Research Development & Innovation required to deliver a High-Temperature Gas Reactor in the UK

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1. INTRODUCTION

The UK Government's commitment to decarbonise the energy sector by 2035 and reach net zero by 2050 is challenging. A July 2021 report on fiscal risks by the Office for Budget Responsibility estimated a net cost of the UK reaching net zero by 2050 to be £321bn, or just over £10bn per year [1]. The Ukraine war has disrupted gas supplies and post-pandemic recovery has increased energy demand, leading to a significant increase in wholesale gas and electricity prices, thus strengthening the argument for the UK to bolster its energy security. Currently, around 40% of the UK's energy supply is imported from overseas [2], and whilst efforts to increase renewable contributions progress, other clean technologies, such as nuclear, must be used in adjunction to maintain energy supplies when wind and solar generation output is intermittent [3].

With its ability to output heat at temperatures above 500°C, the High Temperature Gas-cooled Reactor (HTGR) is increasingly seen as a viable technology to produce high-quality nuclear derived heat to mitigate some of the issues mentioned above. Currently there are three HTGR's in development/ operation internationally. The HTR-10 is a small 10 MWt experimental reactor with a TRISO pebble-bed located at Tsinghua University in China, while the HTR-PM is a 210 MWe demonstration plant, located at Shidao Bay Nuclear Power Plant in Shandong, China. The Japanese Atomic Energy Agency (JAEA) also have a High Temperature Test Reactor (HTTR) in Oarai, Ibaraki, Japan. Historically there have been several other demonstrations of high temperature gas-cooled reactor technology including the Daniel Power Pile at Oak Ridge National Laboratory, USA, and the DRAGON reactor at Winfrith, UK.

The Department of Energy Security and Net Zero (DESNZ) posed the Nuclear Innovation and Research Advisory Board (NIRAB) the question: "What Research, Development and Innovation (RD&I) is needed for the UK to deliver a HTGR Demonstrator by the early 2030's?" [4].

Before delving into how the HTGR could be delivered, the benefits of a HTGR should be highlighted. The HTGR's electrical output could be an important contributor to diversifying the UK's energy sources, but this is not its only advantage; indeed, providing electricity for the grid may well not be the optimal use of the technology. Rather, HTGR's high thermal output could be used as a direct heat supply for industrial applications or to generate hydrogen or ammonia for industrial processes. Heat from a HTGR could help to decarbonise energy-intensive industries with high CO_2 emission levels such as aviation, shipping or chemical manufacturing.

Minister of State for Energy Security and Net Zero Rt Hon Lord Hunt said: "As this [NIRAB] report shows, advanced reactors, such as HTGR's could help decarbonise industries like sustainable aviation fuel and cement manufacturing by providing low-carbon heat and power.

"New nuclear projects can revitalise communities by repurposing old industrial sites and injecting new jobs and investment.

"That's why we are backing nuclear – delivering energy security and growing the economy."

NIRAB has undertaken a comprehensive evaluation of the industrial energy market (Figure 1) to identify a specific example use-case for nuclear-derived heat. Four specific use cases were identified:

- Combined Heat and Power (CHP) for industrial users – HTGRs could exploit their capability to produce process heat at a constant throughput (with stable production or load following capacity mediated by molten salt or similar heat buffer storage), flexible siting (driven by improved safety cases) and semi-autonomous operation to provide a replacement for Combined Heat and Power (CHP) fossil fuel plants, equivalent to 3.7Mt CO_2 (total UK emissions in 2020 were 582 Mt CO_2) [5] [6].
- Heat and Hydrogen – Industry generates 16% of total UK CO_2 emissions [7] and foundation industries such as steel, glass and cement manufacturing require heat at temperatures of 1000°C or greater (steel 1375-1530°C; glass 1000°C (soda-lime) 1250°C (borosilicate); cement kiln 1300-1450°C). HTGRs could help mitigate this through a combination of providing initial heat in the region of 500°C, in parallel with hydrogen generation.
- 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 green methanol as a transport fuel or industrial feedstock. HTGR powered green fuel hubs could be responsible for the offset of over 22 Mt CO_2 or approximately 4% of UK totals [6].
- Synthetic hydrocarbon generation – Production of Synthetic Aviation Fuel (SAF) is currently limited by the requirement for hard-to-acquire biological feedstock but this could be replaced through use of hydrogen and captured carbon using a Reverse Water Gas Shift (RWGS) reaction and the Fischer-Tropsch process, with a HTGR providing the heat and power for both hydrogen production and direct air capture of carbon (or carbon recovery).

A deep-dive into the production of SAF was used by NIRAB to identify what Research, Development, and Innovation (RD&I) is required from a use-case perspective (Figure 2). Why SAF? The aviation sector is financially important, valued at £22 Bn input to UK GDP and with aerospace exports worth £34 Bn [8]. It is expected that by 2035 the development of a domestic industry for the production of sustainable fuels could support up to 5,200 UK jobs and contribute Gross Value Added up to £2.7 Bn from UK production and global exports. Hence Government has made a commitment to build five SAF production plants by 2025 and has a "jet zero strategy" to support the sustainability of the aviation industry [8]. NIRAB found that the economics of SAF production are dominated by operational costs, which a consistent supply of high temperature heat and electricity would control. Development of hydrogen production by steam electrolysis and of carbon capture methods would further streamline SAF production, making it a highly credible end-user of HTGR technology.

Interfacing HTGRs with end uses such as SAF production will require smart reactor manifold designs to manage reactor heat outputs at the 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 are needed. This RD&I will also benefit other sectors that are considering molten salt or similar high temperature energy storage/transmission.

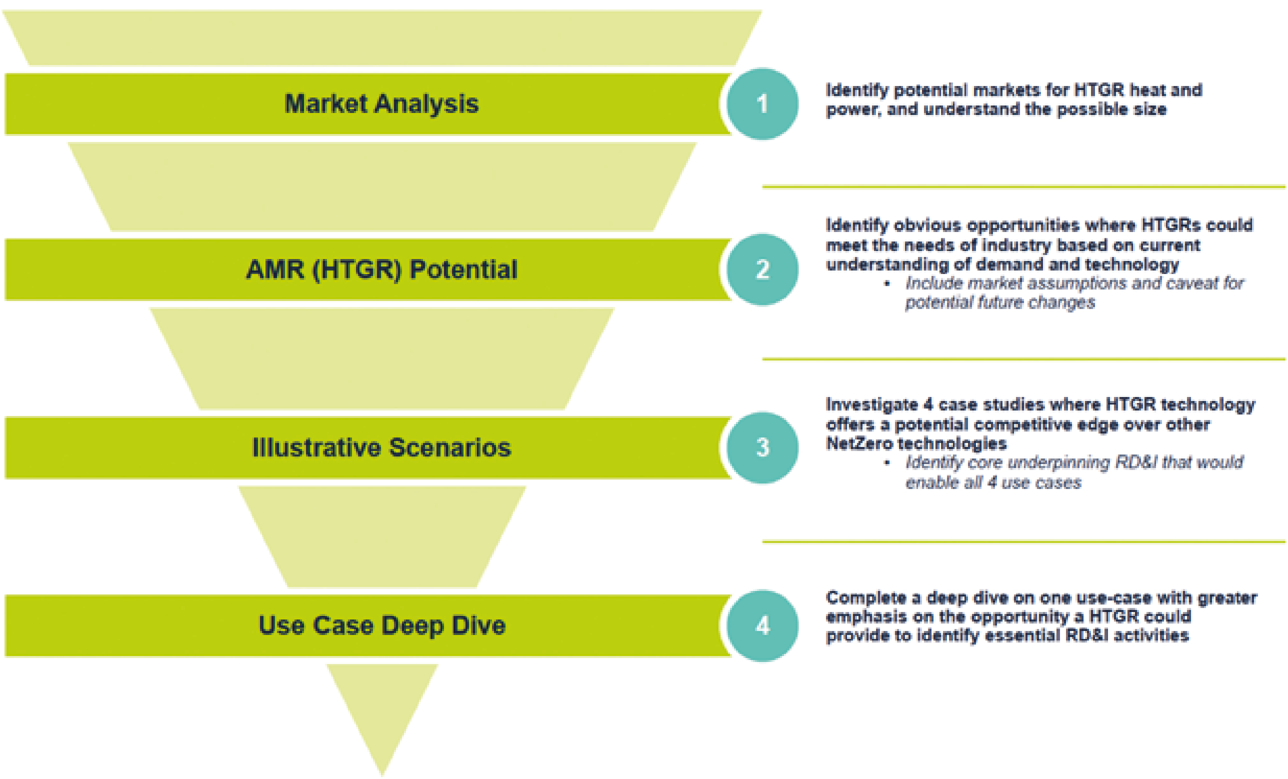

Figure 1. A pictorial view of the process NIRAB undertook to identify a market and use-case for HTGRs.

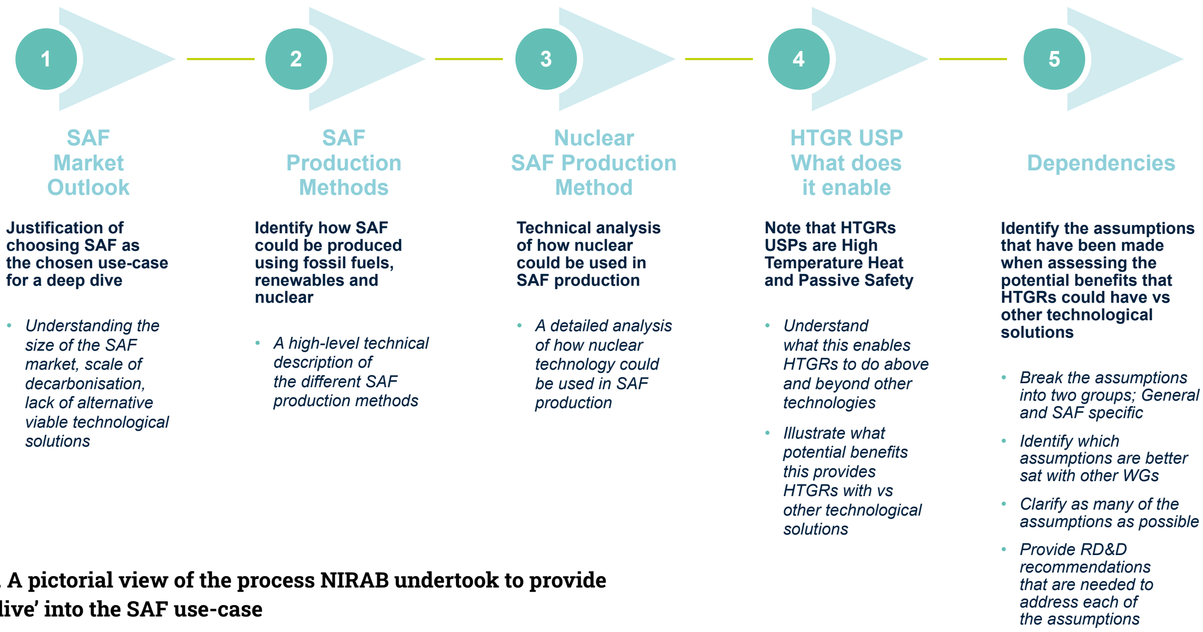

Figure 2. A pictorial view of the process NIRAB undertook to provide a 'deep-dive' into the SAF use-case

NIRAB has also looked at the RD&I needed to support HTGRs through a technology-agnostic lens and identified a number of areas where it believed further substantiation is needed, both to underpin safety cases and regulatory applications but also to support timely delivery. This has been done without assessing specific reactor designs or details of the proposed engineering methodologies. NIRAB recommended that such RD&I should be centred on three themes of:

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

Delivering a demonstrator plant by the 2030's is challenging (Figure 3). The novel features of HTGR technology, location and application will require adaptation of current arrangements and some very specific aspects require attention, including consenting processes, planning and siting, and also revision of the scope within the nuclear National Policy Statement. For example, the Development Consent Order (DCO) thresholds are currently based upon electricity generation and not heat. Similarly, there is ambiguity in the roles and responsibilities of organisations including identification of the Client. Regulatory guidance is also needed, both to address the more novel safety features of HTGR and also coupling of the reactor output to an industrial plant that requires process heat or similar.

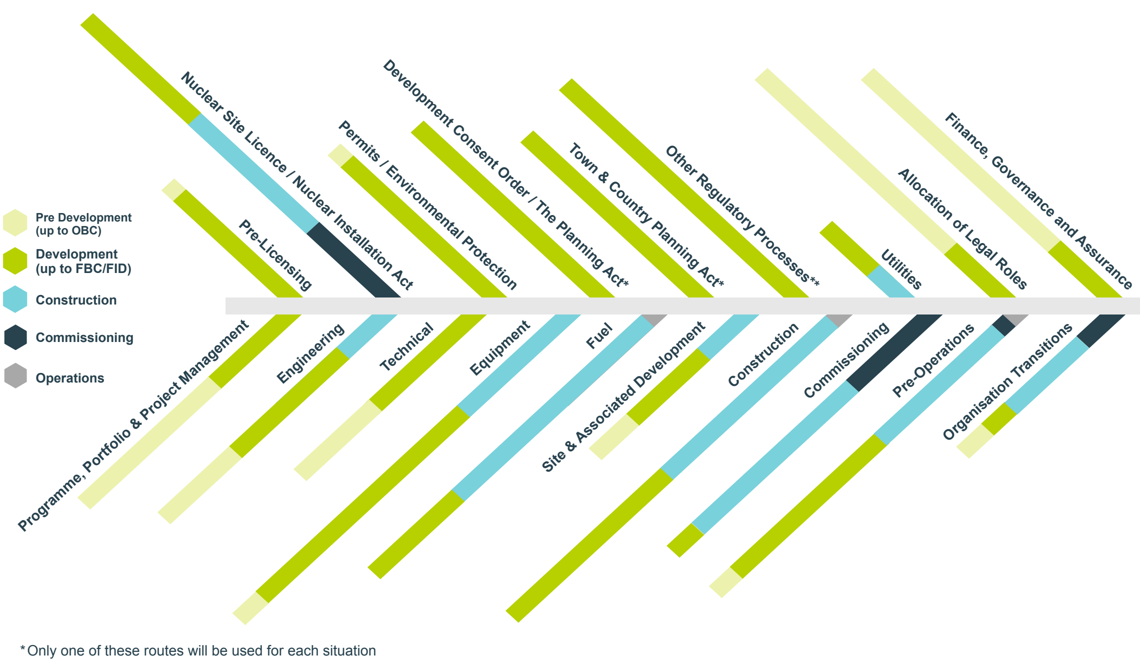

Figure 3. Programme delivery steps for a HTGR demonstration.

HTGR demonstration will require specialist skills and people with specific subject matter knowledge. Whilst many of the skills required for construction and general operation may be sourced from the existing supply chain or from the Advanced Gas-cooled Reactor (AGR) fleet, some skills, e.g. design capability, knowledge of helium chemistry, TRISO fuel specialists, structural integrity specialists, will need knowledge unique to the HTGR design which therefore needs to be developed through specific RD&I activities and/or training initiatives. A strategic workforce plan and potentially some specific, targeted interventions will be needed to source sufficient technical specialists to provide either underpinning support to the demonstrator or, at least, for the UK to act as an intelligent customer should it buy a reactor from the international market.

NIRAB also recognised the waste management and decommissioning challenges associated with all nuclear technologies. From the outset developers should assess what waste streams will be created and ascertain whether they are covered by existing waste treatment routes. Research on the disposability of TRISO fuel and HTGR graphite in a repository is also essential and must dove-tail into the work being undertaken by the Nuclear Decommissioning Authority and associated regulators.

HTGR demonstration should not be viewed in isolation but should be seen as contributing to Government's wider net zero agenda. A UK route to commercial impact/benefit from HTGR demonstration should be defined, given the profile of UK capability. Specific opportunities include:

- The commonalities between the HTGR demonstration and other major nuclear programmes, Gigawatt power and defence but particularly Small Modular Reactors and the Spherical Tokamak for Energy Production, allowing reciprocal learnings.
- While it is not credible to develop a UK-origin HTGR in the time available, a partnership model seems most plausible, so the UK should develop the unique experience and capabilities it has into market leading opportunities, and partner internationally on areas where capability is lacking.
- The abundant high temperature heat from HTGR provides an obvious market for this technology so this should be used as a development stimulus. However, a full economic assessment of the technology should be undertaken.
- Both competition from other programmes and the rundown of the Advanced Gas Reactor (AGR) fleet will make skills a critical enabler for the Gas-cooled demonstration, and early intervention is needed to ensure the necessary capacity is available when needed.

While the demonstration has specific objectives, it is important to consider from the start how it will lead to fleet build, for example, in identifying opportunities for cost-savings and bulk ordering to ensure the supply chain is ready and able to deliver on time.

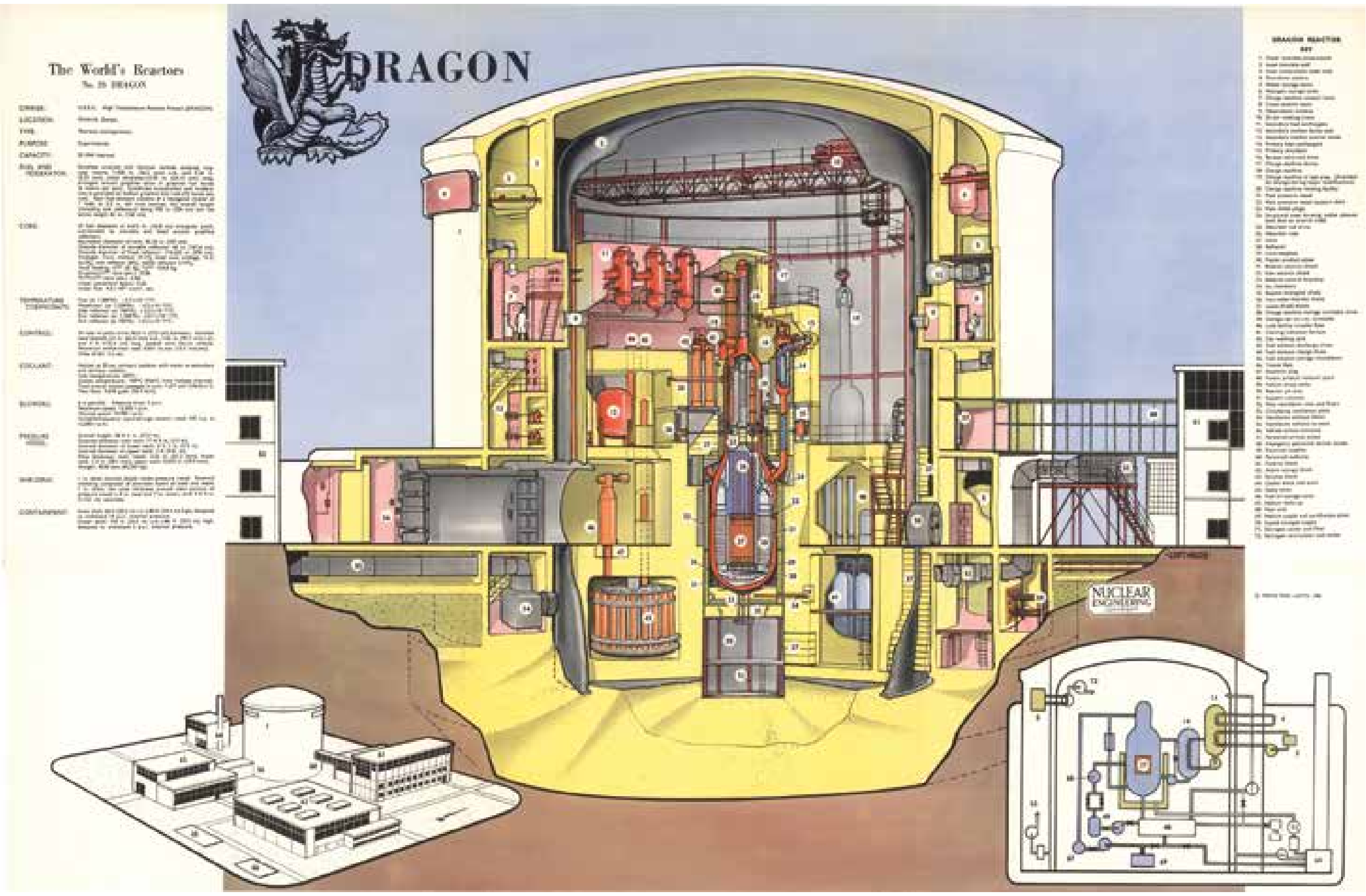

Figure 4. Winfrith Dragon Reactor Cut-away, Published with permission for Nuclear Engineering International (www.neimagazine.com)

Whilst the foundations for an HTGR have been laid, NIRAB has recognised that much remains to be done, with six key essential RD&I areas needing further investment:

1 Connecting the HTGR to a use-case application.
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 gases (e.g. helium) and liquids, 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.

2. SUMMARY

In summary, to deliver a HTGR successfully, NIRAB advises the demonstrator should ideally be as close as possible to a First of a Kind (FOAK); to de-risk and support efficient roll-out of a fleet. Engagement with end user industries and collaboration across sectors is vital if the UK is to reap all the benefits of a HTGR. A clear end-user for the heat/ electricity needs to be identified. Engagement and collaboration need to be initiated and scoped alongside a delivery plan. Whilst the development of a HTGR exclusively of UK origin by the early 2030s does not seem feasible, NIRAB suggests the UK develops the unique knowledge and capabilities it has into market opportunities and partners internationally on areas where there are capability gaps or risks.

Progressing a HTGR Demonstrator in the UK is a complex journey although the UK has operated the DRAGON High Temperature Gas-cooled reactor (Figure 4), a fleet of AGRs and the very first commercial large-scale nuclear power station, Calder Hall. Thus, the UK has a rich heritage of design and operation of nuclear facilities which should be built upon in order to deliver a HTGR which will aid in the decarbonisation of other sectors and assist in achieving the grand objective of hitting net zero by 2050.

NIRO OVERVIEW

The Nuclear Innovation Research Office (NIRO) is an independent strategic and technical advisor to the government, providing technical input, feedback or peer review for submissions, policy papers, business cases, tender documents, advice to Ministers and design of projects and programmes. NIRO's work aims to inform policy, support the governmental goal of hitting net zero by 2050 and enable maximum value for money to the UK taxpayer.

NIRO supports NIRAB in its preparation of advice and guidance for nuclear energy to play a crucial role in securing a low carbon future for the UK and ensuring energy security.

NIRAB OVERVIEW

The Nuclear Innovation Research Advisory Board (NIRAB) is an advisory board of individuals with vast experience across the whole nuclear fuel cycle sector, along with experts from other related specialisms, convened by NIRO. In partnership with NIRO, NIRAB advises Ministers, Government Departments and Agencies on nuclear research and innovation in the UK. NIRAB's support includes monitoring the UK civil nuclear research and development landscape, identifying opportunities for greater collaboration with industry and international partners, fostering greater cooperation and coordination across the UK's nuclear research and innovation capability, portfolio and capacity.

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