreted the question as meaning the Demonstrator should couple electricity production with high temperature heat output suitable for use in industrial applications and it must be able to operate under conditions representative of a full-scale reactor for substantial periods of time. Whether the electricity is output to the national grid or by private connection has not been considered. NIRAB has also emphasised the 'early 2030s', which it takes to be between 2030-2034 and has therefore deprioritised some aspects of RD&I which would take longer to implement. Based on this interpretation, NIRAB advises that the Demonstrator be as close as possible to a First of a Kind (FOAK) or prototype to de-risk and support timely roll-out of a fleet (provided the Demonstrator meets programme objectives and the business case can be made for fleet build), to enable HTGRs to make a significant contribution to net zero by 2050.

These deployment timescales are extremely challenging and require innovative but pragmatic solutions and high levels of ambition and commitment, underpinned by RD&I, if they are to be achieved. There is also likely to be some prioritisation and sequencing required in ordering the RD&I activities, running some in parallel and identifying those which are more complex and will require longer to solve. The Demonstrator will also need to have some attributes of an experimental, research and training reactor to support this aim, and it will also need to deliver significant improvements in HTGR reliability and operability compared to historical plants.

The basic science and engineering behind HTGR technology is mature. But a reliable, licensable, commercially viable plant of any size has yet to be developed anywhere in the world outside of China. The experience of connection of a civilian nuclear reactor to a non-electricity use case is particularly limited. NIRAB therefore undertook a thorough review of all RD&I objectives needed to generate evidence/data to underpin licensing across the HTGR lifecycle to understand the possible users of the reactor's outputs and their requirements for high temperature heat (greater than 500oC). Secondly, we looked at the technological challenges associated with the HTGR reactor, highlighting areas that will need specific research, development, or innovation. Lastly, we looked at what is needed to deliver a HTGR Demonstrator. We have described the main RD&I objectives in this report and have provided a thorough list in an appendix. We have not gone so far as to imply who should do these RD&I activities or where they should be done, indeed we acknowledge that in some cases work to deliver some of these objectives may already be in-flight and/or be undertaken overseas.

The RD&I list has been categorised, with NIRAB identifying 'essential' RD&I (without which there cannot be a working Demonstrator), 'highly valuable' RD&I (activities which are needed to realise the full benefits of the HTGR Demonstrator) and 'valuable' RD&I (activities which will generate useful data to benefit the use case, improve efficiency or apply learning to increase the likelihood of an investment decision for fleet deployment).

In this report, we continue to use the italicised words to emphasise the classification which we have assigned to a specific RD&I activity.

From a use-case perspective, there are several industrial sectors in the UK which could be assisted in decarbonisation by using the heat outputs from a HTGR. Synthetic Aviation Fuel (SAF) production is one example that NIRAB wishes to highlight since it provides a good illustration of both the challenges and opportunities of coupling HTGR's to other industries. Production of synthetic aviation fuel is currently limited by the need for hard-to-acquire biological feedstock but could be improved through use of hydrogen and captured carbon using a Reverse Water Gas Shift (RWGS) reaction and the Fischer-Tropsch process. A HTGR could provide the necessary heat and power for both hydrogen production and Direct Air Capture (DAC) of carbon. NIRAB therefore undertook a deep dive into the SAF production process to understand what RD&I may be needed to effectively couple HTGR outputs to this use-case.

Interfacing HTGRs with end users such as SAF producers will require smart reactor manifold designs to manage reactor heat outputs at different temperature ranges required for different steps in the process. Further RD&I is therefore needed on heat exchanger and heat exchange media modelling, looking at, for example, gas-gas or gas-to-molten salt heat exchange, as well as innovation in design and manufacturing for all components attached to the reactor. Research on and down-selection of both heat storage technologies to allow steady state HTGR operation and the associated heat network transmission media is needed. This RD&I will also have benefit to other sectors that are considering molten salt or similar high temperature energy storage/transmission.

From a technology perspective, NIRAB recommends that RD&I is centred on three themes of:

- fuel and core materials
- materials and methods for manufacture
- modelling, simulation, and design

To enable delivery, NIRAB believes that RD&I related to planning, siting, and regulation, especially the interaction with associated industrial plants, is needed. An integrated regulatory approach developed covering nuclear and non-nuclear regulatory regimes if co-location is to be adopted would be highly valuable.

Additionally, NIRAB has identified several areas where decisions on who is responsible and accountable for leading specific aspects of the Demonstration HTGR plant through the design and delivery process needs attention and/or clarification.

In summary, NIRAB believes the following areas of RD&I warrant further investment:

- Connecting the HTGR to use-case applications
- Developing leading UK technology, embedding advanced manufacturing techniques and construction methods in advanced reactor designs
- Supply of fuel and core materials which are not commercially available in industrial quantities in the UK or internationally but will be key to independence in nuclear power
- Reliably harnessing the necessary fluids, and assessing performance of key systems, structures, components, and materials in a hot fluid environment
- Designing and through-life substantiation of a safe and highly thermally efficient system achieving high integrity
- Enabling delivery by clarifying roles and responsibilities and ensuring appropriate siting and regulatory arrangements are in place

Additionally, NIRAB believes engagement with end users and collaboration across sectors needs to ramp up significantly, starting with Government funding of strategic RD&I activities and coordination of related projects. Such collaboration will require significant effort and must be carefully facilitated to achieve the highly ambitious timescales associated with the net zero targets.

NIRAB welcomes the opportunity to provide further independent advice, with the long-term aim of supporting delivery of a HTGR programme.

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Glossary

AGR	Advanced Gas-cooled Reactors
AMR	Advanced Modular Reactors
ANT	Advanced Nuclear Technologies (UK term for SMRs and AMRs)
ASME	American Society of Mechanical Engineers
BPVC	Boiler Pressure Vessel Code
CoRWM	Committee on Radioactive Waste Management
CPF	TRISO Coated Particle Fuel
DAC	Direct Air Capture
DCO	Development Consent Order
DESNZ	Department for Energy Security and Net Zero
EA	Environment Agency
EdF	Electricité de France
EPSRC	Engineering and Physical Sciences Research Council
FDP	Funded Decommissioning Plan
FOAK	First Of A Kind
GBN	Great British Nuclear
GDA	Generic Design Assessment
GIF	Generation IV International Forum
GW	GigaWatt – large nuclear stations of the order of magnitude 1GW electrical per unit
HALEU	High Assay Low Enriched Uranium (~ 20% enriched U-235)
HMG	Her/His Majesty's Government
HoC	House of Commons
HoL	House of Lords
HTSE	High Temperature Steam Electrolysis
HTGR	High Temperature Gas-cooled Reactors
HTTR	High Temperature Test Reactor
JAEA	Japan Atomic Energy Agency
KPI	Key Performance Indicator
LEU+	Low Enriched Uranium with higher enrichment – typically 6-10% U-235
LCOE	Levelised Cost of Electricity
Magnox	Magnox reactor, gas cooled (CO2) with graphite moderator. The fuel is natural uranium in metallic form, canned with a magnesium alloy called 'Magnox'
MoD	Ministry of Defence
NEA	Nuclear Energy Agency
NIP	Nuclear Innovation Programme
NIRAB	Nuclear Innovation and Research Advisory Board
NIRO	Nuclear Innovation and Research Office
NSAN	National Skills Academy for Nuclear
NSL	Nuclear Site Licence
NSSG	Nuclear Skills Strategy Group
ONR	Office for Nuclear Regulation
PWR	Pressurised Water Reactor
RAB	Regulated Asset Base
RAG	Red-Amber-Green
RCF	Recycled Carbon Fuel
R&D	Research and Development
RD&D	Research Development and Demonstration
RD&I	Research Development and Innovation
SAF	Synthetic or Sustainable Aviation Fuel
SMR	Small Modular Reactors
T&CP	Town and Country Planning Act
TRISO	TRi-Structural ISOtropic coated particle fuel
TRL	Technology Readiness Level
VALCOE	Value Adjusted Levelised Cost of Electricity
UKAEA	United Kingdom Atomic Energy Authority
WAC	Waste Acceptance Criteria
WAGR	Windscale Advanced Gas-cooled Reactor

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1. Introduction

1.1 Background to NIRAB

The Nuclear Innovation and Research Advisory Board (NIRAB) is a group of independent experts who work in partnership with the Nuclear Innovation and Research Office (NIRO) to advise ministers, government departments and agencies on issues related to nuclear research and innovation in the UK.

NIRAB also invites the DESNZ Chief Scientific Adviser and observers from the Office for Nuclear Regulation (ONR), Environment Agency (EA) and The Engineering and Physical Sciences Research Council (EPSRC) to attend plenary meetings. The third iteration of NIRAB (NIRAB III) was convened in autumn 2021 with experts from industry, national laboratories, academia, and independent consultants, offering a broad range of expertise.

Details of the current NIRAB membership can be found at the end of this document and terms of reference, meeting minutes and relevant publications can be found at **www.nirab.org.uk.**

1.2 The Ask of NIRAB III

UK Government has stated its aim to have an advanced nuclear programme, including a High Temperature Gas-cooled Reactor (HTGR) Demonstrator operational 'by the early 2030s'[1]. A significant amount of research, development, and innovation (RD&I) will be required to achieve the aim of siting, designing, licensing and permitting, manufacturing, constructing, commissioning, operating and maintaining a Demonstrator as a credible prelude to future commercially viable fleet deployment. Within this context, NIRAB has been asked to consider:

'What RD&I is required to deliver a HTGR Demonstrator by the early 2030s?'

NIRAB recognises that some of the RD&I required will be tailored to the specific reactor design and application(s) that UK Government chooses to progress. In the absence of these details, NIRAB has adopted a technology-agnostic approach to outline

i) essential RD&I to support licensing and permitting of a Demonstrator

ii) highly valuable

iii) valuable RD&I activities that can enhance the investment case by reducing the risk profile of a programme, or operational related RD&I for specific designs

It has also set out to identify those RD&I activities that maximise downstream benefits, including positioning the UK to benefit from a HTGR programme that may not be of UK reactor or fuel design, addressing key security of supply risks, and highlighting supply chain opportunities.

1.3 How has NIRAB interpreted the question?

NIRAB has interpreted the question as meaning the Demonstrator reactor should couple electricity production with high heat output suitable for use in industrial applications and it must be able to operate under conditions representative of a full-scale reactor for substantial periods of time.

NIRAB has also assumed 'early 2030s' to be between 2030-2034 and have therefore deprioritised some aspects of RD&I which would take longer to implement. NIRAB's view is that a 'Demonstrator' will have most value if conducted at near First Of A Kind (FOAK) scale, and that the reactor should be coupled to the use of its heat output.

The basic science and engineering behind HTGR technology is relatively mature, but currently a reliable, commercially viable plant with potential for net zero mitigation has yet to be developed outside of China. Therefore, there are RD&I activities that the government should expect to see in any programme to deliver a Demonstrator in the UK, regardless of by whom or where these activities are undertaken or size (output) of the actual reactor design. These essential RD&I activities could be viewed within the context of a 'delivery roadmap' for a HTGR Demonstrator identifying RD&I that is on the critical path and key areas that could reduce delivery uncertainties, drive down costs and increase the speed of construction and therefore be considered 'no regrets'.

NIRAB is not necessarily saying that the UK has to do all the RD&I recommended itself, rather is providing a checklist of RD&I that we believe must be undertaken in order for a HTGR to be deployed in the UK.

1.4 Definition of Nuclear RD&I

The terms 'Research and Development' (R&D), 'Research, Development and Deployment' (RD&D) and 'Research, Development and Innovation' (RD&I) are used interchangeably across the nuclear sector and there are many definitions in circulation as to what activities can be classified within each definition.

For the purposes of clarification NIRAB considers research, development, and innovation to be the processes of developing and/or commercialising new concepts, implementing new processes, or changing how an activity is undertaken in order to realise new benefits. Hence throughout this report we refer to a combination of R&D and Innovation within the collective RD&I acronym.

NIRAB also recognises that what some organisations describe as verification and validation activities others would class as 'development', hence we wish to emphasise that the RD&I activities we describe span the entire nuclear fuel cycle and will be associated with every milestone on the path to HTGR demonstration.

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[1] HTGRs are thermal neutron reactors which can reach outlet temperatures of greater than 700°C, with a helium coolant, graphite moderator and fully ceramic coated particle-based fuel. Depending on the shape of the fuel compacts, HTGRs can be divided into pebble bed reactors or prismatic block reactors, both of which use Tri-Structural ISOtropic (TRISO) fuel particles with high-temperature resistant coatings.

[2] In the UK, HM Revenue and Customs has a definition for R&D (Section 1138 of the Corporation Tax Act, 2010): 'R&D for tax purposes takes place when a specific project seeks to achieve an advance in science or technology. The activities which directly contribute to achieving this advance in science or technology through the resolution of scientific or technological uncertainty are R&D. Certain qualifying indirect activities related to the project are also R&D. Activities other than qualifying indirect activities which do not directly contribute to the resolution of the projects scientific or technological uncertainty are not R&D. To claim tax relief you need to explain how a project: looked for an advance in the field, had to overcome the scientific or technological uncertainty, tried to overcome the scientific or technological uncertainty which could not be easily worked out by a professional in the field, may research or develop a new process, product or service or improve on an existing one."

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2. HTGR experience

2.1

Summary of UK position as a nuclear nation with experience of HTGR

The UK has a world leading heritage in nuclear operations, having built and operated the first nuclear power station (Calder Hall) and then a fleet of Magnox reactors in the 1950s and on into the 1960's.

Advanced gas cooled reactors, using carbon dioxide coolant, were proposed as a second-generation reactor design offering unique benefits for electricity production in the late 1950's. A prototype Generation II/III reactor was designed, constructed, and built at the Sellafield site in the early 1960's (WAGR: Windscale Advanced Gas Reactor).

It provided a test bed for the development of advanced fuel and components and provided operational experience for power production. Simultaneously a higher-temperature helium gas cooled research reactor, DRAGON, was built and operated by UKAEA, together with an associated UK fuel manufacturing plant (now being decommissioned), on behalf of the Nuclear Energy Agency (NEA) at Winfrith, Dorset.

The facilities' purpose was for testing fuel and materials for the European High Temperature Reactor Programme, which was exploring the use of TRISO fuel and gas cooling for new European reactor designs. Both WAGR and DRAGON reactors operated for circa 20 years, entering decommissioning and post-operational clean out in the late 1970s/ early 1980s, where they again provided a testbed for trialing defueling, waste management, decontamination, and decommissioning techniques.

Decommissioning such facilities, along with the Magnox fleet, has provided the UK with knowledge and experience, and has provided a unique insight into the steps required to ensure safe and efficient end-of-life management of reactors.

Over the last seven decades the UK has built a very wide range of zero power, research, and test reactors. The prototype and research reactors helped the UK develop unique world-leading capability in manufacturing techniques, material performance, operational best-practice as well as engineering system design and regulatory oversight. This overarching capability supported the roll-out of the fleet of Advanced Gas Reactors (AGR) and hence, between 1976 and 1989, the UK built seven twin-unit Generation II AGR stations. Four of which (Hartlepool, Heysham 1, Heysham 2 and Torness) are still in operation today, generating approximately 4.8 GWe electricity.

Since WAGR and DRAGON reactors were shut down in the 1970s much of the UK learning that came about from prototyping AGR and HTGR design, licensing, manufacture, construction, commissioning, and operation now sits in archives. As all of the existing AGR fleet are likely to be shut down by 2030, many of the technical support staff will have retired by the time a HTGR will be built and those remaining will likely be encouraged by their current employer, EdF Energy, to support the PWR (Pressurised Water Reactor) stations or AGR decommissioning plans.

At present though, some detailed technical knowledge of key aspects of a HTGR, including neutron moderation via graphite, high temperature gaseous coolants, helium coolant chemistry, TRISO fuel behavior, is still in circulation within the UK's R&D community and the international collaboration programmes with which they regularly engage.

2.2

International HTGR context

There is a handful of Generation IV HTGRs which have been built and operated commercially internationally, predominantly in the USA and more recently in China. Germany operated a zero-power reactor, then a small very high temperature (950°C nominal outlet temperature) pebble bed AVR reactor from 1967-1988, and then a larger THTR-300, running at a moderately high temperature (750°C) in the 1980s. At present four HTGRs (three designs) are in operation globally, a LEU+ (low enriched uranium) demonstration pebble bed test reactor HTR-10 operating at 700°C in China, and two larger scale commercial pebble bed HTR-PM reactor plants (also in China) operating at 750°C and one prismatic LEU+ fuel demonstration reactor HTTR (High Temperature Test Reactor) plant in Japan, which has occasionally operated to 950°C.

There is significant research being undertaken internationally in the design and development of high and very high temperature gas-cooled reactors. In the USA, BWXT, USNC, X-energy are developing HTGRs. Kairos Power is developing a 320 MWth fluoride salt cooled HTR design fuelled with spherical pebbles containing TRISO fuel. The development of the JIMMY HTGR in France is also notable.

Significant progress has been made in China on the detailed design of the HTR-PM600, a 600 MWe commercial plant with six modules.

In GIF (Generation IV International Forum), collaboration efforts on R&D on very high temperature reactors involve Australia, Canada, China, Euratom, France, Japan, Korea, Switzerland, UK, and USA. Poland is also heavily involved through the GEMINI programme and South Africa is showing signs that its pebble bed programme is restarting, whilst Russia has advanced its plans to build HTGRs.

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3. RD&I required to deliver a HTGR Demonstrator

NIRAB has looked at the RD&I required to deliver a HTGR Demonstrator reactor through three lenses: 1) what the reactor can be used for (its use-case), 2) reactor technology considerations and 3) activities needed to enable delivery.

A list of RD&I objectives has been created. A prioritisation process has been undertaken to ran all RD&I activities via the following criteria:

- 'Essential' RD&I is something that must be completed in order to successfully develop and licence a working Demonstrator plant.
- 'Highly Valuable' RD&I is something that could be integrated to enable the full benefits of the HTGR Demonstrator plant to be realised.
- 'Valuable' RD&I is something that could utilise data from a HTGR Demonstrator to benefit the use case, improve efficiency or apply learning to increase the likelihood of an investment decision for fleet deployment.

NIRAB has developed several RD&I programme objectives to provide context and frame for the RD&I activities (Table 1).

Table 1. HTGR Programme Objectives

No.	Programme Objective	Comments
1.1	Develop an integrated strategy of GW, SMR and HTGR nuclear technology within the context of wider UK industrial decarbonisation. Depending on selection of 'clustered' or 'national' decarbonisation scenarios various plant requirements could change such as: physical size, power output, heat output, size and potential co-location of hydrogen plant, thermal storage and/or long-distance transportation of hydrogen. This will drive the initial system requirements for potential Demonstrator vendors to design against.	For reactor vendors looking to enter the UK market, knowledge of how their technology could be deployed, as well as if they are providing heat, electricity or both will be crucial in helping them understand the business cases and requirements of their eventual customers. Different technologies could be deployed in different scenarios and the varying level of power and heat output requirements need to agree early to allow development of designs. This will also give clarity for prospective developers on whether their technology has a potential entry point into a UK market.
1.2	Define roles and responsibilities so there is clarity on which organisations will fulfil key roles including client, vendor(s), developer, and operator/licensee for the HTGR demonstration plant.	Clarity is needed so that all essential activities are progressed in a timely manner by competent organisations.
1.3	Build a Demonstrator HTGR plant that successfully integrates with an 'at scale' use case technology to demonstrate the viability of HTGR technology and the ability of nuclear power to integrate with UK industry's ambitions for decarbonisation.	**The Demonstrator should prove:** • That HTGR technology can/cannot safely operate for an extended period with a high capacity at the correctly identified temperature outputs. • That a scaled-up use case demonstration (this is assumed to be a hydrogen electrolysis facility) can/cannot utilise the heat provided by the HTGR to run a low/zero carbon industrial process. • That the connection between the reactor and use case (either HTGR specific or deployable for other nuclear technologies) can/cannot cost effectively transfer heat between the two in the required medium for the end user. • That the size and scale of the use case demonstrator connected to the HTGR Demonstrator, is/is not a viable alternative for the end user when compared to a renewable energy alternative or fossil fuel. • Be able to support deployment of a fleet of HTGRs and increased UK capability in key areas such as fuel, graphite, and other materials.
1.4	Develop a UK based fuel manufacture and qualification route for TRISO fuels.	Development of the manufacture, qualification, and quality assurance inspection methods of TRISO encapsulated fuel for prismatic compact and pebble bed reactors unlocks several passive safety benefits to the technology and could be a key variable in achieving regulatory approval to co-locate a plant near an end user. A UK based fuel manufacture is necessary to ensure security of supply.
1.5	Develop knowledge and understanding of the performance of materials within a HTGR reactor environment.	Development of the substantiation (through testing, simulation, inspection) of high temperature materials is a key element of the unique selling point for a high temperature gas reactor.
1.6	Develop options for a feasible UK nuclear graphite supply route.	Development of a UK supply route for nuclear grade graphite is key for UK manufacture of fuel modules and reflector assemblies and to ensure security of supply.
1.7	Develop skills across the UK nuclear industry to support the HTGR from design through to deployment and then decommissioning.	To build and operate a HTGR demonstrator and then fleet, a wide range of skills will be needed across design, manufacture, operation, and maintenance as well as decommissioning and waste management. Some of these skills will pertain to development of the plant itself but many of these skills will need to be embedded within the supply chain.
1.8	Develop regulatory oversight measures to ensure HTGR Demonstrator can be deployed to UK industry in a way that provides a tangible benefit to UK net zero pathways.	Development will need to be carried out in the following areas (more may become apparent through the process): • Implementation of TRISO as a valid fuel source. • Use of novel manufacturing methods such as electron beam welding and modular build of components. • Use of nuclear technology for the provision of heat as well as electricity. • Co-location of plants near to UK industrial facilities and COMAH sites. • Plants with large heat transfer networks (noting a key variable will be the transfer of heat back into the plant as well as out of it).
1.9	De-risk siting and financing by ensuring that all key national and local stakeholders are sufficiently informed about the UK's plans for HTGRs.	Long term community and other stakeholder support is essential for successful deployment of a HTGR Demonstration plant.
1.10	Optimise use of the HTGR Demonstrator as an innovation testbed.	There are many different potential innovations that can be trialled (including to the benefit of UK core science programmes, other reactor types and sectors). This is a unique opportunity for the UK to test these, recognising impact on delivering the main programme goals.

The following sections of this report describe NIRAB's use-case, technology, and delivery RD&I conclusions. It is not possible to list all the RD&I activities here, rather this document is designed to give a flavour of them. The detailed, prioritised RD&I objectives for the three technical topics covered are presented in the accompanying Technical Appendix.

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3.1

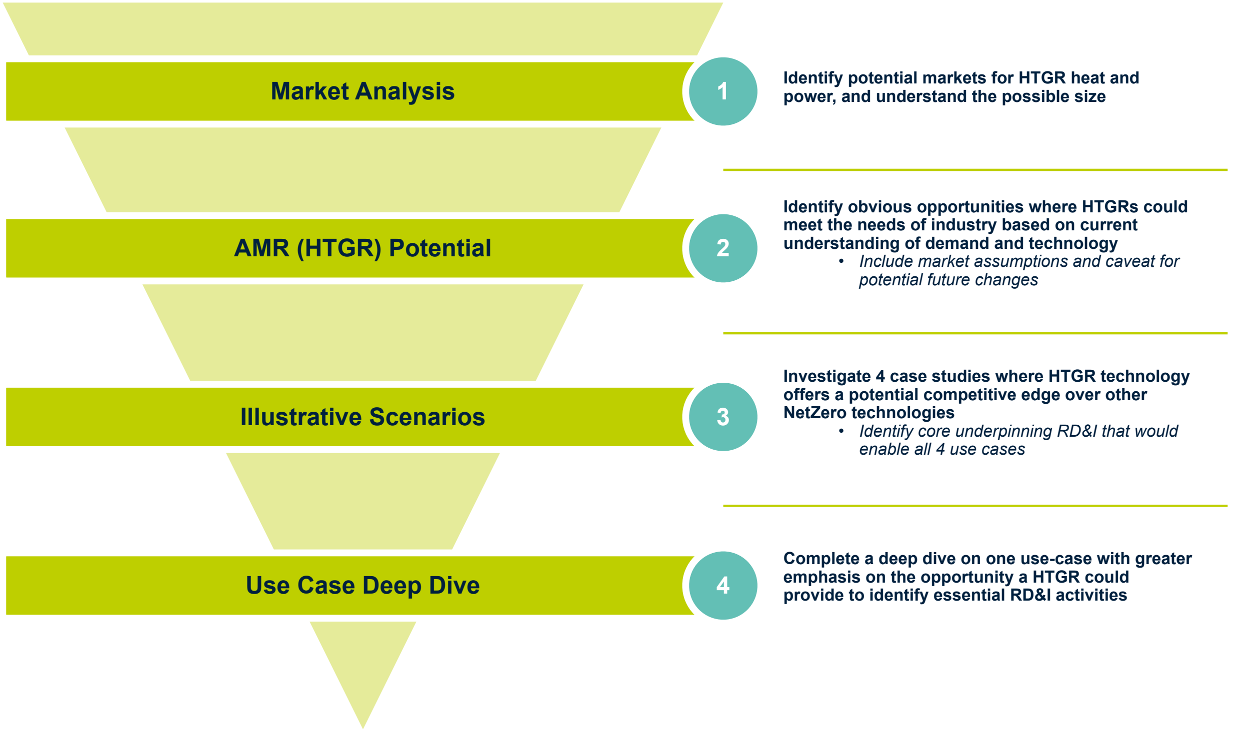
Use-Case

HTGRs offer a number of additional benefits over other reactor designs as they have very high-power generation efficiency and produce outlet heat at much higher temperatures (560°C and upwards) compared to traditional water-cooled reactors (which generate steam in the region of 285 - 340°C). It is therefore postulated that this thermal output could be used as a direct heat supply for industrial applications or to generate hydrogen or ammonia for industrial processes. Hence there are benefits of using HTGRs beyond their electrical output, using their excess heat to de-carbonise UK industries which are typically hard to abate e.g. chemical production processes, or hydrocarbon fuel production.

These industries are currently carbon intensive, with significant challenges that must be solved if they are to ever achieve net zero. NEA (2) predicts that HTGRs could contribute to reducing CO2 emissions from such hard-to-abate industries by 15-30%, depending on the extent of their use. Subject to confirming the claimed levels of safety, co-locating a HTGR near to its end-use could have multiple benefits. For instance, the heat would not need to be transferred very far and thus heat-loss over distance would be minimised. They would be located in areas of high industrialisation where appropriate grid connections are most likely already in place. Perhaps most importantly, integration of such reactors may be more acceptable to local stakeholders supporting a "social licence to operate."

Given the potential benefits mentioned previously, NIRAB has undertaken a broad market analysis to identify the potential demand for a HTGR. This led to identifying beneficial uses and associated industries who may be receptive to coupling their needs with HTGR technology. Finally, a deep dive into what is considered a 'high value' opportunity was undertaken.

Figure 1 below describes the process undertaken to identify suitable use-cases in more detail.



Identify potential markets for HTGR heat and power, and understand the possible size

Identify obvious opportunities where HTGRs could meet the needs of industry based on current understanding of demand and technology
- *Include market assumptions and caveat for potential future changes*

Investigate 4 case studies where HTGR technology offers a potential competitive edge over other NetZero technologies
- *Identify core underpinning RD&I that would enable all 4 use cases*

Complete a deep dive on one use-case with greater emphasis on the opportunity a HTGR could provide to identify essential RD&I activities

Figure 1. A pictorial view of the process NIRAB undertook to identify a market and use-case for HTGRs.

Four example types of output from a HTGR plant that beneficiaries could utilise, either through specific high heat processes, or through the provision of hydrogen and process heat and power, were identified:

Combined Heat and Power (CHP) for industrial users
HTGRs could utilise high availability (with load following capacity or stable production, using molten salt or similar heat buffer storage), flexible siting (driven by improved safety cases) and semi-autonomous operational requirements to provide a replacement for combined heat and power (CHP) fossil fuel plants equivalent to 3.7Mt CO2 (total UK emissions in 2020 were 582 Mt CO2)[3].

Heat and Hydrogen
Foundation Industries such as steel, glass and cement manufacturing require heat greater than 1000°C (steel 1375-1530°C; glass 1000°C (soda-lime) 1250°C (borosilicate); cement kiln 1300-1450°C). In total, UK industry generates 16% of total UK CO2 emissions (4). HTGRs could help mitigate this through a combination of initial heat in the region of 600°C plus hydrogen generation by electrolysis using further residual heat, followed by burning the hydrogen to achieve the required temperatures – HTGR powered heat and hydrogen for foundation industries.

Hydrogen and Liquid Fuels
Green fuel hubs could be connected to HTGR plants with the HTGR providing heat and electricity to manufacture, for example, hydrogen via electrolysis, ammonia as a hydrogen transport vector or shipping fuel, or generation of Green methanol for transport fuel or industrial feedstock – HTGR powered Green fuel hubs could be responsible for the offset of over 22 Mt CO2 or approximately 4% of UK totals (3).

Synthetic hydrocarbon generation
Production of synthetic aviation fuel is currently limited by the need for hard-to-acquire biological feedstock but could be improved through use of hydrogen and captured carbon using a Reverse Water Gas Shift (RWGS) reaction and the Fischer-Tropsch process (a HTGR could provide the necessary heat and power for both hydrogen production and direct air capture of carbon or carbon recovery).

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[3] In 2020 DESNZ estimated a combined 87 GW was produced through CHP schemes at a capacity factor of 58.7%. This translated to roughly 17GW of power which is then converted through a ratio of 0.2 kg CO2 /kWas detailed in (5) to 3.8 million tonnes of CO2 equivalent.

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NIRAB believed, for the purposes of illustration, that the Synthetic Aviation Fuel (SAF) and Recycled Carbon Fuel (RCF) use-case would make an appropriate case-study to identify what generic RD&I is needed from a use-case perspective.

This is a high-value industry. Aviation is reportedly valued at roughly £22 Bn input to UK GDP and aerospace exports were valued at £34Bn (6). By 2035, HMG estimates that the development of a domestic industry for the production of sustainable fuels could support up to 5,200 UK jobs and have Gross Value Added up to £2.7 Bn from UK production and global exports.

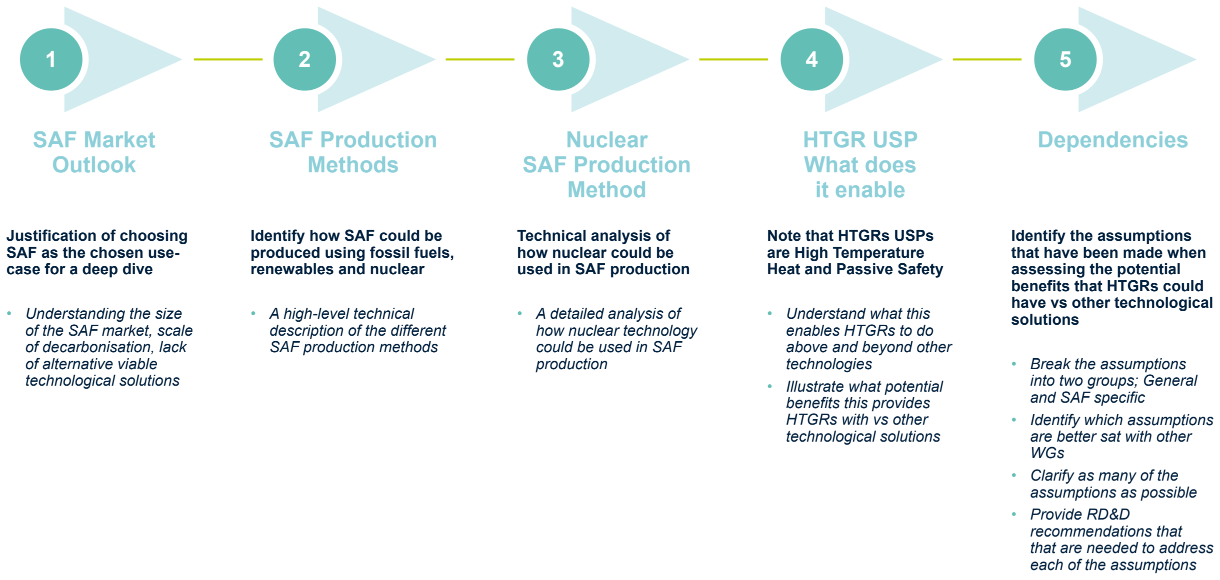
The Jet Zero Strategy sets clear decarbonisation targets (emission reductions targets for 2030, 2040 and 2050 as well as a hydrogen production target and an expected 10% SAF mandate (6).

The commitment to build five SAF production plants by 2025 will be exceptionally hard to achieve as there is insufficient bio-feedstock to support Aviation Zero ambitions due to increased demand for biofuels and a target to plan short rotation forestry has not been met (7).

Therefore, there are clear opportunities for HTGR integration. In addition, research into hydrogen production and carbon capture will have benefits to other use-cases, providing a 'no-regrets' approach. Furthermore, it is possible to make reasonable assumptions for economic benefits when compared against both renewable-led manufacture and current fossil fuel economics.

It is important to emphasise that NIRAB's deep dive into SAF and RCF was not undertaken to confirm SAF as the priority choice of an HTGR use case, but to provide a high-level techno-economic assessment of an industry without a current full-scale solution that HTGR could benefit and to provide a stretching case study of the potential use of HTGR.

A pictorial view of the process NIRAB undertook to provide a deep dive into the SAF use-case is shown in Figure 2.



SAF Market Outlook

Justification of choosing SAF as the chosen use-case for a deep dive

- *Understanding the size of the SAF market, scale of decarbonisation, lack of alternative viable technological solutions*

SAF Production Methods

Identify how SAF could be produced using fossil fuels, renewables and nuclear

- *A high-level technical description of the different SAF production methods*

Nuclear SAF Production Method

Technical analysis of how nuclear could be used in SAF production

- *A detailed analysis of how nuclear technology could be used in SAF production*

HTGR USP What does it enable

Note that HTGRs USPs are High Temperature Heat and Passive Safety

- *Understand what this enables HTGRs to do above and beyond other technologies*
- *Illustrate what potential benefits this provides HTGRs with vs other technological solutions*

Dependencies

Identify the assumptions that have been made when assessing the potential benefits that HTGRs could have vs other technological solutions

- *Break the assumptions into two groups; General and SAF specific*
- *Identify which assumptions are better sat with other WGs*
- *Clarify as many of the assumptions as possible*
- *Provide RD&D recommendations that that are needed to address each of the assumptions*

Figure 2. A pictorial view of the process NIRAB undertook to provide a 'deep-dive' into the SAF use-case.

Our findings are that the economics of SAF production is greatly driven by operational costs and that a regular supply of high temperature heat and power improves the efficiency of the process. Further efficiencies can be gained through development of hydrogen electrolysis and carbon capture methods. For instance, development of the technology to support liquid direct air capture (as opposed to solid) requires temperatures in the region of 900°C but greatly reduces the levelised cost of doing so. There are several parts of the SAF production process where HTGRs can be of benefit, however there are also significant RD&I needs that warrant further investigation.

NIRAB considers that the following are 'essential' RDI activities, further details of which are given in the Appendix.

- The use-case plant will need to be co-located with the Demonstrator as an integrated part of proving the success of the project and to inform the design and business case. It is important to consider just how close the plants will need to be to resolve potential tensions between regulatory requirements and the engineering benefits of co-location
- RD&I related to siting, safety and dynamic systems interaction with associated industrial plant must be targeted, and an integrated regulatory approach developed covering nuclear and non-nuclear elements if co-location is to be adopted. The importance of this regulatory approach and its relationship to current regulatory processes will need careful consideration
- Further development of alternative methods of hydrogen production should properly consider the potential for application of HTGRs as a source of high temperature heat
- Interfacing HTGRs with end users will require smart reactor manifold designs to manage reactor heat outputs at different temperature ranges. Work on materials, heat exchanger and heat exchange media modelling, looking at gas-to-gas, and gas-to-molten salt exchange for example, as well as design and manufacturing innovation for all components attached to the reactor is required. This work will also benefit other sectors that are considering molten salt or similar high temperature energy storage and transmissions. Further research into these areas is needed
- Research on and down-selection of heat storage technology to allow steady state HTGR operation, and associated heat network transmission media would support multiple energy and user sectors to realise the benefits of HTGR heat output at the centre of a heat hub
- Cost modelling and business case innovation to cover full lifecycle costs of both HTGR and other energy sources (covering realistic 'lifetime of technology' costs of transporting and storing energy and related waste and decommissioning costs) would allow users to address previous shortfalls in assessment of the cost of renewable-produced hydrogen or SAF. This work should utilise the more recent development of the VALCOE (Value Adjusted Levelised Cost of Electricity) model as a start, which incorporates information on both costs and the value provided to the system. Based on the LCOE estimate of energy, capacity and flexibility value are incorporated to provide a more complete metric of competitiveness for power generation technologies. There is a need for a new market mechanism to enable pricing of heat as a new nuclear energy vector on a fair and transparent basis, addressing all the hidden costs of competing short-lived technology, availability due to weather/diurnal cycle and reduction of efficiency over time and with increased temperature, additional transmission costs (both grid and losses) as well as unaccounted waste and decommissioning factors
- Engagement with end user industries and collaboration across sectors needs to ramp up and be supported to realise potential benefits of HTGRs, starting within Government funded projects and coordination of hydrogen and nuclear related projects
- Work to understand materials' behaviour and integrity may be needed to substantiate long-periods of operation. The Demonstrator should slowly ramp-up to operate at the top end of its intended temperature range to ensure all systems and materials are able to cope with the high temperature/radiation damage which will endure

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3.2
Technology

There are several technological considerations which need to be addressed in order to demonstrate an understanding of how the fuel and core materials will behave over the life of the HTGR reactor under the higher operating temperatures and greater neutron fluences. Additional activities are also needed to demonstrate and substantiate why the plant will be safe, secure, environmentally benign etc especially given the fact that historic prototype HTGRs have had shorter operating periods and required more outages than commercial systems.

These technological RD&I considerations have been grouped into the following categories.

- **(TRISO) fuel and core**
- **Materials and manufacturing (including graphite reflector)**
- **Modelling, simulation, and design**

A summary of the essential RD&I considerations is provided below. The Appendix provides a full list of considerations and provides more technical detail, including an explanation of what RD&I is highly valuable/valuable.

3.2.1 Fuel and Core

It is currently assumed that the Demonstrator will be fuelled with LEU+ (Low Enriched Uranium) or HALEU (High-Assay Low Enriched Uranium) Tri-Structural ISOtropic (TRISO) coated particle fuel either as compacts (in columns) or as pebbles. NIRAB has considered the more probable use of HALEU.

TRISO fuel is not commercially available in industrial quantities anywhere in the world at present, although the US is close to developing a commercial scale capacity having demonstrated fuel from a pilot plant, and there are some pilot plants that are able to achieve semi-commercial production rates internationally. Within the UK, NIRAB understands UK TRISO coated particle fuel manufacture sits at a technology readiness level (TRL) of 3-4, with compacts potentially lower (8). Whilst it may be possible that a Demonstrator could be fuelled for its first cycle using fuel produced overseas, relying on a subsequent supply of internationally produced TRISO fuel will largely depend on whether an international commercial market emerges and hence security of future supply is also an issue.

In the US, the fuel kernel specification preference is UCO/UOC, uranium oxycarbide. However, the advantages of UCO over other fuel particle choices (UO2, UCN or UN) is not clear cut. Technical research in both TRISO fuel manufacture and cost modelling to address economic considerations would be beneficial to support decision making related to fuel particle choice for the UK. NIRAB believes that further work is required to land on a 'UK' kernel, coated particle, and compact specification, with a clear understanding of qualification gaps. It is vital that reactor vendors, fuel vendors and potential licensees work together to agree a fuel specification and performance characteristics to be substantiated. Such decisions may also be informed by the Operator of the future reactor fleet. NIRAB strongly recommends significant RD&I to improve the understanding of the manufacture and performance of different kernel types to inform the business case for a UK TRISO fuel plant.

NIRAB recommends that it is essential for the UK to continue to develop a full UK TRISO fuel capability, to ensure security of supply and capitalise on export opportunities. Fuel-related research is also essential to ensure an Intelligent Customer capability which may be needed to support fuel procurement from abroad for early cycles of operation. Opportunities to address potential for improvements in coated particle and compact quality through technology such as Artificial Intelligence (AI) and Machine Learning (ML) are highly valuable and should be embraced due to the need to have a large number of measurements and high-quality statistics to substantiate production methods. NIRAB also believes it is highly valuable to progress understanding on burnable poisons, control rods, and the fuel columns themselves in parallel.

A key licensing risk is that, whilst fuel qualification research has progressed nationally and internationally, claims that TRISO coated particles can be treated as pressure vessels are not yet fully supported by substantial evidence. Further work is required to adequately understand topics such as fission product migration, chemical attack, and physical degradation. Developing this understanding will require post-irradiation examination. This may mean that additional safety systems would be a pragmatic addition to the Demonstrator whilst research is undertaken to inform a fleet design. Similarly, decisions on whether fuel compacts need to be separated from fuel columns for disposal of prismatic fuel may require further RD&I.

Disposability assessments will need to be carried out on fuel compacts of all types, as well as fuel column graphite, to ensure compatibility with existing or new, agreed Waste Acceptance Criteria (WAC) for final storage/disposal.

Transportation solutions for all types of fuel product through the lifecycle should be expedited. Fuel modelling and simulation tools should be developed further for design and licensing purposes for the fuel manufacturing plant, transport, storage, in reactor and in disposal circumstances.

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3.2.2. Materials and manufacturing

Graphite

There is a relatively immature commercial supply chain for HTGR components and systems outside of China, including some key materials. There is therefore a security of supply risk and potential commercial business opportunity. Graphite is a key example of such components that NIRAB wishes to highlight.

Nuclear grade graphite is a key component of both fuel columns and the reflectors surrounding the reactor core in HTGRs. Nuclear graphite needs for HTGRs are substantial, as prismatic designs assume replacement of most of the reflector and fuel graphite each cycle.

HTGR reactors will use a different type of graphite from existing UK reactors. Thus, it will be essential to further explore with reactor and fuel vendors and reactor operators the potential to develop the UK graphite specification, building on historic UK operating experience and international developments. Balancing structural integrity with the requirement to ensure waste arisings are ALARP will also be important, and all interested stakeholders will need to understand such factors in more detail.

It should be noted that there will likely be a significant time gap between the last AGR station closing and the HTGR Demonstrator starting up. This discontinuity may cause a risk to the maintenance of key skills and research facilities which NIRAB believe will need to be proactively managed.

Whilst the UK had a long history in manufacturing nuclear grade graphite, no commercial production capability/facilities exist in the UK today. However, the UK retains world-leading knowledge in graphite behaviour and despite small funding streams, nuclear graphite research for HTGRs is advanced and continues to progress well. There is therefore an opportunity to capitalise on UK experience and expertise in nuclear graphite behaviour and attract/develop a supplier to establish a UK base, ensuring security of supply of raw materials as well as capability in processing and machining the components.

Investment in facilities, tools, and people for post irradiation examination (PIE) will be essential to this activity.[4]

Disposability of graphite will require development of waste disposability cases and application against Waste Acceptance Criteria (WAC). It is most likely that there will be a need for a new waste transport package/container. A packaging and disposability assessment is required during the early stages of licensing. Current policy assumes disposal of graphite as Intermediate Level Waste (ILW) in a Geological Disposal Facility (GDF), although there is a valuable opportunity to investigate recycling of graphite for future re-use. At present, there is a limited range of packages available and further development would be needed to identify suitability for both reflector and fuel graphite and for fuel, and possible combinations of the two. RD&I on management of waste HTGR graphite is therefore essential.

Materials performance

Materials in and around the core will experience conditions of high temperature, neutron flux and chemical environments which vary significantly from current UK reactors, so the reactor designer and ultimately the operator will need to ensure that they understand how core and non-core materials will behave under these conditions (detailed in the Technical Appendices). This will require irradiation in representative environments and subsequent PIE which is essential RD&I. The resultant evidence will need to be incorporated into a suitable regulator-facing safety case and likely deploying the RDoC or similar procedures[5] (R6-fracture, R5-creep) to cover defect tolerance assessments for high temperature reactors intended to be operational for extended time periods (9).

NIRAB believes that under likely HTGR operating conditions of irradiation and coolant temperature, pressure, and purity, materials currently referenced in ASME Boiler Pressure Vessel Code (BPVC) section III or ASME BPVC section VIII are sufficient (10), and it would not be necessary to codify a new material with consequent long implementation timescales. However, it is recognised that safety cases may well need to justify safe operation in out-of-specification coolant compositions.

Furthermore, additional material performance data and associated structural integrity assessments are likely to be required, particularly for high temperature operation, as is believed to have been undertaken by JAEA to enable Hastelloy XR[6] to be used in its HTTR reactor. The UK Demonstrator could be used to test performance of materials at higher temperatures and/or to irradiate new materials during its operating life to extend beyond the levels experienced in the HTTR.

NIRAB believes that it is sensible to plan for using the Demonstrator reactor and associated testing equipment to generate information supporting UK licensing and permitting and this information will need to be gathered through use of active demonstration and post irradiation examination (PIE). Irradiation damage as such may not be problematic for an HTGR Demonstrator, but neutron activation for example of some cobalt-containing materials could be a concern. Performance data for non-irradiated materials under in-service conditions is essential to satisfy regulatory requirements. RD&I to develop more advanced materials with suitable lifetimes and low activation, thus minimising higher activity wastes, requires access to facilities that are not available in the UK and would be highly valuable. Such tests could be facilitated by the HTGR Demonstrator.

NIRAB suggests a basic programme to justify use of ASME-coded materials from traditional manufacturing routes under the chosen operating conditions, and that progress to the same materials made using advanced manufacturing techniques is undertaken. If necessary, new materials may be developed and assessed in the Demonstrator reactor to support subsequent testing.

Innovation in manufacturing

Opportunities exist to take advantage of advanced manufacturing techniques such as hot isostatic pressing, 3D printing, laser cladding, electron beam welding, combined welding and inspection, modularisation, advanced heat exchanger technology etc and to explore alternatives to heavy forgings. This work, vital for cost optimisation of a fleet, could be progressed in parallel to the Demonstrator to enable substantial cost savings and develop leading UK technology. Such activities would also deliver benefits in construction for a wide range of reactor systems, in addition to HTGR's.

A Demonstrator could be built without having to use advanced manufacturing methods. However, such manufacturing methods represent a real opportunity to reduce risk (and hence cost) and potentially have significant positive impacts on the associated delivery schedule, as such advanced manufacturing methods can reduce the time needed for fabrication, build and assembly of component parts. It also has great potential to create business opportunities for UK enterprise. Collaborative irradiation programmes such as FIDES-II irradiation programme (11) could be a useful delivery platform for seeking data on performance of materials under irradiation.

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[4] It is noted that there is a need for advanced UK-based Post Irradiation Examination (PIE) capabilities outside the proposed HTGR programme.

[5] RDoC procedures are used to assess the integrity of components under high temperature creep regimes.

[6] Hastelloy XR is a solid-solution strengthened nickel-chromium-iron-molybdenum alloy that combines good oxidation resistance, high-temperature strength, and exceptional stress-corrosion resistance for use in harsh chemical environments.

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3.2.3. Modelling, simulation and design

Modelling and simulation of performance of a HTGR reactor island

HTGRs present some unique challenges for modelling and simulation, due to the more extreme scales that need to be covered from modelling of the sub-millimetre kernels, millimetre-sized coated particles to centimetre fuel compacts, and metre-scale fuel columns. For pebble fuelled HTGR reactors there is the additional challenge of being able to accurately model pebble flow through the core. Whereas there is a good selection of commercial and R&D modelling systems for LWR fuels and reactors, there is more limited choice in HTGRs. Some good R&D tools exist today, and the UK has some leading research on physics codes and fuel performance that could be built upon, but investment is required in code development and validation. NIRAB therefore believes reactor modelling and simulation tools should be developed further, for design and licensing purposes, to support the Regulator, as well as supporting fuel cycle management of a potential fleet, where commercial grade codes will be needed. NIRAB has identified the need to confirm missing or incomplete/uncertain nuclear data sets for UK application and to identify and address gaps in reactor physics codes necessary to support the safety case. It is also essential that we identify/address gaps in codes used for containment performance and source term production.

Many developers claim that even if a severe accident causes the HTGR cooling system to fail, there will be no core meltdown and no release of radioactive material into the environment. Although HTGRs have not fully experienced or been tested in all severe accident conditions, there have been operational tests to simulate some accident conditions, and some benchmarks produced to support code development and validation.

In March 2024 JAEA announced it had successfully demonstrated, using HTTR, that core melt does not occur even in the loss of forced cooling accident scenario. Although there have been some bold claims made about the high integrity of the fuel, less effort has been spent on developing a full commercial suite of safety analysis computer codes for HTGRs compared with LWRs. Severe accident R&D is essential for the HTGRs Demonstrator. Such research will also be needed to support a future fleet programme.

The Demonstrator reactor will be located close to and linked to other facilities (e.g. hydrogen production). There are therefore new challenges here to consider, that will not necessarily be addressed by the introduction of TRISO fuel alone. NIRAB is advising that an assessment of investment needs is made urgently to address what is required in terms of modelling computer code development, and verification and validation evidence, to support licensing of the Demonstrator. This will include clarification of the safety, security and environmental features required for the design to be progressed and for a safety case to be developed. Comprehensive accident and consequence analysis is essential to support bold claims around emergency planning and to address co-location challenges. Techniques to cope with limited system and component operational reliability data should be further developed. It is essential to define accident scenarios and adapt models to predict performance under accident scenarios. It is assessed that a methodical approach could be taken using the Demonstrator to support validation of computer codes using a careful approach to criticality and reactor physics experiments, as well as thermal hydraulic and equipment qualification tests.

Benefits could be realised from modelling of existing UK reactors and from developing tools and services in the UK that could be marketed overseas and used to support licensing. With challenges seen in modelling HTGR reactors, we believe that modelling and simulation related research is essential to develop an Intelligent Customer capability.

NIRAB believes that using advanced digital techniques could provide many direct and indirect benefits but is not essential for a Demonstrator, although a control system simulator is. Underpinning work to progress a full Digital Twin (DT) to support a fleet would be highly valuable.

Design

It is NIRAB's belief that it is essential RD&I to focus on integrated design and through-life substantiation of a safe and highly thermally efficient system, achieving the right level of integrity. This may be a high integrity design approach, particularly for the Demonstrator whilst the gap analysis in design maturity is carried out to address readiness to deployment for unique and known life limiting features of HTGRs (helium pump, cross vessel duct, internals), including neutron detectors and heat removal systems, to increase Technology Readiness Level (TRL) prior to commercial rollout. This could be usefully informed by the set of safety design criteria established by GIF (12). RD&I to underpin claims related to materials performance, reduction in volumes of concrete, and simplifications of safety systems will be essential. This could include modelling software, incorporation of irradiation testing capabilities and component replacement planning into the design and safety case of the Demonstrator and development of an Instrumentation and Control strategy informed by a clear understanding of performance under accident conditions. Due to a combination of use of more novel plant and equipment, fault sequences, new external hazards etc, investment in RD&I in Probabilistic Safety Assessment will be highly valuable, as a key tool to inform design.

Full integration of considerations of safety, security, safeguards, environment, and sustainability from the start is valuable RD&I for a Demonstrator, but it could bring significant benefits to a fleet in terms of safety, time, and cost, and make It much easier for the future operator.

Designs should be qualified to cope with realistic hot helium atmospheres in normal and accident conditions, potentially with dust, lubricant or water ingress or carburisation resulting from steel degradation, to address life-limiting factors in previous operating HTGRs. Given that helium is a scarce resource, leakage experienced in previous operating HTGRs must be minimised, and RD&I will be essential. Operating experiences with early HTGRs showed that designs were susceptible to both water and lubricant ingress and helium leakage. Early focus on helium purification and inventory control is essential and links to an understanding of tolerable levels of impurity and of safety consequences.

Optimisation of the cross-vessel duct and heat exchanger designs is essential and could also take advantage of advanced manufacturing techniques and provide UK supply chain opportunities.

Modularisation research will be highly valuable to any AMR programme as it will be a key challenge for a fleet, where economies of scale will mean a factory-built module-based approach is cost-effective. While it may not be essential to have a modular manufacturing facility available for the Demonstrator designing for modular build might progress very differently from a conventional stick-built plant, and as such modular build research would be highly valuable. It is essential to define a pathway to deployment of advanced manufacturing and other alternative routes to manufacture of major nuclear components.

3.2.4. The role of the Demonstrator as a test and training reactor

An appropriately designed and instrumented Demonstrator would support the necessary data gathering and evidence capture for the ongoing licensing and permitting of the Demonstrator and of the future fleet roll-out. Areas covered by the Demonstrator include, for example:

- Demonstrating the ability to design, licence, manufacture etc
- Training people in the design, licensing, construction, commissioning, and operational phases
- Providing opportunity for benchmarks for criticality, reactor physics and thermal hydraulics for example
- Testing existing and new fuels and materials and components in a realistic hot helium environment, including materials produced through advanced manufacturing techniques
- Testing different options to address helium leakage
- Validation of computer modelling
- Addressing materials challenges related to the interface between the reactor and potential use cases
- Testing detectors
- Gathering component reliability data
- other activities required to reduce risks for a potential future fleet

3.2.5. Key auxiliary facilities

Post irradiation examination (PIE) is a theme that emerges across several areas of consideration. PIE will need to be carried out on fuel and other materials, requiring skilled people, facilities, and tools. There is a choice to make about local or national PIE facilities. There is likely to be a strong need for PIE for other advanced nuclear technologies and the defence sector also has significant requirements which makes investment in this area particularly beneficial.

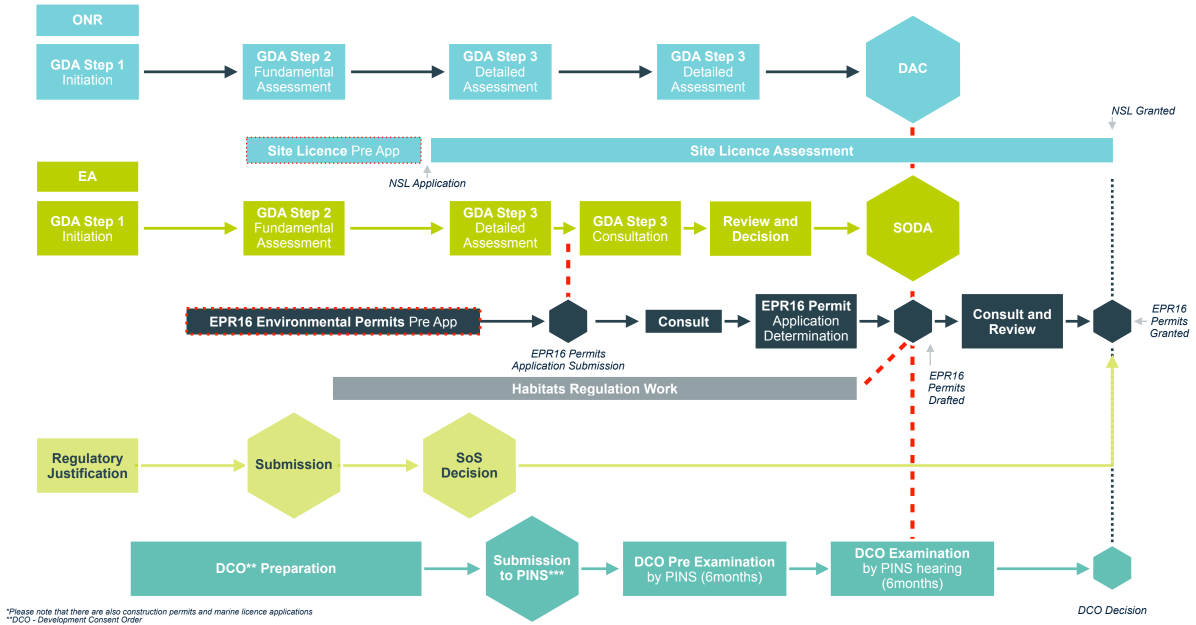
Further work is required to determine whether additional testing facilities are required for type testing/equipment qualification or functional testing, as well as code validation.

3.3 Delivery

The essential areas which require RD&I for the delivery of a HTGR Demonstrator are:

- Regulation and approval processes
- Roles and responsibilities / operational capability
- Siting, engagement, and planning
- Skills, expertise, and the workforce
- Waste management & decommissioning

Other areas such as economics and investment have been reviewed briefly but are outside the scope of NIRAB's current work.



*Please note that there are also construction permits and marine licence applications
**DCO - Development Consent Order
***PINS - Planning inspectorate

Figure 3. Steps in the regulatory approval process for new nuclear programmes

* Only one of these routes will be used for each situation

** Other Regulatory Processes includes:

- Regulatory justification
- Waste assessment
- Decommissioning arrangements
- Electricity Generating Licence
- Heat Networks arrangements
- Marine Licence
- HSE notification
- Fuel transport arrangements
- Emergency arrangements
- HSE consents
- International transboundary processes

Figure 4. Programme delivery steps for a HTGR Demonstration

3.3.1 Regulation and approval processes

All new nuclear build projects in the UK follow well-established statutory approval processes illustrated by Figure 3.

At present the planning, schedule and costing of work activities needed to progress a HTGR Demonstrator through this, or similar processes, and beyond into construction are in the early phases of development and unavailable to NIRAB. An outline programme of activities and decisions required to progress through the design, develop, manufacture, construct, commission, operate phases and through the approvals required for a new nuclear plant in the UK has been developed to identify the range of delivery activities, links and dependencies and to map out the full extent of a programme i.e. through to operation. The main strands of these activities are summarised in Figure 4. NIRAB has assumed that the HTGR Demonstrator will be subject to similar regulation and approval processes as other new build programmes and has identified aspects which we consider to require further consideration to enable delivery of a HTGR Demonstrator, thus paving a pathway for future commercial HTGR deployment.

Regulatory Justification

Whilst the "Operation of Nuclear Fission Reactors for R&DI purposes" is recognised as an existing practice in the Justification of Practices Involving Ionising Radiation Regulations (13), there is an opportunity to provide additional guidance on Justification of Practice, particularly offsetting the use of HTGRs as mitigation of risks of climate change and confirming if the Demonstrator would be covered as an existing Practice, as it was for DRAGON. Recent Regulatory Justification processes and approvals have focussed on the impact from Light Water Reactor (LWR) nuclear electricity generation, and not considered decarbonisation of hard-to-abate systems through heat and secondary products such as hydrogen. There is an opportunity to consider regulatory justification of a HTGR technology group, including setting a bounding case for a potential family of HTGRs, including the Demonstrator if necessary. Early Justification of Practice of HTGRs would help to provide clarity on the unique benefits that the HTGRs can realise, which would in turn help to provide confidence to invest in a fleet further down the line and thus we believe this to be an essential activity.

Regulation

Regulators should embed the recently announced early engagement to industry to de-risk entry into GDA, licensing and permitting. The role of the regulators in overseeing component manufacture/assemble of the Demonstrator is of modular/factory construction, including graphite, fuel, large component production etc should be clarified.

Understanding the use-case and the interplay of nuclear and non-nuclear regulation will be important to ensure harmonisation between different regulatory bodies. It will therefore be essential to review the regulation of non-electricity generating applications alongside the generating applications to ensure they are complementary and to highlight any areas which require further consideration.

Design Assessment

Regulators should review the Generic Design Assessment (GDA) process to ensure it enables entry and assessment of innovative and novel reactor designs. However, GDA is not necessarily the right route for a Demonstrator and thus should be examined further, including considering how to progress an assessment aligned to technology demonstration when the results of such a demonstration are required to further substantiate claims, arguments, and evidence. We believe that guidance is required on the re-use of submissions from other countries in the assessment process and explore harmonisation between design assessment processes for efficiency purposes.

There are a number of features of the regulation of the Demonstrator where further RD&I would be highly valuable. These are outlined in the technology section of this report.

Nuclear Site Licensing

The route to enabling siting of a HTGR Demonstrator needs to be accompanied by guidance on HTGR-related technology licencing, considering non-traditional nuclear deployment models, including alternative protection and control strategies, multi-unit sites, co-generation, and cross-boundary regulatory approaches. Selection of an existing nuclear licenced site for potential HTGR Demonstrator deployment does not mean that the said site is already licenced for operation of that technology.

Environmental Permitting

The environment agencies (working with other UK agencies and Nuclear Waste Services) should ensure an integrated approach between radioactive and non-radioactive assessment and permitting processes and avoid any duplication between the two (including planning and Habitats Regulation).

3.3.2 Roles and responsibilities/operational capability

NIRAB has considered the various roles and responsibilities associated with the delivery of the Demonstrator. In some cases, NIRAB has recognised gaps in responsibility for certain tasks and in other areas there is some ambiguity as to the exact role organisations will play in relation to the development of a HTGR Demonstrator. In summary, NIRAB believes clarity is needed on:

- The role of Great British Nuclear (GBN) in siting decisions, operator and technology selection, and pre-final investment decision making for the demonstration plant
- A strategy for supply chain development to support HTGR design and manufacture, including module factory build/assembly
- Who is responsible for developing/maintaining intelligent customer/subject matter expertise across the HTGR lifecycle. Whilst this is the Licensees responsibility, this is raised as there is a lack of clarity in the programme about who the Licensee would be for the Demonstrator
- The role of the NDA in approving/supporting the waste management and decommissioning plans and managing the future liability for any site on which the Demonstrator may be housed
- It would be sensible to clarify how the outputs from the Demonstrator would be regulated. Whilst this is a minor issue, for a future potential fleet, clarification of the regulation of both electricity and heat generation and end-use would be beneficial, especially in support of cost modelling

Above all, there needs to be a client for the reactor who defines the Demonstrator's requirements, including how it will be financed, from the outset. Currently, the UK does not have a client ready to support deployment of an HTGR Demonstrator. There will also need to be a customer identified to define the requirements for the non-electrical outputs from the Demonstrator (e.g. heat, hydrogen), though at present there is not a clear understanding of who the customer for the HTGR is. NIRAB therefore believes HMG should support UK operator capability through enabling funding, policy development, and associated activities to identify/define who the operator and client are for the Demonstrator.

3.3.3 Siting, Engagement and Planning

Siting

The current National Policy Statement (NPS) relating to nuclear power (EN-6) provides a framework for assessing development consent applications for new nuclear power stations expected to deploy by the end of 2025 (14). A government consultation is due to report back at the time of writing this report, to revise this policy statement and create NPS EN-7 which will be applicable for future nuclear power deployments (15). NIRAB considered the key elements of siting and planning policy relevant to a HTGR Demonstrator and concluded:

Clarity is needed on the scope of the details of the new NPS and whether it will adequately cover siting requirements for the HTGR Demonstrator. NIRAB recommends that EN-7 should provide a route to enable both siting of a HTGR Demonstrator and subsequent HTGR fleet. A broad scope of NPS-EN7 will limit the need for significant revisions and avoid delaying other nuclear projects such as SMR's and other AMR technologies in the future.

In order to realise the benefits of HTGRs it is likely that future fleet will not be all located on an existing 'named' nuclear licenced site. Therefore, the existing licenced sites named in NPS EN-6 should be reviewed and provision made in NPS-EN7 to define the properties that would make a site eligible for nuclear reactor siting thereby allowing new licenced sites to be identified.

Whilst there are likely to be limited changes between the current and new NPS for general safety case factors (which are considered as part of nuclear site licensing), specific updates may be needed to address climate impact at potential sites; technology impact such as reduced cooling water needs, infrastructure requirements; and the implications for demographic siting assessment, such as potential for reduced Emergency Planning Zones (EPZ).

Engagement

Locating the Demonstrator on an existing nuclear licenced site would require significant amounts of community engagement to achieve a 'social licence to operate'. It is likely extensive engagement with new communities, unfamiliar with nuclear power, would be required for locating on totally new sites. Early engagement with the relevant stakeholder communities will therefore be key to enabling sites to be licenced without significant opposition. Recognising communities which are broadly welcoming of new nuclear and have an industrial development need will help in identifying a suitable site for the demonstration plant and negate some of the challenges associated with selecting the location for the Demonstrator. A comprehensive plan to engage both nationally and locally would help de-risk siting particularly at new nuclear sites. Due to the lack of a developer this could be led by UK government.

Planning

The current electrical output-based Development Consent Order (DCO) thresholds (50 MWe in England and 350 MWe in Wales) could result in nuclear power projects undergoing approval via the Town and Country Planning Act (T&CPA) route, requiring Local Authorities to engage in nuclear planning. NIRAB does not believe that the T&CPA route should be considered for a HTGR Demonstrator (despite the size, or outputs of the reactor), due to the unique benefits and features of nuclear power facilities. DCO thresholds and alignment to electricity should therefore be reviewed to ensure they are suitable for the HTGR Demonstrator (Section 15 of Planning Act, 2008). However, NIRAB wishes to note that the T&CPA may remain applicable for activities such as site investigations and preparatory activities that are required to inform the DCO application.

3.3.4 Skills, expertise and the workforce

The majority of job roles involved in the design, licensing, construction, and operation of a HTGR are largely similar to other reactor types. Thus, it is possible to identify the key skills and expertise required for a HTGR by identifying what is different about a HTGR compared to an AGR, specifically production and use of higher enrichment TRISO HALEU fuel and the very different safety case that may flow from this, management of coolant (helium), the experimentation required for the Demonstrator, the heat or co-generation application processes, energy storage systems and potentially some of the control systems. All these different attributes will require the reactor and systems operators as well as associated regulators to know and understand the inherent differences in both normal and maintenance periods. The skill sets required vary, but include all engineering disciplines, chemists, physicists, computer modelers, data analysts, safety case and criticality specialists at all skill levels. The UK will also require a significant number of Subject Matter Experts to act as an intelligent customer/design authority on the intricacies of the Demonstrator throughout its lifecycle. A comprehensive training and up-skilling programme will be required to support training and development for new knowledge and experience to be gained in these key areas.

Nuclear criticality skills for the manufacture, movement, storage, loading and post-irradiation management of HALEU fuel, and in ensuring its safeguarding and security, will also need to be considered given its higher enrichment. Other features will be analogous to AGRs, including the graphite moderator, although even here, there are key differences in specification and replacement during each outage. The shared features will nevertheless be of great benefit as the UK has world-class expertise in graphite behavior and operability of AGR reactors and associated regulation. There may also be an opportunity to learn from the operational experience from other international programmes which may expedite time to competence when training new specialists.

There is a need to accelerate development of expert capability. A simulator and training facility that could act as a training hub for other advanced reactor programmes could be a highly beneficial and cost-effective way to train and develop such people. NIRAB recommends that training and developing highly skilled experts in the UK should be undertaken through both funding relevant research programmes and in sharing knowledge and learning across multiple reactor programmes. A coordinated approach, for funding postgraduate and postdoctoral research centred around future nuclear programmes, aligning with the Nuclear Skills Taskforce outputs, would be highly beneficial in this regard.

One of the biggest challenges in delivering the HTGR Demonstrator will be in securing the core skills needed at the peak times for the HTGR project which will be competing with GW, SMR and fusion reactors in the civil side, as well as GDF and Defence programmes. Whilst there is much work currently being undertaken within the nuclear sector to investigate the inter-linkages and over-laps between major projects, there will undoubtably be challenges in attracting, training, and developing sufficient expertise in the timescales required to meet the 'early 2030s' time goal. Estimating workforce needs for the nuclear industry in totality and the timescales for when each programme may require resource is critical to understanding how educational institutions, training providers, unions and workforce development initiatives can recruit, train and prepare workers for the future nuclear ambitions to ensure that the UK has sufficient numbers of the right skilled individuals available on the timescales required for delivery.

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3.3.5 Waste management & decommissioning

It is essential that waste arising from any new nuclear facilities is considered during the design and planning stages not just during decommissioning/delicencing. During operations all waste generated should be managed in accordance with the waste management hierarchy. Any new or novel wastes generated by a HTGR should be assessed to ascertain whether they are covered by existing Waste Acceptance Criteria (WAC) to permit disposal in current/planned facilities from the outset. Current understanding on waste arisings from the HTGR are insufficient to access compliance against existing WAC, and work is required to assess every stage of the lifecycle from the enrichment and production of HALEU fuel to the management of spent fuel and graphite and reactor decommissioning.

As mentioned in the technology section, research on the disposability of TRISO fuel, as well as graphite, in a future repository is essential RD&I. The UK has some irradiated HTGR fuel from the DRAGON programme, NIRAB believes there are advantages to be gained from doing some PIE on it.

Whilst specific RD&I has not been identified, further understanding the decommissioning of HTGRs within the UK, including DRAGON, and overseas, will be useful to ensure lessons learned are built into the HTGR Demonstrator design. However, we believe there may be limited additional novel features to address in the decommissioning of the Demonstrator. That said, current requirements for Funded Decommissioning Plans (FDPs) set out in guidance to support the Energy Act are for reactors that produce electricity and do not explicitly cover research reactors or reactors purely for process heat. This is a gap which we believe needs to be addressed by Government. Clarification of the need, ownership, and responsibility to make provision for full decommissioning costs of the HTGR is needed from the outset as the lifetime and income streams for such plans may be different for a Demonstrator than for power -producing reactors/ or fleet build.

Finally, we also draw attention to the recent Committee on Radioactive Waste Management' (CoRWM) Management's (CoRWM's) position paper on SMRs and AMRs (CoRWM, 2024) which contains a number of findings and recommendations relevant to the Demonstrator which NIRAB broadly supports, including.

- Opportunities to undertake post-irradiation testing on irradiated TRISO fuel could give useful insight to the characteristics of such material and its behaviour within a disposal environment, helping to underpin a disposability case
- The UK is currently deficient in the skills necessary to support the RD&I required to underpin the treatment, conditioning and disposal of novel radioactive wastes arising from advanced nuclear fuel cycles, and those skills are necessary to optimise the operation of a new fleet of reactors to minimise its waste burden
- The NDA has a vital role to play in assessing disposability, as a consultee in Justification and GDA. Early discussion between developers and NDA is clearly advisable
- It needs to be clear that it is for developers, not the NDA/NWS, to fund and undertake the necessary research on new waste arisings. NWS must be consulted about such research, and they will need to have full access to it for use in support of disposability assessment and development of the Geological Disposal Facility (GDF)
- 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

3.3.6 Other issues

Whilst the economics and investment case for a Demonstrator are outside of NIRAB's remit, we have briefly considered the interplay between financial investment of different types, and a technology, noting that it will be essential to take the financial community on a journey to understand the potential benefits of the technology as well as the Green ambition it could deliver. NIRAB considers the Regulated Asset Base (RAB) model is not suitable for funding early phase design development or significant RD&I for a Demonstrator as the uncertainties associated with the success of the project (the likely load factor of the Demonstrator, and the life of the demonstration plant) mean that the monetary rate of return on the investment will be uncertain and most likely small, even considering the Demonstration use case and optional electricity production which may defray some costs.

The Demonstrator's role is to demonstrate the effectiveness of the technology to allow future investment decisions, not to itself provide an invisible project. Hence, wider societal benefits e.g., building UK capability and skills development, future reduced cost of decarbonisation, self-sufficiency and security, export of expert services, etc are likely to be needed to be claimed to justify the initial project spend. Further work is recommended to look at the financial planning for the Demonstrator, including clarifying the level of nuclear liability insurance required for a research reactor. Similarly, further work is needed to explore funding models for a fleet of heat producing reactors. Given the importance of financing to progress any nuclear project, HMG should review the applicability of all existing finance models and any new models that could relate to heat and explore how they may be suited to novel reactor designs or First Of A Kind projects, including the novel factory build/modular construction projects and factory investment required.

NIRAB also notes that The Energy Act (16) requires a nuclear electricity station operator to submit a Funded Decommissioning Plan (FDP) to be approved by the Secretary of State before nuclear-related construction can begin. HMG should consider how to approach this key financial instrument for the HTGR Demonstrator, noting that the HTGR is not exclusively for electricity generation and that the designer/developer should introduce decommissioning considerations into the reactor design. A broader consideration of the insurance liabilities for a Demonstrator also will need to be carefully considered.

In summary, there are several regulatory aspects to the successful delivery of a HTGR which NIRAB suggests need careful consideration.

Table 2 provides the (Red-Amber-Green) RAG ratings that reflect NIRAB's view on the status and applicability of key areas to be considered for delivery of a HTGR Demonstrator and what may constitute 'essential' considerations.

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Table 2. RAG (Red-Amber-Green) status to each of the aspects considered here for delivering a HTGR Demonstrator.

(Where red is on the critical path and requires significant action (i.e. showstopper without change); Amber is on the critical path and requires some change, or not on the critical path but action would provide useful benefit; Green are activities which we feel do not require any further changes).

Key areas for Delivering a HTGR Demonstrator	RAG rating for current readiness of processes for HTGRs	NIRAB recommended improvements
Regulatory justification	Amber	Streamline the process considering multiple applications in parallel or undertaking regulatory justification on technology groups.
Early regulatory engagement	Amber	Regulators should offer pre-GDA engagement de-risking entry to GDA, licensing and permitting.
Design Assessment	Amber	Regulators should: examine whether GDA is the right route for a Demonstrator, review the GDA process to ensure it enables entry and assessment of innovative and novel reactor designs, produce guidance to re-use submissions from other countries and explore further harmonisation.
Nuclear Site Licensing	Amber	ONR should produce guidance on non-traditional deployment models, including for alternative protection and control strategies, multi-unit sites, co-generation, and cross boundary regulatory approaches.
Environmental permitting	Amber	The EA (working with other UK agencies including Nuclear Waste Services) should ensure an integrated approach between radioactive and non-radioactive assessment and permitting processes and avoid any duplication between processes (including planning and Habitats Regulation).
Siting	Amber	Clarity is needed on the scope, on the details of the new NPS and whether it will adequately cover siting requirements for the HTGR Demonstrator.
Engagement	Amber	Early engagement with the relevant stakeholders will be key to enabling a site to be licenced for a Demonstrator.
Planning	Red	Nuclear specific siting policy should be updated urgently. The current thresholds for DCO applications should be assessed, as well as the feasibility of non-DCO application routes via Town and County Planning (T&CP).
Roles & Responsibilities	Red	Gaps have been identified in roles and responsibilities, including the Client and operator for the Demonstrator.
Skills, Expertise & Workforce	Amber	Skills required to deliver a Demonstrator by the early 2030s assume leverage of significant skills and knowledge from existing AGR stations, which may close leaving a gap. Significant UK capability is required in the production of HALEU TRISO fuel, management of the coolant (helium), the experimentation required for the Demonstrator, the control systems and the heat or co-generation applications. Development of scarce nuclear science, engineering and criticality skills are key to the successful development and operation. Technical research programmes will be needed to develop key skills. Recognise and tackle demands from competing nuclear programmes.
Waste Management & decommissioning	Red	Current understanding on waste arisings from the HTGR is immature. Work is required to assess every stage of the lifecycle from the enrichment and production of HALEU TRISO fuel to the management of spent fuel and graphite, and reactor decommissioning to meet the Waste Acceptance Criteria. It is not clear whether a Demonstrator will need to have a funded decommissioning plan from the outset.

4. Forward Look

This work by NIRAB has focussed on identifying the RD&I objectives to facilitate development of a HTGR Demonstrator by the early 2030s in the UK. NIRAB has interpreted the question broadly and has taken a 'bottom up' approach, considering all the RD&I that may be needed across the Demonstrator's lifecycle.

This approach has helped to identify six main RD&I themes. We have prioritised the detailed RD&I objectives and in doing so have identified a number of areas which require clarification or decisions to be made in order for the Demonstrator to be progressed. In essence, NIRAB's work has produced a 'checklist' which may assist decision makers in determining whether everything is in place to allow an existing or future HTGR proposal to meet all the requirements for it to be licenced and built in the UK.

It is important to note that NIRAB is not saying the RD&I to meet these requirements must be carried out in the UK, or that it all needs to be Government funded, merely that the information needs to be known and shared with the relevant UK authorities and regulators for the UK to have a sufficient intelligent customer capability. NIRAB's work may also support vendors in understanding the key features of their reactor designs which need to be substantiated to receive approval for development in the UK.

There are some very clear overlaps between other major nuclear programmes including gigawatt power plants, Small Modular Reactors, the Spherical Tokamak for Energy Production (STEP) and defence programmes. NIRAB believes it would be beneficial to provide mechanisms to ensure reciprocal learnings across major nuclear programmes. Similarly, some of the RD&I activities identified herein will have benefits across the related programmes.

Both competition from other programmes and the timing of the rundown of the AGRs will make skills a critical enabler for the HTGR demonstration. Early, top-down intervention is needed to ensure that the necessary capability and capacity is available within the UK.

5. Conclusions

The science and engineering behind HTGR technology is relatively mature, but a reliable, licensable, commercially viable plant of any size has yet to be developed outside of China in recent times. Experience of connection to a non-electricity use case is particularly limited but has huge benefits especially when considering net zero targets and on-going challenges in the hard-to-abate sectors requiring high temperature heat.

NIRAB does not believe it is realistic to develop a completely UK-origin HTGR by the early 2030's, so a partnership model seems more plausible. The UK should develop the unique experience and capabilities it has into market opportunities but partner internationally on areas where there are capability gaps or risks.

The abundant high temperature heat from HTGRs provides an obvious market for High Temperature Steam Electrolysis (HTSE) technology. This should be used as a development stimulus with HTSE being developed in conjunction with and as part of the HTGR demonstration.

NIRAB has undertaken a detailed analysis of RD&I needs for a HTGR Demonstrator from a technology agnostic position through three separate, but inter-linked lenses (use-case, technology, and deliverability). We have considered a wide range of RD&I objectives, including many relevant to any advanced reactor programme, and their applicability to HTGR technology. We have also developed a prioritisation process to identify not only which activities are 'essential' to provide substantiation in the regulatory and permitting process, but which are highly valuable, valuable, or potentially operationally important.

The plans for the HTGR Demonstrator reactor and an associated use case should not be viewed in isolation but should be seen as contributing to Government's wider net zero ambitions. NIRAB has considered potential commercial impact/benefit to the UK of the proposed HTGR Demonstrator, and more importantly a potential follow-on, fleet, given the profile of UK capability, the technology maturity of HTGRs, the regulatory, planning and licensing context, and the diversity of possible use cases. Whilst the demonstration has specific objectives, it is important to consider from the start how it will lead to fleet build.

NIRAB has identified many RD&I objectives that will need to have been met in order to deliver a successful Demonstrator by the early 2030s. Some of these RD&I objectives will take some time to achieve and therefore we wish to emphasise the need to start critical (essential) activities at the earliest possible opportunity to enable HTGR's to be a component of the Net Zero strategy.

There are a number of activities which will support the development of UK operator capability. We believe HMG should help to identify/define who the operator and client are for the Demonstrator and undertake the necessary policy amendments to enable delivery.

In summary, NIRAB believes the following areas of RD&I warrant further investment:

1. Connecting the HTGR to use-case applications.
2. Developing leading UK technology, embedding advanced manufacturing techniques and construction methods in advanced reactor designs.
3. Supply of fuel and core materials which are not commercially available in industrial quantities in the UK or internationally but will be key to independence in nuclear power.
4. Reliably harnessing the necessary fluids, and assessing performance of key systems and structures, components, and materials in a hot fluid environment.
5. Designing and through-life substantiation of a safe and highly thermally efficient system achieving high integrity.
6. Enabling delivery by clarifying roles and responsibilities and ensuring appropriate siting and regulatory arrangements are in place.

We believe the approach we have taken has been robust and has produced a soundly underpinned list of considerations. NIRAB welcomes the opportunity to provide this independent advice, with a long-term aim of integrating HTGR to support the ambition set in the UK Nuclear Roadmap (17).

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NIRAB
NUCLEAR INNOVATION AND
RESEARCH ADVISORY BOARD

Research, Development and Innovation required for a High Temperature Gas Reactor Demonstrator

Technical Appendices

Introduction

The Nuclear Innovation and Research Advisory Board (NIRAB) is a group of independent experts who work in partnership with the Nuclear Innovation and Research Office (NIRO) to advise ministers, government departments and agencies on issues related to nuclear research and innovation in the UK.

The Civil Nuclear: Roadmap to 2050 stated the UK Government's intent to have an advanced nuclear programme, including a High Temperature Gas-cooled Reactor (HTGR) Demonstrator operational 'by the early 2030s' (HMG, 2023).

To support this aim, they have asked NIRAB to consider:

What RD&I is required to deliver a HTGR Demonstrator by the early 2030s?

NIRAB has looked at this question through three lenses:

1) What the reactor can be used for (its use-case)

2) Reactor technology considerations

3) Activities needed to enable delivery

This document provides a technical appendix to the main report and lists out all the RD&I objectives that NIRAB believes are important to consider. Readers are encouraged to consider this document alongside the explanatory text in the main report.

NIRAB welcomes the opportunity to discuss the RD&I activities presented in this report further with the long-term aim of supporting delivery of a HTGR programme.

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RD&I Prioritisation

Several programme objectives have been set out by NIRAB in Table 1 to support the delivery of a HTGR Demonstrator. These are set to provide a context and frame for the RD&I activities recognising the programme objectives would need to be augmented in line with the delivery strategy.

RD&I activities have been identified and objectives developed through the ‘use-case’, ‘reactor technology’ and ‘enabling delivery’ lenses described above. These RD&I activities have then been prioritised, using the terms essential, highly valuable, and valuable and are listed in Tables 2-4. This process is illustrated in Figure 1.

‘Essential’ RD&I is something that must be completed or initiated to successfully develop a working Demonstrator plant. It includes the following types of activities:

- RD&I that is on the critical path for delivery of a HTGR Demonstrator in the UK.
- Non-negotiable RD&I which will be required to support Licencing & Permitting, the development of safety, security, safeguards, environment, sustainability cases etc.
- RD&I that enables the substantiation of a safe, highly thermally efficient integrated heat system, coupling the end use of the heat output to the HTGR.
- RD&I that helps to achieve a successful outcome in pre-licensing/licensing/permitting stages including early action to meet disposability assessment needs.
- RD&I to support planning processes.
- RD&I that underpins the safe operation of the Demonstrator for example the behaviour of materials under high operating temperatures.
- RD&I to support demonstration of the feasibility to extract and use heat from an HTGR.
- Those which are essential for building base level of critical HTGR skills in the UK that are either strategically important or cannot be bought in, including intelligent customer capability and regulatory skill development.

‘Highly Valuable’ RD&I is something that will enable the full benefits of the HTGR Demonstrator plant to be realised. RD&I activities in this category include:

- RD&I that address long lead time items to enable a more efficient/ UK supply chain.
- RD&I to support planning or meeting community engagement expectations.
- RD&I that could help to accelerate time to deployment.
- RD&I that improves the operational output/ flexibility of outputs from the reactor.

‘Valuable’ RD&I is something that could utilise data from a HTGR Demonstrator to improve the efficiency of the Demonstrator or to help support fleet roll-out. Valuable RD&I activities include:

- Those that will have a benefit to the use case.
- RD&I that improves the operating efficiency of the demonstrator.
- Those that enable a step-change to be made against achieving sustainability targets for fleet roll-out.
- Those that de-risk future demonstrator programmes for other types of technologies.
- Things that will increase the likelihood of an investment decision for fleet deployment.
- Research that will increase the TRL of innovations that will help scale from Demonstrator to a fleet.

NIRAB has identified other RD&I that may well be beneficial but could be very design specific/ operational and may also have an adverse impact on delivery time for the Demonstrator which we wish to highlight (termed operational RD&I for a demonstrator).

The following tables list the programme objectives, then the RD&I objectives ranked in order of prioritisation and finally a table summarising operational RD&I for a Demonstrator. Where appropriate additional commentary has been provided to explain the significance of an RD&I activity or to highlight where work is needed or where a decision needs to be made.

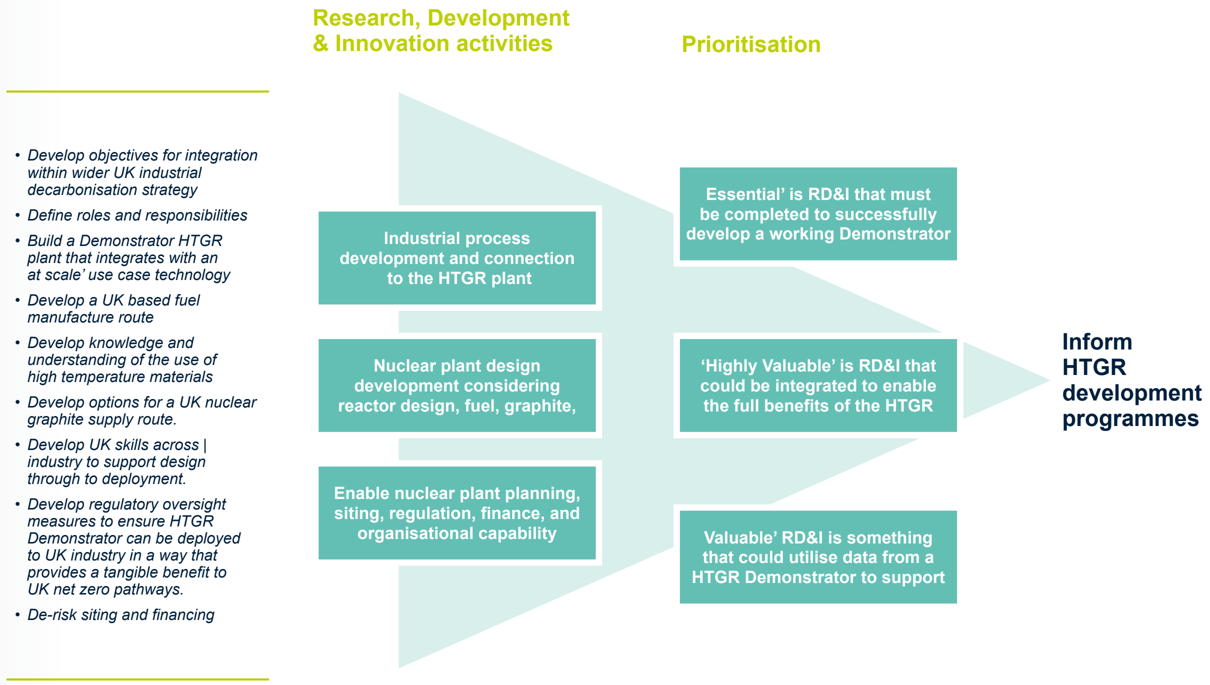

Figure 1. Programme Objectives, RD&I Objectives and Prioritisation Criterion

Table 1 RD&I Programme Objectives

No.	Programme Objective	Comments
1.1	Develop an integrated strategy of GW, SMR and HTGR nuclear technology within the context of wider UK industrial decarbonisation. Depending on selection of 'clustered' or 'national' decarbonisation scenarios various plant requirements could change such as: physical size, power output, heat output, size and potential co-location of hydrogen plant, thermal storage and/or long-distance transportation of hydrogen. This will drive the initial system requirements for potential Demonstrator vendors to design against.	For reactor vendors looking to enter the UK market, knowledge of how their technology could be deployed, as well as if they are providing heat, electricity or both will be crucial in helping them understand the business cases and requirements of their eventual customers. Different technologies could be deployed in different scenarios and the varying level of power and heat output requirements need to agree early to allow development of designs. This will also give clarity for prospective developers on whether their technology has a potential entry point into a UK market.
1.2	Define roles and responsibilities so there is clarity on which organisations will fulfil key roles including client, vendor(s), developer, and operator/licensee for the HTGR demonstration plant.	Clarity is needed so that all essential activities are progressed in a timely manner by competent organisations.
1.3	Build a Demonstrator HTGR plant that successfully integrates with an 'at scale' use case technology to demonstrate the viability of HTGR technology and the ability of nuclear power to integrate with UK industry's ambitions for decarbonisation.	**The Demonstrator should display:** • That HTGR technology can/cannot safely operate for an extended period with a high capacity at the correctly identified temperature outputs. • That a scaled-up use case demonstration (this is assumed to be a hydrogen electrolysis facility) can/cannot utilise the heat provided by the HTGR to run a low/zero carbon industrial process. • That the connection between the reactor and use case (either HTGR specific or deployable for other nuclear technologies) can/cannot cost effectively transfer heat between the two in the required medium for the end user. • That the size and scale of the use case demonstrator connected to the HTGR Demonstrator, is/is not a viable alternative for the end user when compared to a renewable energy alternative or fossil fuel. • Be able to support deployment of a fleet of HTGRs and increased UK capability in key areas such as fuel, graphite and other materials.
1.4	Develop a UK based fuel manufacture and qualification route for TRISO fuels.	Development of the manufacture, qualification and quality assurance inspection methods of TRISO encapsulated fuel for prismatic compact and pebble bed reactors unlocks several passive safety benefits to the technology and could be a key variable in achieving regulatory approval to co-locate a plant near an end user. A UK based fuel manufacture is necessary to ensure security of supply.
1.5	Develop knowledge and understanding of the performance of materials within a HTGR reactor environment.	Development of the substantiation (through testing, simulation, inspection) of high temperature materials is a key element of the unique selling point for a high temperature gas reactor.
1.6	Develop options for a feasible UK nuclear graphite supply route.	Development of a UK supply route for nuclear grade graphite is key for UK manufacture of fuel modules and reflector assemblies and to ensure security of supply.
1.7	Develop skills across the UK nuclear industry to support the HTGR from design through to deployment and then decommissioning.	To build, operate a HTGR demonstrator and then fleet, a wide range of skills will be needed across design, manufacture, operation and maintenance as well as decommissioning and waste management. Some of these skills will pertain to development of the plant itself but many of these skills will need to be embedded within the supply chain.
1.8	Develop regulatory oversight measures to ensure HTGR Demonstrator can be deployed to UK industry in a way that provides a tangible benefit to UK net zero pathways.	**Development will need to be carried out in the following areas (more may become apparent through the process):** • Implementation of TRISO as a valid fuel source. • Use of novel manufacturing methods such as electron beam welding and modular build of components. • Use of nuclear technology for the provision of heat as well as electricity. • Co-location of plants near to UK industrial facilities and COMAH sites. • Plants with large heat transfer networks (noting a key variable will be the transfer of heat back into the plant as well as out of it).
1.9	De-risk siting and financing by ensuring that all key national and local stakeholders are sufficiently informed about the UK's plans for HTGRs.	Long term community and other stakeholder support is essential for successful deployment of a HTGR demonstration plant.
1.10	Optimise use of the HTGR Demonstrator as an innovation testbed.	There are many different potential innovations that can be trialled (including to the benefit of UK core science programmes, other reactor types and sectors). This is a unique opportunity for the UK to test these, recognising impact on delivering the main programme goals.

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Table 2 Essential RD&I for a Demonstrator

No.	Essential RD&I for the Use Case	Comments
2.1	Develop technical solutions for the transfer of residual heat energy back into the nuclear plant from the use case. This should include development/ study of heat exchangers, different secondary/ tertiary coolants and efficiencies of multi-stage/temperature heat transfer networks. It could also include design substantiation of circuits with higher temperature materials, cogeneration of heat and electricity, addition of further heat through electrical heating (if required by end user).	To ensure closed loop systems can run self-sufficiently, residual heat and coolant materials that have passed through use case (i.e. condensed water from high temperature steam) must be successfully cycled back into the primary reactor plant so that they can be re-used within the system. Failure to do so would limit the siting and economics of future plants as continual supplies of fresh coolant would need to be added to the system.
2.2	Develop technical understanding of the High Temperature (Solid Electrode) Steam electrolysis hydrogen production methodology options and their potential integration with a nuclear plant through reactor supplied heat and electricity. Define the intended hydrogen production quantities and the requirements for HTGR Demonstrator heat and power input that this will drive, assessing different options. This then drives intended heat and power output of the HTGR Demonstrator plant.	Integrating the designs of the HTGR reactor and hydrogen production system is an essential activity. Regardless of future chosen HTGR use case, hydrogen production is likely to play a significant role in decarbonisation more generally with input from nuclear and renewables.Development of electrolyser technology is key to unlocking higher efficiencies and economies of scale when connecting to a true fixed source of energy and heat such as a nuclear plant. Technology development at present may be more tuned to available heat rather than optimised and aligned to the potential benefits of HTGR that could be explored. The aim is to ensure that options are not foreclosed where high temperature reactors have not been considered and that other potential options are also considered fairly, so the UK can pivot to demonstration of hydrogen production using the best available methods and ensuring that use case technology develops in parallel to reactor technology. There has been little work done in this field to demonstrate the connection, and NIRAB believes that this active demonstration is essential to work out how an integrated safety case is developed as well as to benchmark cost modelling.
2.3	Undertake a whole system level techno-economic analysis of a potential use case with HTGR integration AND co-location, to demonstrate full benefit of the technology. Cover build, regulation, operation, potential on-site heat storage vs transport of hydrogen and long-distance grid integration. This should include detailed analysis of latest use case economics and comparison to current costs (i.e. for SAF where hydrogen and carbon capture methods are used, how does it compare to today's kerosene production etc.).	It is essential the Demonstration project develops all the tools needed to appraise the project and future potential options in a fair and transparent manner, including those to support the business case for a fleet. For successful integration of a HTGR into an industrial use case, a true value and lifetime cost will need to be understood. This will allow an accurate comparison to both fossil fuels and renewable energies, allowing for an informed decision on the most appropriate technology for each use case to be made. Analysis should cover the cost of intermittent renewables (such as the need to store and transport heat and/or electricity, store and transport hydrogen over long distances), CAPEX & OPEX, maintenance costs, waste management and decommissioning as well as the cost of generation (including any need for additional burning of hydrogen or electrical heating to reach the higher required temperatures for industrial processes that cannot be directly achieved by renewable led technology – for instance in Liquid DAC). This should then be compared against current fossil fuel prices to give a realistic estimate of cost competitiveness (not accounting for unknown variables such as the price of oil or exchange rate in 2050). This could include addressing different metrics such as LCOE, VALCOE.
2.4	Complete safety modelling of the reactor plant and use case plant, alongside a control of major hazard (COMAH) site regulations, to understand potential roadblocks to co-location as well as opportunities where regulatory safety features overlap.	Previous regulatory guidance considers the context of rural or semi-urban deployment of reactors. The guidance treats such plant through assessment of external hazard cases, assuming they are distant, but is silent on an integrated energy hub type model which is emerging as a potential deployment case for HTGRs. A review of the appropriateness of such criterial in light of TRISO fuel and advanced reactors would be important for companies considering colocation type use cases. Co-location is a huge potential benefit of a HTGR plant. Before decisions on siting and sizing of plants it must be known how they can safely be integrated with sites which have non-radiological hazards. This should include physical distance between the reactor and its use-case (does a HTGR need miles of pipework to transport heat, or can it be integrated in current pipework?) as well as regulatory safety overlap – can regulation be reduced through combined safety features, overlapping exclusion zones, are there any hazards from the user that present an additional risk to the nuclear site etc.). This should also consider whether design features are suitable to provide the appropriate separation. This work will support development of guidance supporting innovation in delivery of how the regulatory spheres overlap and interact.
2.5	Develop model to aid decision making on implications of setting or not setting power size / size range of reactor.	NIRAB has recommended that the HTGR Demonstrator approaches FOAK reactor design. It is essential that choices are made on appropriate scale of plant, given the need for the programme to have an impact on Net Zero, there must be a clear strategy to deliver appropriate power needs.It is expected that there will be an optimum size point in terms of costs and deployability and investibility of such reactors. Understand It is essential to both requirements for and possible scope of scalability of HTGR plant for various sites and use cases (to address decision making on need for large GW scale hydrogen production facility, higher capacity 100s MW SMR for multi-user industrial cluster, smaller 10s MW SMR for single remote industrial user, micro reactor for heat network for local district, remote GW electricity generation), addressing unit size and fleet options. This should be combined with siting assessments so most optimum locations for plant can be selected early and size of plants to be built can be confirmed. This would inform and be informed by more detailed cost models. Scalability of plants will open new siting options that may not be available to large scale nuclear currently, and new siting options will open new use cases as requirements change, thereby making the technology more appealing to investors. Scaled plants might also open new and more competitive supply chains as materials and components can take advantage of newer and more modern manufacturing methods (such as electron beam welding reducing the need for large scale forgings with year long lead times). This will also open the market to new potential vendors as it unlocks similar pathways to deployment for small and micro reactors.

No.	Essential RD&I for technology (fuel manufacture)	Comments
2.6	Develop an understanding of all stages of TRISO fuel manufacturing processes, their performance limitations, and manufacture to inform decision on domestic fuel manufacture.	NIRAB notes that there have been recent developments with qualification of UCO fuel in the USA for example. We also note UK experience with UO2 production, and we recommend bringing forward specifications and analyses of fuel cycle performance and costing so that HMG can consider the investment needed for a UK strategic fuel supply chain for HTGRs and other Advanced Reactors that may use TRISO fuel. It is acknowledged that subject to availability and price international options may be used to supply early fuel cycles. There is limited international capacity. For security of supply the UK should explore domestic production. The outcomes will support a follow-on decision to develop and optimise a UK domestic advanced fuel pilot production capability for HTGR and other AMR optimised compact fuel, addressing prismatic and pebble designs, capable of being scaled quickly for UK and export market.
2.7	Establish a Post-Irradiation Examination (PIE) facility, tools, people, and skills capable of providing PIE for a range of current and future high burnup materials.	PIE will need to cover a full range of materials including TRISO fuel kernels, compacts, and columns, as well as graphite, SiC, control rods, burnable poisons (integral to fuel and discrete), and other metallic and composite materials. PIE will be required to generate the evidence to support licensing and permitting and to support Qualification of codes and materials. This PIE facility, capabilities, and capacity would support other nuclear programmes, which NIRAB believes is essential. There is likely to be strong alignment on the need for new and enhanced PIE services with other reactor types and the Defence programme.
2.8	Develop commercial volume multi-modal transport packages for precursor materials, fresh and irradiated fuel, and irradiated materials, covering all stages of the HTGR fuel cycle.	It is vital that a full set of transport packages are available in time for the Demonstrator for loading material and to support PIE. Packages to cover LEU+ and HALEU UF6 UCO and UO2 fuel compacts and assemblies are required.
2.9	Conduct generic and specific disposability assessments of TRISO fuel as compacts and loaded graphite columns (develop Waste Acceptance Certificate required for Licensing Demonstrator as part of licensing process) and identify needs for related RD&I.	Fuels will not be handled as they have been for the DRAGON reactor. Some early work has been undertaken on previous HMG funded ANT programmes, but there is much more to do. It is vital that the question of disposability is confirmed early in the programme, and to inform fuel handling requirements. Support R&D mapping through the assessment of benefits and risks of using existing irradiated materials (1).

No.	Essential RD&I for technology (manufacturing & materials)	Comments
2.10	Ensure evidence base exists to demonstrate an understanding of how existing base metals, vessel cladding, and weldment materials will behave under the realistic operating conditions in an HTGR environment throughout its life.	Sufficient evidence, either from collating data from overseas operations or from undertaking irradiation and post-irradiation evaluation within the UK will be needed for design substantiation to underpin the deployment of a HTGR. Additional performance data to underpin a licence application. i.e. address missing data through testing may be required if this hasn't already been generated.
2.11	Evaluate the extrapolation of materials performance in AGR reactors/ CO2 environments to helium to establish whether the evidence base is sufficient.	It is essential to consider how we maximise use of UK IP from the AGR programme, in terms of materials, models, use of facilities etc.
2.12	Develop optimal physical and chemical graphite specifications for fuel columns and moderator graphite, including any surface treatments.	Several prototype HTGR candidate graphite specifications have been established recently internationally. Supply chains outside of China are small scale. Specifications should consider needs for UK HTGR, ensuring design is appropriately underpinned to support a licence & permit application and Best Available Techniques (BAT) case.
2.13	Undertake R&D to support development of optimised graphite flowsheets and stimulate UK supply chain capable of supplying graphite to the necessary specification, quantities and on the timescale needed.	A number of candidate graphite specifications exist. Supply to nuclear sector is usually secondary and is not thought to be optimised or have the quality standards necessary. UK has experience in nuclear graphite manufacture. International supply is limited. We believe this requires intervention. As HTGR prismatic reactors have a significant need for graphite replacement each cycle, this will address an important security of supply consideration.
2.14	Sustain UK graphite skills and explore potential growth of UK supply chain for manufacture through a related RD&I programme.	There is a potential gap in understanding graphite behaviour in a HTGR. In addition, UK manufacturing would need additional skills to support qualification.
2.15	Demonstrate a suite of qualified Non-Destructive Techniques (NDT) applicable for HTGRs from cradle to grave, i.e. design (for inspection), manufacture, assembly, in service inspection in operation and decommissioning, covering conventional and factory-built environments.	Some components of HTGRs may be more complex and require adapted NDT. There may also be opportunities to innovate, taking forward developments made in the Nuclear Innovation Programme (2).
2.16	Demonstrate a suite of advanced conformity assessment techniques which would meet regulatory expectations for Quality Assurance (QA) and Quality Control (QC) for supporting a HTGR demonstration on a graded approach i.e. safe critical components have the highest level of QA/AC.	This is starting internationally but has not yet been adopted consistently. Such advanced systems, which may include use of Artificial Intelligence and Machine Learning could be of significant benefit for all reactor types and the defence and fusion sectors (3).

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No.	Essential RD&I for technology (fuel manufacture)	Comments
2.17	Conduct the necessary RD&I required to underpin HTGR deployment to support specific UK design codes or analysis procedure adaptations.	In some areas the existing codes may be considered overly conservative, incompatible with the reactor type being considered, or contain gaps with respect to UK regulatory expectations e.g. high integrity component classification, alternative to leak before break arguments, fracture toughness, R5 and R6 defect tolerance assessment procedure, low cobalt, involvement of Independent Third-Party Inspection Agency, use of Inspection Qualification. Independent confidence building measures (4).

	Essential RD&I for technology (reactor design modelling & simulation)	Comments
2.18	Identify and address gaps in the full set of HTGR modelling codes, including application within potential digital twin models, used for containment performance, source term production, consequence analysis and emergency planning requirements for HTGR application.	HTGR codes have some length scale challenges not seen in other reactor types. In the UK there has been limited investment in this area. A designer may need up to twenty computer codes to model an HTGR reactor. With the potential for multiple units and reloads, commercial scale tools will be required. Specific modelling to support timely fuel and materials qualification is likely to be needed. Whilst qualification could be done using conventional techniques and timescales, these will not be sufficient to meet the Demonstrator's timescales. Whilst deploying this into the Demonstrator for first cycle is not essential, the development of the modelling capability is. A staged approach to development of new materials, including use of computational techniques to support design and qualification in silico is recommended: **Stage 0** - Gap analysis for design codes to assess need for new materials or existing materials made using advanced manufacturing techniques, to be deployed in the Demonstrator. **Stage 1** – Explore modelling of such materials as a pre-cursor to using the Demonstrator as a testbed. This includes risk analysis using modelling to determine the need for new materials, to determine if physical tests are needed ahead of use of Demonstrator itself. **Stage 2** – Additional testing as required.
2.19	Carry out a gap analysis in design maturity to address readiness to deployment for unique and known life limiting features of HTGRs (Helium pump, cross vessel duct, internals) to increase Technology Readiness Level (TRL) in readiness preparationfor commercial rollout.	There is a limited supply chain for components outside of China. It is important for vendors to work up designs in conjunction with the potential supply chain, ensuring issues such a conventional safety for UK is built in early. The supply chain may need some pump-priming to get this moving on the timescales needed (5).

No.	Essential RD&I for technology (manufacturing & materials)	Comments
2.20	Define a pathway to deployment of advanced manufacturing and other alternative routes to manufacture of major nuclear components.	Whilst planning to deploy the Demonstrator using advanced manufacturing techniques is not Essential for Licensing and Permitting of a demonstrator, if the Government wishes to maintain an option for a fleet, RD&I to support advanced manufacturing, particularly techniques that reduce manufacturing time for Reactor Pressure Vessel (RPV) should continue to be addressed. As conventional RPV manufacture is a very large component of the cost of the asset, it is recommended to explore the impact of cost and schedule and safety case using modelling to support the assessment of benefits of utilising differing RPV manufacturing methodologies (conventional high integrity forging vs plate, conventional welding vs electron beam welding (EBW), use of Hot isostatic pressing (HIP) etc.). Where there is evidence, this could speed up manufacture and decrease cost without comprising performance (taking lessons learned from the EPRI-NAMRC electron beam and advanced manufacturing projects). Vendors could move to incorporate such techniques in plans in a phased way from a base which assumes conventional techniques, with an emphasis on understanding the gaps and business case for introduction of new techniques.
2.21	Develop a forward-looking HTGR Instrumentation & Control strategy which seeks to exploit digital techniques.	There have been significant challenges for licensing reactors in the UK particularly related to the use of digital control and protection systems which have led to analogue protection systems being designed specifically for the UK. There is some experience in designing analogue protection systems for LWR reactors, but limited experience and capability for AMRs. To ensure reactor designs can be transferred easily from country to country, it is important to find a pathway to move to digital systems. NIRAB believes that it is essential to address the potential issue early to bring forward evidence to underpin arguments about the use of alternative control and protection systems.
2.22	Develop Intermediate Heat Exchanger *(IHX) design to address known performance issues (effects of known flow distribution problems and hot leg stress challenges in some reactors). The usual geometry of an HTGR sees a 90-degree cold leg.	There are some features of this objective which are common with objectives related to the heat exchangers to be deployed on the "heat island". What distinguishes this item is the connection and location near the reactor core, the orientation challenges of the IHX, the need to address tritium migration, contamination, and irradiation (6). There is a difference in Classification of the components.

No.	Essential RD&I for technology (fuel manufacture)	Comments
2.23	Identify missing, incomplete, or uncertain nuclear data sets for UK application to address areas of concern e.g. graphite, structural materials, $^{235/238}$U, boron etc. Identify any nuclear data challenges and recommend a way forward for UK nuclear data files, addressing RD&I needs for nuclear data to enable coated particle fuel pilot and demonstrator reactor to proceed. Assess any gaps in UK codes including confirming any need for long lead criticality and or / nuclear data experiments or opportunity for nuclear data R&D.	Improving nuclear data is a live issue for improving modelling for criticality, reactor physics and modelling of the inventory of fission/activation products. RD&I in this area would address the need for UK nuclear data skills development more generically. There are international nuclear data collaborations that UK needs to continue to work with.
2.24	Further develop UK criticality tools to enable CPF pilot and demonstrator to proceed, including addressing lessons learnt from HTTR and Pre-HTTR criticality benchmarks, and experience from fuel manufacturing criticality analysis from HTTR fuel manufacture to enable CPF pilot and Demonstrator to proceed.	Optimise criticality safety margins through well validated computer codes capable of modelling the required geometries and able to address the modular manufacture needed for HALEU TRISO fuel, such that the evidence is there to support a fuel manufacturing safety case. Conduct HALEU TRISO criticality benchmark studies to support identification of opportunities for reduction of criticality safety margins in a systematic way, to support improvement of efficiency of material processing and movement.
2.25	Identify and address technical gaps in thermal hydraulics codes to ensure one can accurately model an HTGR reactor system (different gas, dust, fuel, layout, integration of reactor physics). Following this stage, develop validated fuel nuclear thermal hydraulic performance models/codes (addressing all modelling related heat transfer and gas flow challenges for fuel and reactor, including addressing lessons learned of flow distribution and cooling integrated head package.)	Assess the need for auxiliary facilities such as thermal hydraulics test facilities for validation of modelling of core, emergency cooling, and primary heat exchange, and provision of guidance around non-conventional qualification and validation that might be needed in lieu of traditional approaches.
2.26	Develop validated reactor physics models suitable to support fuel design (across kernels, compacts, and fuel assemblies) and addressing reflectors and related internals. Extend R&D on physics and thermal hydraulics codes as well as in the coupling of the physics and thermal hydraulics models. Identify and address any gaps in reactor physics codes necessary to support safety case e.g. addressing multi-scale challenges of TRISO CPF, modelling of flux discontinuities etc.	Validation requires access to appropriate modelling capability.

No.	Essential RD&I for technology (manufacturing & materials)	Comments
2.27	Develop validated fuel performance code addressing mechanisms in manufacture and operation. Address emerging issues such as manufactured stresses and gaps in fuel qualification databases to underpin licensing.	Validation requires access to experimental facilities.
2.28	Incorporate irradiation testing capabilities and component replacement planning into the design and safety case of the Demonstrator.	If the Demonstrator needs to become a test reactor it will need in-reactor and ex-reactor facilities to do so. It is essential they are designed in at the start and are part of the safety case etc.
2.29	Generate information and or data to support the safety case for the decay heat removal exchanger.	Vertically oriented HTGR designs use passive heat dissipation in the form of conduction and radiation to remove heat from the core to the vessel. Conventional HTGRs are designed to remove core heat by multiple methods such as active and passive cooling systems. NIRAB has assumed that the Demonstrator would test the operation of the decay heat removal systems but assume that development will require both modelling and or experimental validation.
2.30	Validate advanced elevated temperature neutron detector systems qualified for normal and accidental conditions.	The UK has considerable IP in neutron detection, including operation in high temperature conditions. Validation will need to be completed. Neutron detector lead times can be 2-5 years, and not considering them early enough can lead to redesign of reactors.
2.31	Define accident scenarios for HTGRs and adapt models to predict performance under accident scenarios.	Whilst some progress has been made, e.g. recent Loss of Forced Cooling trials at HTTR, there is much more to do.

No.	Essential RD&I for delivery	Comments
2.32	Review existing guidance on environmental discharge limit setting to address the situation of a HTGR Demonstrator with TRISO fuel in the absence of, or uncertainty in, operating experience and source term analyses.	Initial limit setting whilst development of a source term model often relies upon international operating experience related to discharges, but this may be limited for HTGRs. Reactor designers will need to demonstrate mitigation through use of Best Available Techniques. Whilst existing limits setting guidance is already flexible, the context of the use of TRISO fuel may benefit from further review.
2.33	Guidance on regulation of factory build environments to ensure that they are integrated with the regulation of nuclear reactor designs. Provide powers for nuclear regulators to inspect supply chain and address conventional safety standards for modular build to support preservation of Factory Acceptance Tests.	Ensure nuclear regulators have powers and capability to appropriately regulate manufacturing facilities - graphite, modules, fuel, which may be away from the nuclear licensed site. There may be R&D required to support understanding risks and opportunities in the supply chain.

No.	Essential RD&I for delivery	Comments
2.34	Optimise the requirement for introducing sustainability measures in Consenting and Justification of Practice for future designs.	Sustainability is now addressed in the current GDA Process. Guidance on new nuclear reactors currently assumes electricity production, but there may be a different case to be made from a sustainability point of view for a heat producing HTGR reactor. With a new reactor design, there may be increased opportunity to influence increased built-in sustainability through innovation and opportunities to innovate further. Justification of Practice is a required step. There is an existing Justification of Practice for research reactors. It is not clear whether a Demonstrator would be considered within this approved practice. A clean justification could be undertaken with generic information to cover a family of reactors and assumed use cases, including the Demonstrator. We need to make sure we know what is safe enough in the broader context of climate change risks. Guidance on how to approach Justification of Practice for a Demonstrator and family of HTGRs, covering the overall context of what is ALARP and BAT, including Guidance on how to approach decarbonisation benefits from HTGRs on hard to abate sectors supporting Justification of a Demonstrator but also the follow-on family of reactors.
2.35	Ensure there is access to a range of independent expertise to support regulatory assessment on key innovation subjects such as advanced materials & manufacturing.	Advanced materials and manufacturing might not be essential for a Demonstrator but could add significant value for a fleet. For example, NIRAB welcomes UK nuclear regulators' involvement in recent R&D programmes e.g. on Electron Beam Welding (EBW) and recommends this continues. Other Regulators such as USNRC have been active in this field in the context of their local supply chain and level of maturity (7).
2.36	Review needs for independent graphite research and regulatory advice.	Review learning from experience from ONR's existing Graphite Technical Advisory Committee suggesting RD&I and relevance of information from AGR programme. Review needs for independent models of graphite behaviour.
2.37	Review access to support Regulators, including code development needs, to support long term assessment of discharges and consequences of accidents from HTGRs.	
2.38	Review the status of HTGR design codes internationally including level of maturity, need for UK Adaptation and form a regulatory view on need for the Demonstrator to gather data to support ongoing substantiation.	
2.39	Review reactor core modelling systems to assess whether ONR needs to do independent modelling of reactor performance and whether there is independent expertise to support this.	ONR contracts out a Technical Support Organisation to undertake independent confirmatory modelling of a nuclear reactor during GDA or later. In the LWR world, there are a range of well validated code package available, meaning it is usually able to procure analysis independent from that undertaken by the vendor or licensee. For HTGRs this choice may be more restricted and may mean that there are regulatory drivers for additional codes.
2.40	Further develop regulatory guidance for fuel manufacture and reactor use in the UK.	To enable CPF pilot and demonstrator to proceed include addressing lessons learnt from HTTR and pre-HTTR criticality benchmarks and assessment of manufacturing criticality analysis.
2.41	Define RD&I to support regulatory position where a reactor has lost forced cooling and passive cooling but reactivity is held down by temperature coefficient but there is no risk of fuel melting.	JAEA has undertaken loss of forced cooling tests on the HTTR which have been successful. How transferable to other designs this is has yet to be ascertained. A safety case needs to be written in the UK context. It may be that RD&I is needed to support through provision of additional evidence including code development (8).
2.42	Develop guidance to inspectors and vendors on how to approach cross-regulatory assessments.	Develop guidance on integration of regulation of nuclear reactor, hydrogen production on site and hydrogen production offsite on COMAH sites, such that the internal and external hazards can be addressed with synergy. Guidance on siting AMRs near industrial centres and how the regulatory regimes could work most effectively together is needed. Address lessons learned from Multi-Regulator Observation Processes- NUWARD SMR joint early review (9).

Table 3 Highly Valuable RD&I for a Demonstrator

No.	Highly Valuable RD&I for Use Case	Comments
3.1	Develop technical understanding of the Direct Air Capture (DAC) process and technical options for carbon capture and its potential integration with the Demonstrator in the context of Synthetic Aviation Fuel production.	For SAF, DAC economics is likely to be one of the key cost drivers. The research NIRAB has undertaken has highlighted that a key cost reducer could be the development of Liquid DAC at high temperatures in the region of 700-900ºC – greatly increasing the amount of CO2 produced and reducing the size and quantity of the apparatus needed to do so. Understand potential temperature ranges that are required, considering achievable and current developments in the end user industries that would lead to a decision on potential integration of the high temperature liquid DAC process or the lower temperature solid DAC process.
3.2	Develop a specific strategy for HTGR integration aligned to the unique needs of the UK industry clusters (chemical processing, oil refining and iron/steel production, metal and minerals industries as well as food and drink, ceramics, paper, and pulp etc.). Development a deep understanding of their heat and power requirements to inform whether direct connection or distributions through heat hubs is required.	This study would build on the Hartlepool Heat Hub study to address other UK clusters. Understanding of the processes used in each of the clusters, how their requirements differ from each other, and their key inputs/outputs allows the potential for integrated system design where heat can be recycled through different stages, showing how a nuclear plant could most effectively support numerous industries as opposed to a single end user.
3.3	Develop cost reduction strategies for potential integrated HTGR and use cases to reduce complexity in build and operation and improve likelihood of final investment decision.	Moving from Demonstrator to FOAK and fleet deployment could create large opportunity for lessons learned, for example through the integration of more efficient technologies and modularisation of manufacturing processes for both reactor and use case. This would target reduction of the CAPEX cost of plant deployment, thereby aiding the technology in providing a cost competitive solution to the consumer.
3.4	Develop technical understanding of Syn-Gas generation through the reverse water gas shift process and its potential integration into a nuclear plant. This opens further use cases where nuclear could be used for direct support of Synthetic Aviation or Maritime fuel production.	SAF has been identified through a HTGR use case deep dive as a very viable potential market for HTGR integration. There are clear targets on the aviation decarbonisation road map and as such integration of nuclear technology should be pursued at pace alongside the HTGR Demonstrator so that it can take advantage of this emerging market as it develops.
3.5	Develop robust solutions for in-service TRISO fuel monitoring and inspection, coupled with associated data analysis tools to support ongoing fuel qualification, licensing for future deployment in the Demonstrator.	Whilst early indications show that TRISO fuel behaves well in reactor, the statistics are such that there will be a small proportion of failed kernels. Fission product monitoring of TRISO fuel is different from traditional oxide pellets contained in fuel pins. The lack of a pulse of radioactivity, different signature nuclides of concern, and the implications of failed fuel kernels based on statistics warrants investigation (10).

No.	Highly Valuable RD&I for technology (fuel manufacture)	Comments
3.6	Review complete reactor core design features and supporting evidence (kernels, fuel compacts, columns, burnable poisons, control rods, emergency shutdown system, neutron sources, reflectors, in core and ex core detectors) to develop a supporting RD&I plan, ensuring the right balance between innovation, cost and licensability and waste optimisation, and ensure the evidence is there to support licensing and permitting.	With longer fuel cycles targeted and higher reactivity at start of life, it is important to include a review of advanced control rod materials, design, and associated modelling, followed by qualification, to support the elevated temperature operation, partial insertion during operation, and improved control rod lifetime/reduction of wastes. Note this assumes access to existing designs of control rods for first cycle of the Demonstrator and sufficient information to initially licence the Demonstrator but acknowledges the potential needs for fleet to support longer term operation and any replacement needs.
3.7	Determine how fuel testing can be accelerated, such that sufficient confidence is available to support Licensing of the Demonstrator in a timely manner.	Fuel manufacturing RD&I for TRISO fuel is ongoing and keeps options open for the UK to be an intelligent customer or move to be a producer for fuel for the UK and the export market. A decision is needed to invest at scale to proceed to manufacture. The RD&I needed will then follow. NIRAB has provided some thinking on what may be needed. It will be for the fuel vendor to put forward a case for the use of a specific fuel in a specific reactor and to ensure there is sufficient evidence to justify safe operation within operational limits. Irradiation testing programmes take a long time and can be expensive, particularly if done on a bilateral basis, NIRAB has assessed that it should be possible to secure fuel for the first cores that has evidence to support the licensing We expect that the fuel vendor will have undertaken qualification in this way, to secure access to an Irradiation testing facility to enable independent irradiation testing of fuels prior to loading in the Demonstrator. Access to a Materials Test Reactor as a pre-requisite for further qualification of the fuel before starting the reactor up is highly valuable to support Licensing. NIRAB believes that given the timescales, it is necessary to use the Demonstrator to test fuel, and to evaluate existing and potential new fuels. Qualification data sets are likely to be needed to be complemented with additional data, or to complete qualification of fuel manufactured elsewhere. Development of a UK Materials Test Reactor to accelerate irradiation to support licensing in advance of the Demonstrator would be beneficial to the programme but is not credible on the required timescales.
3.8	Develop an approach and set down a strategy for fully characterising fission product migration and attack behaviour in coated particles, e.g., Tritium, Ag, Pd-SiC Interaction etc, with the opportunity to use the Demonstrator and associated PIE to support such targeted research. It is essential to explore methods in parallel to support safety cases and licensing.	Recent fuel qualification has advanced understanding of fuel performance of TRISO fuels and has identified some specific fission products of more concern that can challenge integrity of barriers. Whilst to some extent this has been seen previously, limited progress has been made to eliminate fission product leakage. If the intent is to make a claim on freedom of leakage of fission products, further work should progress.

No.	Highly Valuable RD&I for Use Case	Comments
3.9	Carry out R&D into innovative Quality Assurance and Quality Control (QA/QC) methods that demonstrate TRISO fuel has been manufactured to specification to optimise production processes and to ensure failed particles are not put into the reactor, and to build the confidence in the fuel needed to meet the safety claims being made on high integrity.	These are quite different to conventional fuel QA methods and there is an opportunity to update/modernise the methods that were originally developed ~50 years ago (11).
3.10	Develop robust solutions for in-service TRISO fuel monitoring and inspection, coupled with associated data analysis tools, to support ongoing fuel qualification, licensing for future deployment in the Demonstrator itself.	TRISO fuel is likely to release fission products in a very different way to traditional fuel pellets encased in fuel cladding. Statistically, there will be failed fuel particles in TRISO fuel, but they may not cause a spiking signature on monitoring instrumentation. There may also be nuclides which are of different concern which are important to measure.

No.	Highly valuable RD&I for technology (materials and manufacturing)	Comments
3.11	Demonstrate an adequate understanding of how existing reactor materials, modified using advanced techniques/surface finishing will behave in HTGR under operational conditions (if it is proposed that such materials are to be used).	NIRAB believes that advanced materials and methods of manufacture, whilst highly valuable for the medium-term future, may not present the lowest risk to a Demonstrator at first build. Deployment could be expedited for fleet use by using a Demonstrator as a tool to test samples in situ.
3.12	Investigate RD&I to support potential scale up of graphite manufacture to support HTGR fleet.	RD&I to support increasing output whilst retaining quality of nuclear graphite.
3.13	Develop in-service inspection methodologies for HTGR graphite, building on UK experience with operating AGR reactors.	
3.14	Develop European Network for Inspection Qualification (ENIQ IQ) processes for use of advanced materials/manufacturing methods to manufacture HTGR components and systems and address potential advanced inspection techniques.	There may be different types of defects introduced through new processes and it is important to assess how non-destructive techniques would be qualified to define a structural integrity strategy for such materials. The UK adopts the European Network for Inspection Qualification (ENIQ IQ) processes (12).
3.15	Demonstrate applicability of a suite of new base materials for high integrity safety critical HTGR reactor demonstration components, reducing cost, saving time, improving through life performance, and increasing potential outlet temperatures.	NIRAB sees potential advantages for new materials manufactured through advanced manufacturing techniques. It is not essential to use those at the start of life of the Demonstrator, but this would be an ideal platform to test such materials for later deployment.

No.	Highly valuable RD&I for technology (materials and manufacturing)	Comments
3.16	Support the accelerated development, qualification, code case development demonstration and deployment of materials made using advanced manufacturing techniques to support the UK HTGR RD&D Programme within demonstration deployment period.	Given the short timescales for deployment of a Demonstrator, NIRAB believes it is not essential to use advance manufacturing techniques at the start of life of the Demonstrator, but this would be an ideal platform to test such materials, and as such is highly valuable, as this may support accelerated qualification methodology that could benefit other sectors. This may also have relevance to other AMRs and SMRs.
3.17	Demonstrate a suite of advanced welding techniques using a range of HTGR applicable materials helping to increase their Technology Readiness Level (TRL) to ensure that the welding can perform in a realistic environment in a future plant.	
3.18	Demonstrate a suite of instrumented advanced automated Non-Destructive Testing (NDT) techniques (including combined welding, inspection, and testing methods).	Moving their Technology Readiness Level (TRL) to levels 6 and 7 to support advanced manufacture and on-site assembly & maintenance.
3.19	Underpin embedding of advanced manufacturing and materials applicable to supporting HTGR deployment, including addressing needs of UK code adaptations.	Examples include the R6 structural integrity procedure to address materials with defects. Code cases that address UK requirements could be explored. This activity may need to include provision of supporting materials performance data.

No.	Highly valuable RD&I for technology (reactor design, modelling, and simulation)	Comments
3.20	Further develop integrated methodologies and tools for undertaking Digital Twins (DT) at an early stage of the nuclear design of the HTGR.	Important for fleet, but not essential for a Demonstrator. However, programme timescales are such that development should start on the same timescales. As this innovation has importance to multiple reactor types, NIRAB rated this as Highly Valuable. A digital twin is a virtual representation of an object or system designed to reflect a physical object accurately. It spans the object's lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help make decisions (13). NIRAB advises that work being undertaken by others on modular factory construction processes continue and extend RD&I on development of Digital Twins of possible Reactor Factory Build environments (14). Explore the benefits of a digital twin as a dynamic aid or primary tool for design communication for the Demonstrator creating a roadmap for potential use of digital twins and manufacturing advances. Develop a DT platform that is capable of 'stitching' different length scale models to provide an accurate digital representation of safety-critical components (from entry to service conditions, in-service materials behaviour, to supporting lifetime extension justifications). Develop Digital Twin models capable of supporting future manufacturing of the HTGR, including fleet manufacture through modular build. This is to predict areas of process that create quality related risk. Determine modelling code needs for off-site release from HTGRs with TRISO & explore potential to integrate them in a digital twin.

No.	Highly valuable RD&I for technology (reactor design, modelling, and simulation)	Comments
3.21	Further develop methodologies/tools for undertaking Probabilistic Safety Assessments (PSAs) at an early stage of the nuclear design of the AMR HTGR, addressing implications of limited HTGR component reliability data set, passive systems etc.	A PSA is a key tool to support design development. It is often particularly challenging to produce a PSA until later in the design process when there is operating experience of plant. This should include extending understanding of HTGR fault schedules, accident, and severe accident performance to highlight any gaps early around the safety case for TRISO fuel. In some cases, this is expected to identify key data that the Demonstrator needs to generate e.g. for use of probabilistic methods in structural integrity e.g. suitable materials performance data (including in out-of-spec coolant).
3.22	Investigate the development of a method of incorporation of burnable poisons into TRISO fuel.	Burnable poisons are added to a core to balance excess reactivity at the start of a cycle of operation. It is important for the Demonstrator to be able to run for long fuel cycles, as this is key to commercial operation. Fuel cycles for HTGRs are less mature, and experience of TRISO fuel with burnable poison is even less well known. This research should be combined with core physics research, including addressing the impact of self-shielding in poisoned TRISO fuel. With criticality risks of HALEU fuel cycles, it may be possible to explore the potential introduction of blended burnable poison earlier in the fuel production flow sheet which could have benefits for fresh fuel handling.
3.23	Develop/refine integrated validated computer codes to model HTGRs under normal operations and transients.	Models of HTGRs are much less mature, and there are fewer off them than models of LWRs, and as yet they are less integrated. As a minimum, coupled reactor physics and thermal hydraulics codes will be vital as the physics is very much interlinked. There is a need for models to be integrated such that they pass input/output data to each other. This can be done with different software tools. An approach was demonstrated in previously funded AFCP work that looked at how to develop a digital twin that could be built upon. Development of models to help quantify uncertainties (i.e. manufacturing uncertainties, uncertainty quantification in fuel power, temperature from uncertainties in nuclear data, physical models, measured data etc.) will also assist understanding of the key parameters and how sensitive they are, and what focus there should be in future work.
3.24	Quantify benefits from integration of the different sub-components of reactor models using artificial intelligence (AI) and surrogate models to underpin a potential business case.	The use of AI is not essential, but NIRAB believes it shows much promise, including supporting reactor physics modelling and core design decisions that this assessment merits a rating of Highly Valuable to determine potential investment needed to take such a cross-technology objective further forward. The importance is to assess the information needed to underpin a prospective business case to address the potential use of AI in reactor physics modelling more generally.
3.25	Develop or extend validated models for calculating fission product inventory & release from TRISO fuelled reactors.	UK codes: FISPIN, STRESS3, MELCOR etc could be adapted/used to address uncertainties around nuclear data.
3.26	Develop robust and credible energy, cost, and other models to demonstrate optimisation of reactor output, linked to model of reactor and use case system.	To model value-adjusted lifetime cost of electricity (VALCOE) metrics.
3.27	Further development of UK fuel plant cost and reactor fuel cycle economics cost models to support modelling of HTGR fuel cycles and address higher unit fuel supply costs of HALEU TRISO compared with conventional fuels and enrichments.	To build on recent work on ANT cost models by GIF and EPRI (15).
3.28	Review lessons learned from pre-engagement, pre-licensing and licensing processes and apply these for the Demonstrator.	Lessons learned reports have been produced looking at GDAs for AP1000, ABWR and EPR GDA. The HPR1000 GDA is now also complete. GDA processes have already addressed lessons learned and moved to a 3-step process for the RR-SMR design for the first time. This reactor is due to complete Step 2 in Summer 2024. Production of lessons learned would be valuable for a range of technologies. This review of guidance should include a review of the potential adoption of a more realistic multi-unit site basis for GDA of an SMR/AMR rather than a single unit. The aim of the AMR R&DD programme was for the submissions to be at a technical maturity required to enter GDA Step 2. with the programme setting challenging timescales, and the Demonstrator likely to undertake a test reactor function, moving straight to nuclear site licensing may be more appropriate for the Demonstrator. Currently, AMR RD&D aims to get the projects to the equivalent of GDA Step 2 by the end of Phase B. If GDA Step 1 had to be repeated, this could extend the duration of the project. Specific guidance on how projects within the AMR R&DD programme transition to Nuclear Site Licensing would also be highly valuable. It may be that the Demonstrator makes use of a direct Nuclear Site Licence application. Lessons learned reports on recent nuclear site licensing would be beneficial covering small and large licence holders.
3.29	Develop guidance to inspectors and vendors on how to make maximum use of international regulatory submissions for reactor and fuel.	This was rated highly valuable but not essential as designs have been successfully brought into the UK from overseas. Feedback can be provided based upon submissions, but it would be highly valuable to have such guidance up front.
3.30	Undertake RD&I to support evidence needed to support site selection for HTGR Demonstrator.	Develop criteria for which to evaluate potential sites for co-location.

No.	Highly valuable RD&I for delivery	Comments
3.31	Develop consistent guidance on the use of Artificial Intelligence and Machine Learning (AI and ML) to support design, licensing, validation, and continued operation of reactor and or fuel plant.	AI and ML may be promoted as a key innovation, so NIRAB suggests holding an international regulatory review, leading to a position statement on AI to determine how it may be approached so there is consistent guidance.
3.32	Conduct a regulatory assessment of remote operation for small HTGR fleets.	Research to support a regulatory assessment would be long lead. This was set at highly valuable due to the perceived importance of this potential innovation for fleet economics and first of a kind challenge for licensing.
3.33	Provide advice and guidance to fuel and reactor vendors on UK regulatory view on need for additional qualification.	Review and report on adequacy and sufficiency of qualification of TRISO fuel through US AGR and other programme, including the review by USNRC and CSNC (16).
3.34	Identify gaps and needs for RD&I to support Nuclear Waste Services (NWS) & Regulatory assessment of Disposability assessment of TRISO fuels and packaging.	Consider how to approach disposability more generically collaborating with Vendors. It is vital to have a coordinated demonstration of disposability of all types of TRISO fuel, including fresh and irradiated fuel. Opportunity to do a pilot generic disposability assessment for TRISO fuel early. Opportunity for using DRAGON fuel to support disposability cases and research by vendor and EA/NWS alike should be explored. Includes R&D to support case to dispose of compacts and graphite together / separate covering a range of kernels and compact materials. Review of impact of single fuel cycle use of replaceable reflectors on wastes and doses and need for graphite monitoring.

Table 4 Valuable RD&I for a Demonstrator

No.	Valuable Use Case Related RD&I	Comments
4.1	Develop technical understanding of the lower temperature steam electrolysis hydrogen production methods and potential integration into a nuclear plant. This retains the ability to switch to this technology after a Demonstrator if industry requirements preclude high temperature electrolysis and could open the use case to further nuclear technologies operating at lower temperatures, or from an HTGR fed heat hub.	High Temperature Electrolysis (via SOEC or other method) remains the preferred technology, however there are variables in play to integrating it into HTGR that are out of scope of the nuclear industry – development of the technology may not be fast enough to maintain progress with HTGR and there may be a need to pivot to lower temperature electrolysis if timescales demand it. Additionally, lower temperature electrolysis is a viable hydrogen production route for other nuclear technologies (i.e. LWR) if HTGR technology proves unviable for 2050.
4.2	Develop technical understanding of potential high temperature heat storage technologies and their potential integration into a HTGR Demonstrator plant. Heat storage may be necessary for use cases including district heating or if an offsite hydrogen plant is operated in a peak/trough cycle.	Heat storage research could benefit several power sources. Unlocking heat storage at higher temperatures (through media such as molten salt) remains a key unique selling point that HTGR can take advantage of, with the potential to one day offer 100% capacity for heat provision or full baseload heat coverage at times of low renewable generation. It could also be siphoned off to provide additional heat energy for very high temperature industries such as steel or ceramics. This research would address specific challenges in high temperature storage, and challenges related to failure of such systems.
4.3	Demonstrate heat storage solutions integrated with the Demonstrator. The ability to trial different storage solutions (coolants, containment, controls, and heat exchangers) and explore how an operating would be valuable.	Understanding of how different storage technologies interact, both with the inputs from the demonstrator plant and the required outputs to a hydrogen facility will be valuable in making fleet decisions re. efficiency, OPEX, areas of cost reduction, maintenance, and safety as well as pairing potential solutions with the best technology to take advantage of them (not just HTGR but learning can be applied across LWRs, Gen IV reactors, even renewable technologies).
4.4	Build UK capability and skills for potential nuclear thermochemical hydrogen production routes.	Whilst Low TRL technologies like thermochemical hydrogen production methods, are not commercial options now (for a 2030s demonstrator). They could become viable and even more commercial sensible options for producing hydrogen in the run up to 2050 and could therefore be integrated with later plants as GWs are added to the grid. For low TRL level projects the highlighted organisations can spend time doing the vital research to understand and develop the technology (such as by carrying out study on the recent Japanese HTGR plant that has successfully utilised the Sulphur-Iodine process) and develop the knowledge and expertise that can then be taken advantage of in the national roll out of nuclear hydrogen. Support academic institutions, SMEs, and national labs in doing work to generate such skills may be appropriate.

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No.	Valuable Use Case Related RD&I	Comments
4.5	**Support R&D projects that:** • Aim to increase HTSE cell lifetime. • Reduce manufacturing costs. • Improve cell efficiencies. • Reduce the use of rare minerals. • Identifies how to connect HTSE to HTGRs.	All the listed projects would allow options that could be best aligned with development of HTGRs. This could lead more generally to reduction in cost & lead times in plant manufacture and construction, improvement in operating efficiencies and therefore OPEX costs, increased capacity by either reducing maintenance downtime or increasing the life of the plant and the environmental impact associated with building and maintaining a plant (environmental aspects that come above and beyond the generation of electricity which in itself is a zero-carbon process). Being potentially reduced.
4.6	Develop methods of dealing with out of specification materials for HALEU TRISO (fresh fuel) for industrialisation, reduce wastes, increase sustainability, and reduce fuel cycle costs.	10% out of specification is typical experience. With HALEU this increases costs further.

No.	Valuable technology RD&I (fuel manufacture)	Comments
4.7	Extend understanding of the stability and performance of TRISO fuel in accident and extended Operational conditions for larger sample sizes/full cores.	We believe that this is essential for licensing, however it will be heavily design dependent, and is therefore not listed as Essential to undertake in advance for licensing of the Demonstrator, which will need to consider the evidence that exists at present. Selection of a design, using the Demonstrator to support operational testing will be a core activity. Further testing of irradiated fuel at higher powers and temperatures should be further considered later.
4.8	Support licensing and permitting of local interim storage of TRISO fuel for the life of the plant followed by transport to disposal facilities – to cover TRISO kernels, compacts, and columns, including failed fuel or PIE samples, control rods, burnable poisons etc.	RD&I to support transport of irradiated fuel has been recorded elsewhere. Once a container exists for irradiated fuel to cover the needs of PIE, it could also subject to agreement be used to remove fuel promptly from the reactor site.
4.9	UK TRISO fuel manufacturing commercial scale-up.	Whilst it appears possible to purchase fuel from overseas, NIRAB believes that RD&I to scale up from a UK TRISO Fuel Pilot Plant towards commercial scale production is at this stage, before the demonstrator, highly valuable but not essential to pursue. However, a fuel order should be treated as a key long lead item, and it will be essential to test the fuel market for the Demonstrator. This investment needs to be kept under review and may need to be reprioritised. Such scaling up in the UK should be undertaken if a market emerges, and if friendly sources cannot be secured.

No.	Valuable Use Case Related RD&I	Comments
4.10	Determine need for and progress RD&I in robotic irradiated fuel handling to facilitate the removal of compacts from columns.	HTGR TRISO fuel compacts may be placed in prismatic reactors in different ways, with a loose fit, allowing gas flow over the compact, in pins more like conventional LWR reactors, or in snug fitting chambers in the graphite columns. At present designers propose not to remove fuel compacts from HTGR prismatic fuel columns. RD&I in robotic irradiated fuel handling to facilitate the removal of compacts from columns is not essential, however, this current practice does lead to creation of additional wastes, and this needs to be tested in licensing and permitting and if necessary reprioritised. Addressing the potential need for Fuel route RD&I early is essential as this will form an important part of the safety, security, safeguards, and environmental case.
4.11	Develop methods of dealing with out of specification materials for HALEU TRISO (fresh fuel) for industrialisation, reduce wastes, increase sustainability, and reduce fuel cycle costs.	Ten percent out of specification is typical experience. With HALEU this increases costs further.

No.	Valuable technology RD&I (manufacturing and materials)	Comments
4.12	Develop new materials required to meet end use requirements by demonstrating new low activation metal at scale designed to be tolerant of the operating conditions in a HTGR.	
4.13	Evaluate recycling of graphite from the HTGR demonstrator to enable assessment of feasibility of graphite recycling for future programmes.	There are already large volumes of irradiated graphite from AGR programmes. HTGR reactors will increase this legacy. It is important to determine whether recycling of nuclear graphite from the HTGR fleet would be beneficial from an ALARP/ BAT perspective on reducing the ILW inventory.
4.14	Evaluation of ASTM graphite specification against UK experience and propose updates, including addressing surface finishes, and issue of dust.	Graphite specifications may not have built in UK operating experience. It would be beneficial to align standards as for design codes to support internationalisation of such a design.
4.15	Assess applicability of ceramics including Silicon Carbide (SiC) for HTGR and wider application in a UK context.	Some assessment has been made to use SiC in wider nuclear sector.
4.16	Assess the applicability of composites for HTGR application in a UK context.	For example, steel-concrete composites.

No.	Valuable Use Case Related RD&I	Comments
4.17	Explore alternatives to traditional nuclear concretes.	Concrete is carbon intensive. With reactor cores deployed in small cavities below grade, there is a potential for activation which should be minimised to reduce decommissioning costs and wastes. The project should develop green low activation concrete, capable of being poured as civil engineering modules. There may be alternatives outside of nuclear design codes that may be attractive and could be qualified. R&D is underway to explore blending graphene, potentially using recycled concretes. Graphene is being trialled by the NDA (17) to ensure the right mechanical properties for recycled concretes. Adding graphene to a concrete mix could also reduce our carbon emissions from concrete. It has the potential to set harder and faster than a mix that doesn't contain graphene which might mean we can reduce the cement content in the concrete, or even reduce the amount of concrete we need to use, and importantly the finished construction will still do what we need it to.
4.18	Develop appropriate civil engineering design code case / validation to address elevated HTGR temperature operation / citadel wall heating effects in HTGRs.	
4.19	Further develop aseismic bearing techniques relevant to HTGR technology to reduce equipment qualification challenges.	Aseismic bearings have been deployed in a small number of nuclear power stations such as Koeberg and are part of the design for ITER.
4.20	Develop a coordinated accelerated qualification R&D Programme to evaluate the corrosion performance of advanced materials and advanced manufacturing techniques (linked to relevant R&D developments in e.g. materials, coatings, fuels, modelling & simulation, inspection/detection) Integrated thermal hydraulic and corrosion testing and qualification in representative helium atmosphere.	

No.	Valuable RD&I for technology (reactor design modelling and simulation)	Comments
4.21	Develop a fully optimised regulatory case for Demonstrator.	NIRAB recognises that a vendor may underestimate the challenges of producing an integrated and balanced case that covers Environment, Safety Security, Safeguards, and Sustainability suitable to fulfil UK regulatory needs. There is opportunity to use technology to support the full integration of Environment, Safety Security, Safeguards, and Sustainability (E4S) cases.
4.22	Assess need to develop innovative solution for detection of failed TRISO fuel (through on-line gas sampling and analysis system, discharge, and chemistry monitoring).	Subject to understanding safety significance of failure this RD&I objective may be elevated higher.
4.23	Understand the impacts of heat and electrical load following on I&C requirements.	This is to address the increased responsiveness that might be required for load following.
4.24	Assess the potential of unmanned autonomous operations of an HTGR to support potential for operation of a fleet of small reactors.	May not be necessary unless operators plan to operate in those modes, and hence not higher rated.
4.25	Assess the potential impact on safety and security case etc of remote HTGR operations to support potential for operation of a fleet of small reactors.	May not be necessary unless operators plan to operate in those modes, and hence not higher rated.
4.26	Develop, design & validate a passive safety system thermal hydraulics testbed to manage risk that such a system will not work for the Demonstrator.	This was not ranked higher as active systems could be used for the Demonstrator.
4.27	Substantiate thermal flow phenomena in a realistic He environment (using separate and integral effects) and addressing design specific requirements (for example may need to develop demonstrator instrumentation to undertake testing).	
4.28	Undertake further development of UK reactor modelling codes.	Moving from slower running, manually run codes, to a commercial standard providing easier refuelling safety analysis (which would be required for HTGR fleet application).
4.29	Validate use of advanced qualification materials performance simulation techniques for e.g. a) in-silico crystal plasticity modelling and materials qualification b) use of fine mesh and multi-group Monte Carlo modelling by comparing results from Demonstrator and having a large experimental programme for a) materials, b) reactor physics, c) others tbc - building on the work from SINDRI etc.	

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No.	List of valuable RD&I for delivery	Comments
4.30	Extend 2021 Public dialogue on advanced nuclear technologies Engagement report, July 2021 to support engagement in support of planning.	There is currently a project underway "Exploring the social, environmental, and economic benefits of Small Modular Reactors in Communities Sandpit." (18). There is little evidence to support analysis of public opinion on the use of Advanced Reactors or of RD&I to underpin the socio-economics case of SMRs more generally. BEIS reported on this in 2021 (19).
4.31	Survey Local Authorities Planning Departments on readiness for accepting and taking on Town & Country Planning Act (TCPA) based planning applications for the planning permission for a Demonstrator.	Currently, development projects for reactors of electrical power levels 50MW or less and in Wales 350MW or less are not required to apply for a Development Consent Order and would therefore likely use the Town and Country Planning Act, which would increase load on Local Authorities on specialist topics. Not withstanding nuclear siting and implications for planning have recently been the subject of consultation for application to ANTs, such a survey would be useful to support decision making around a planning strategy for a Demonstrator.
4.32	RD&I to support regulatory assessment of autonomous operation e.g. for a fleet of HTGRs.	NIRAB believes that the Regulator would need to be prepared for such a case to be brought forward. Such regulatory positions would be long lead and would require cross-sector review.

Table 5 Operational RD&I for a Demonstrator

NIRAB has identified other RD&I that may well be beneficial but could be very design specific/ operational and may also have an adverse impact on delivery time for the Demonstrator which we wish to highlight.

No.	Operational RD&I for fuel manufacture	Comments
5.1	Address data gaps and caveats in existing fuel qualification databases.	This is an important issue for vendors to undertake but this is very fuel design and manufacturer specific.
5.2	Address environmental sustainability issues with TRISO fuel chemical process flowsheets and support qualification of new fuel recipes.	
5.3	Review gaps/need for changes in codes for criticality in Geological Disposal Facility (GDF).	Spent fuel from the Demonstrator would undergo some burnup in reactor. However, assessments may treat this as unirradiated or make assumptions that there is residual 235U. It is important to check for any RD&I needs to support codes use to support assessment of re-criticality in GDF.

No.	Operational RD&I for materials and manufacture	Comments
5.4	Progress UK Adaptation / Code cases for ASME III Div 5 (HTRs) Graphite Design Code specifically taking on board UK licensing & environmental requirements.	

No.	Operational RD&I for reactor design, modelling & simulation	Comments
5.5	Evaluate use of AI and/or ML to predict behaviour of the Demonstrator linked to a complete digital twin (DT) including training of models of reactor performance, materials performance, flow induced vibration, addressing human factors, safety, and cyber security implications.	Whilst NIRAB recommends considering the adoption of AI and ML tools to simulate and predict the behaviour of reactors in the longer term, having a qualified system ready before deploying the Demonstrator is admirable, but not considered feasible as it would present a major risk to schedule.
5.6	RD&I to support modelling to identify optimal HTGR Demonstrator main component sizing limits (i.e. maximum size of forgings and components, road transport limits, etc.). Consider utility advanced manufacturing techniques and advanced material.	
5.7	Prove potential of augmented reactor and secondary side control systems to support load following and impacts from the use case technology.	Whilst the use of coupled technology may well provide the most optimal performance, keeping the secondary side controls separate from the reactor controls for simplicity is a lower risk approach.

No.	Operational RD&I for regulatory matters	Comments
5.8	Underpin guidance on how to approach licensing of a Demonstrator that may need more safety systems to start with that the fleet may need.	It should be clear that relevant good practice for a Demonstrator when data may be incomplete may see the introduction of more safety systems, may not then apply to a fleet if the evidence supports this.
5.9	RD&I to support safeguards inspections for pebble-based reactors.	This is very design specific. Pebble based reactors have fuel moving through the core and back out. A typical pebble in a pebble bed reactor will have several return passes, but this requires different safeguards and reactor physics controls to assess where the fuel is and what burnup it has reached (20). Clearly such processes and technologies have been solved in China.

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