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Key conclusions from UK strategic assessment studies of fast reactor fuel cycles

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ABSTRACT

The UK Government has made a commitment to reduce greenhouse gas emissions by 80% from 1990 levels by 2050. Achieving this goal may demand a significant expansion of nuclear power and the Government has been exploring some very challenging scenarios with up to 75 GWe of nuclear capacity by 2050. Prior to establishing a national R&D programme, the Government commissioned the National Nuclear Laboratory (NNL) and the Dalton Nuclear Institute (DNI) to lead a preliminary R&D programme to fill in some gaps that have been identified. This initial R&D included a programme of work on Strategic Assessment, which will look at possible future energy and nuclear deployment scenarios to identify the important constraints and limitations. The nuclear expansion scenarios envisage a new build programme based on a Light Water Reactor (LWR) fleet and in some of these scenarios the LWRs are at some point replaced by a fleet of fast reactors with recycle that would allow a self-sustaining fuel cycle independent of world uranium supplies. This paper focuses on the high level conclusions that arise from the fast reactor scenarios studied. The high level conclusions relate to constraints on timescales for expansion of nuclear capacity and technical specifications for fuel cycle and waste management plants. In particular the work illustrates how the driving factors for fast reactor deployment have changed since the UK was last involved seriously in fast reactor development work in the mid-1990s.

1. Introduction

The UK Government has been exploring options for meeting the UK's future energy demand while also complying with stringent carbon emissions targets. Recognising the potential contribution of nuclear power, the UK Government has developed a Nuclear R&D Roadmap Nuclear Energy Research and Development Roadmap (2013) which considers future New Build scenarios with nuclear generating capacities ranging from 16 GWe to a very challenging 75 GWe. In this context, the UK Government commissioned the National Nuclear Laboratory (NNL) and Dalton Nuclear Institute (DNI) to carry out in-depth studies on different New Build scenarios and ultimately seek to be able to underpin a Roadmap of nuclear R&D which is congruent with nuclear policy within overall UK energy strategy.

Fuel cycle strategic assessment was a key component of the work, with the primary objective being to establish the reactor systems and associated fuel cycles that are most suited to meeting the UK's strategic needs with respect to energy security and future greenhouse gas emissions targets. NNL analysed 18 different future UK nuclear scenarios using its ORION fuel cycle simulation tool Gregg and Hesketh (2013). The scenarios ranged from one with no new nuclear build in the UK to others with new nuclear build for nuclear replacement (16 GWe), major nuclear expansion (40 GWe) and very ambitious nuclear expansion (75 GWe). The scenarios included different mixes of reactors, different timings for the introduction of breeder reactors and different strategies for recycling spent fuel. Because one of the key objectives of the UK Roadmap is to identify what could be the role of breeder systems, it was essential to include a breeder reactor system in those scenarios where ensuring continuity of fuel supply is the goal. The breeder scenarios assume a sodium fast reactor (SFR) as the reference breeder system, simply because suitable core design models for ASTRID were already available (see Section 3 for further explanation).

It is important to make clear at this stage that the UK Government at this time has no specific plans to commit to implementing a breeder fuel cycle, nor are there any plans to adopt any specific fast reactor system and that there are other scenarios considered where nuclear capacity is provided by LWRs only. In the absence

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of firm evidence to the contrary, the current premise is that fast reactors and their recycle plants are inherently more complex than thermal reactors with a once-through fuel cycle. The formal justification process for New Nuclear Build is specifically tied to a once-through LWR cycle and to which UK Government remains committed at present. The assumption is that the fast breeder fuel cycle would only be implemented in the event that trends in the world uranium market lead to price increases that would bring the overall generating cost of fast reactor breeder cycle in line with the thermal once-through cycle. It is not at all clear when this might materialise or even if it is ever likely to occur. Nevertheless, it is prudent for the UK Government to consider all the possibilities and this is why fast reactor breeding cycles were specified as cases to be considered.

The strategic assessment work was concerned with a broad range of issues, not just those that are connected to the deployment of breeder reactor systems. However, this paper focuses on the high level findings from the breeder scenario assessments, many of which are also relevant outside the UK context. The high level conclusions relate to constraints on timescales for expansion of nuclear capacity and technical specifications for fuel cycle and waste management plants. The work illustrates how the driving factors for fast reactor deployment have changed since the UK was last involved seriously in fast reactor development work in the mid-1990s.

2. Historic and current drivers

The UK Government supported a major fast reactor R&D programme for more than 40 years until the mid-1990s when low uranium prices, combined with privatisation of the electricity supply industry led to the R&D funding being withdrawn. The UK built and operated two sodium cooled fast reactors and the R&D programme culminated in the UK contributing to the design of the sodium cooled European Fast Reactor (EFR). The UK's fast reactor R&D was entirely driven by the assumption that world uranium reserves would become scarce and that a transition to a self-sustaining breeder cycle would become essential for energy security. It was recognised that the introduction of a fast reactor fleet would be limited by the availability of separated plutonium from the preceding generations of thermal reactors and there was a strong driver to maximise the breeding ratio as much as possible in the designs. The rate of introduction of new breeder plants would have been expedited by a combination of high breeding ratios and short spent fuel cooling times prior to reprocessing, which would have stretched the fuel and core designs and the fuel cycle plant designs. The fundamental limitation is that the rate of fissile plutonium breeding is small compared with the fissile inventory needed to fuel the first core and the first few reloads until the first recycled fissile material becomes available in a self-sustained cycle. For example, a 1 GWe plant with a very high breeding ratio of 1.3 would consume about 1000 kg of fissile material in a year and generate about 1300 kg. Of the fissile material generated, the 300 kg remaining after accounting for the 1000 kg needed to fuel the plant for a year, is small compared with the total fissile inventory in the core (typically 5000 kg or more). This, combined with the time needed for spent fuel to cool after discharge prior to reprocessing, typically results in doubling times measured in decades, not years and quite severe limitations on the rate at which a breeder reactor fleet can be built up. The out-of-core time during which the fuel is in the cooling ponds and undergoing recycle makes a significant contribution to increasing the doubling time.

The main drivers for an expanding UK nuclear capacity are now primarily the need to meet demanding greenhouse gas abatement targets, combined with maintaining a secure electricity supply. Secondary to this is an uncertain requirement for decoupling from the world uranium market that might drive the UK towards a fast reactor breeder fuel cycle. In the UK there is no consensus as to whether there will be a future shortage of uranium and therefore high uranium market prices within the time period covered by the Nuclear R&D Roadmap. As explained in Section 3, most of the scenarios considered did not specify the use of a breeder fuel cycle. But the Nuclear Roadmap would have been incomplete had breeder fuel cycles not been included and this paper focuses on the high level strategic conclusions that emerged from analysing that option.

In modelling the breeder fuel cycle scenarios, the decision was made to specify an *iso*-breeder reactor which has a breeding ratio only marginally above 1.0. One reason for this arises from best practice according to Gen IV and INPRO recommendations Nuclear Energy Systems (2011); INPRO (2004), which advises that radial breeder blankets should be avoided so that high fissile quality material produced in the radial breeder does not pose a proliferation risk. Without a radial breeder blanket region, it will be more difficult to achieve a high breeding ratio and so specifying an *iso*-breeder as the reference system is more realistic. Also, fuel and core designs which maximise the breeding ratio may not be the most economic to manufacture, since high breeding ratio fuels require smaller fuel pin diameters and lattice pitches, increasing fuel fabrication costs per tonne of fuel.

For the breeder fuel cycles specified, a key question is how soon might it be realistic for the UK to become strategically decoupled from the world uranium market? Scenarios which demand self-sufficient fuel cycles on timescales that are earlier than this can be ruled out as unrealistic and unhelpful. The earliest decoupling date is one of the key questions addressed in the strategic studies, along with others that are discussed later in this paper.

3. UK fast reactor deployment scenarios

Table 1 identifies UK future nuclear scenarios that were assessed with ORION. There were five basic scenarios, but many of these had sub-variants so that the total number of scenarios

Table 1
UK reactor scenarios modelled with ORION.

Group	Description	Fuel cycle variants
1	No new nuclear build with phase-out of current AGR and the single UK PWR plants at the end of their design lives	None
2	16 GWe new build LWR capacity with no fast reactor component. The new build LWR capacity is expected to comprise a mix of PWRs and BWRs, with construction of the first two PWRs recently started. The baseline assumes a once-through fuel cycle, though there are variants with MOX recycle.	Once-through plus 2 recycle variants
3	40 GWe new build LWR capacity. This scenario assumes a large expansion based on a mix of PWRs and BWRs, with a once-through fuel cycle as the baseline and several recycle variants.	Once-through plus 3 recycle variants
4	75 GWe new build capacity PWR capacity with no fast reactor component. This case is intended to represent the most ambitious nuclear expansion programme that could be considered reasonable and to act as a bounding case. Again there are once-through and recycle variants.	2 once-through plus 2 recycle variants
5	75 GWe new build capacity PWR capacity with SFR plants providing replacement capacity at phase-out of the LWRs. Again this is intended to be a bounding case, but in this case it is assumed that there is a strong driver for minimising uranium ore dependence, with SFR breeder plants providing a long term self-sustained fuel cycle.	6 recycle variants