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New Nuclear Power Technologies

Nuclear power stations provide a low carbon source of electricity, which could help the UK achieve its policy to reduce greenhouse gas emissions by 80% by 2050. This POSTnote reviews new and potential future nuclear power technologies. It also outlines the regulatory approach toward new nuclear build and summarises some of the related challenges.

Overview

- Most UK nuclear power stations are due to close by 2023. Government is encouraging investment into new nuclear with contracts introduced by the 2013 Energy Act.
- New nuclear reactors will come from a novel set of designs, which are more safe, secure and fuel efficient than previous reactors.
- Safety and security regulators are assessing companies' plans for new reactors.
- There are concerns about price, a potential skills shortage and the involvement of overseas state-owned companies.
- There are plans to bury some nuclear waste deep underground. However, the site selection process is under review after an attempt to gain agreement fell through.
- Future technologies could allow serial production of reactors, reduce fuel constraints and lower the volume of waste.

Background

Eight of the UK's nine nuclear power stations are due to close by 2023. These nuclear power stations produced 18% of the UK's electricity in 2012. In 2013, the Government set out a strategy to develop new nuclear power stations in England and Wales to replace closing stations.[1] It plans to have 16 GW of nuclear power by 2030 and up to 75 GW by 2050. To encourage construction of new nuclear the 2013 Energy Act legislated for contracts that guarantee new nuclear power station operators a long-term fixed price for the electricity they generate ('Contracts for Difference'). However, the UK has not built a new nuclear power station since privatisation in the 1990s and nuclear power technology has developed since then.

Generations of Nuclear Reactors

Nuclear reactors (the part of the nuclear power station where the nuclear reaction occurs, Box 1) have evolved through several generations (Gen).

- **Gen I** reactors were early designs, such as the UK's Magnox reactors built in the 1950s-70s.
- **Gen II** were more advanced than Gen I and built from the 1960s-80s. All of the UK's operational reactors are Gen II.
- **Gen III** are more fuel and heat efficient than Gen II. Two designs are currently under review to be built in the UK.

Box 1. Nuclear Reactors

Nuclear reactors work by harnessing the energy released when a heavy atom, like uranium, is split. This is known as fission. An alternative approach, which joins two light atoms, is known as fusion (POSTnote 192). Fission nuclear reactors are the focus of this note as all current and proposed commercial nuclear power stations are fission-based. Fission reactor designs may vary by their:

- **fuel** (used to generate heat in the reactor, typically uranium)
- **moderator** (used to control and sustain the nuclear reaction, examples include graphite and water)
- **coolant** (used to take heat from the reactor to drive turbines to generate electricity, either a gas or a liquid).

- **Gen III+** designs are evolved from Gen III. Two designs are currently under review to be built in the UK.
- **Gen IV** reactors are advanced designs, which are not expected to be available for construction before 2030.

This note looks at new (proposed Gen III and III+ reactors) and potential future (alternative and Gen IV) technologies.

Key Areas of Regulation

A release of radioactive material could harm health and the environment. To minimise risks, the safety and security of nuclear reactors and management of radioactive wastes are regulated nationally and promoted internationally (Box 2).

Box 2. Nuclear Regulators and Authorities

- The Office for Nuclear Regulation (ONR) regulates the safety and security of nuclear facilities, transport of materials and ensures compliance with international obligations. The ONR will be independent from Government as of 1 April 2014.
- Regulation of radioactive waste disposal is devolved in the UK. The regulators are the Environment Agency (EA) in England, Scottish Environment Protection Agency and Natural Resources Wales.
- The ONR and EA established the Joint Programme Office to manage the assessment of new nuclear build.
- The European Atomic Energy Community and International Atomic Energy Agency (IAEA) promote international safety and security.

Safety measures aim to prevent accidents, which may occur during normal operational activities. Nuclear reactors must meet three fundamental safety requirements that: (1) the reactor can be shut down safely at any time; (2) the reactor can be kept cool (radioactivity continues to generate heat after the reactor is shut down); (3) all radioactive material is confined behind barriers.

Security measures protect against intentional threats from individuals or organisations looking to cause harm. POSTnote 222 discussed two categories of nuclear security threats that have some relevance to nuclear power stations: attacks on power stations, facilities or transport vehicles; release of radioactive material using a 'dirty bomb'.

Radioactive waste has been produced by the UK's previous and existing nuclear programmes and the clean-up is funded by the Nuclear Decommissioning Authority (NDA). There are three levels of radioactive waste: (1) low level waste (such as protective clothing) is disposed of in a near-surface facility; (2) intermediate level waste (such as reactor walls); (3) high level waste (mainly extracted from used fuel) is currently kept at nuclear sites. Long-term policy in England is to bury intermediate and high level waste deep underground in a Geological Disposal Facility (GDF), although one has not yet been built. Scotland's policy is for long-term storage in a near-surface facility. Wales is not seeking to build a GDF, but would consider a GDF if a local community expressed an interest in hosting one.

New Nuclear Build

Companies are planning to build new power stations. This involves **vendors** (who design and build reactors) and **operators** (who build, own and run power stations). Prior to construction, regulators will assess the safety and security of designs, the types of fuel that will be used and plans to handle waste and decommissioning.

Assessment of New Nuclear Build

New reactor designs undergo two assessment stages prior to construction, the Generic Design Assessment (GDA) and Site Specific Assessment (SSA). The two assessment stages combined take around seven years to complete and are overseen by the Joint Programme Office (Box 2). The GDA assesses the generic acceptability of vendors' reactor designs by considering the environmental impacts, safety and security. The SSA ensures a selected site is suitable to host a nuclear power station and that the operator is capable of running it safely and securely during its lifetime.

There are three nuclear reactor designs that vendors have entered into GDA (Box 3). These are Gen III and Gen III+ designs and all use uranium as the fuel and water as the moderator and coolant (Box 1). The designs are expected to operate for at least 60 years. Three operators are considering building these designs (Box 3).

Safety and Security of New Reactors

Reactors will continue to rely on safety systems to meet the fundamental safety requirements outlined above. All designs proposed for the UK use active and passive safety systems.

- **Active safety** relies on backup power, controlled by machine or human. For example, in the event of a nuclear reaction overheating, electricity is required to mechanically insert horizontal moderator (Box 1) rods into the reactor core to keep the reactor cool.
- **Passive safety** takes advantage of natural processes like gravity. For example, if power to electric magnets holding vertical moderator rods is lost, the rods drop into the reactor by gravity to keep the reactor cool. Passive safety systems can maintain correct operation for up to 72 hours if electrical power is lost.

In addition, reactors have redundant, diverse and segregated safety systems. For example, to prevent a failure, such as fire or flood, affecting all safety systems a reactor may have several copies of an active safety system (redundancy), plus passive safety systems (diversity) and different safety systems are kept apart (segregation). The ABWR and EPR (Box 3) designs have four-fold active redundancy (two or three-fold was common in Gen II) and the AP1000 (Box 3) relies on more passive redundancy.

Security will be regulated in accordance with the Nuclear Industries Security Regulation.[2] Security will also be improved by new specifications for reactor safety systems.

Box 3. Reactor Designs and Potential Operators

Three vendors' designs are being considered in the UK. They fall into two design types, the Advanced Boiling Water Reactor (ABWR) and the Pressurised Water Reactor (PWR). An ABWR generates steam directly from the reactor core, whereas a PWR generates steam indirectly by heat transfer.

- **EPR** is a Gen III+ PWR designed by the French company AREVA, which has completed GDA.
- **AP1000** is a Gen III+ PWR designed by Toshiba's US subsidiary Westinghouse, which has nearly completed GDA.
- **Advanced Boiling Water Reactor (ABWR)** is a Gen III design by Japan's GE-Hitachi Nuclear Energy, which has begun GDA.

Three operators are considering these designs, which could generate up to 17.8 gigawatts (GW) of electricity:

- **New Nuclear Build Generation Company** (a subsidiary of EDF Energy) has begun SSA for two EPR reactors at Hinkley Point C and is considering two more at Sizewell C.
- **Horizon Nuclear Power** (a subsidiary of Hitachi Limited) plans to build two or three ABWRs at both Wylfa and Oldbury.
- **NuGeneration** (a joint venture between Toshiba and GDF Suez) intends to build three AP1000s at Moorside, near Sellafield.

For example, redundant safety systems also protect against sabotage, so if attackers disabled one safety system there would still be multiple backups.

Safety Following Fukushima
Following a major release of radiation at Fukushima in Japan (Box 4) the Office for Nuclear Regulation (ONR) reviewed the safety of UK nuclear reactors, focussing on extreme natural events. Several recommendations were made, which included strategies to ensure power is maintained if electricity from the national grid failed and that on-site electricity generation is robust enough in the event of extreme conditions.[3] The ONR notes that the UK has a good safety record.[2] There has only been one significant nuclear accident in the UK, at a military site in 1957, before an independent regulator was established. Although safety regulations are designed to protect against all credible hazards, NGOs say it is not possible to identify all hazards and point to Fukushima as an example.

Sourcing and Reprocessing Fuel
The UK has no natural reserves of uranium fuel, so it relies on imports, with Australia, Canada and Kazakhstan being the biggest uranium producers. In 2008, the World Nuclear Association concluded that there are sufficient uranium reserves available to meet future global demand. However, the IAEA suggest a global resurgence in nuclear power may put pressure on prices.

Reprocessing could reduce the amount of uranium needed, by extracting unused uranium fuel from used uranium fuel. However, reprocessing increases costs and leads to the separation of pure plutonium, which is used in some types of nuclear weapon. In 2008, the Government said operators should build new nuclear power stations on the basis fuel will not be reprocessed. The NDA has decided to close its reprocessing plants at Sellafield by 2018.

Waste and Decommissioning
The 2013 Energy Act requires operators to set aside funds for the decommissioning of new nuclear power stations and the storage and disposal of their radioactive waste.[4] These funds will be transferred to the NDA, which will manage the waste and decommission the site.

Challenges for New Nuclear Build
Public Concern and Building a Geological Disposal Facility
Recent studies by the UK Energy Research Centre on the public's attitude toward nuclear power show that it is the least favoured form of generating electricity, but is accepted as part of an energy mix.[5] Public opinion of nuclear power and Geological Disposal Facilities (GDF) is more favourable in communities that have a history of a nuclear industry. However, selection of a site has proven to be difficult. In 2013, the Government failed to gain agreement about siting a GDF, when the only group of councils that had expressed an interest in hosting a GDF withdrew its application because of opposition from one council. Government is reviewing the site selection process.[6]

Box 4. Fukushima Accident: Safety System Failures
There are six nuclear reactors at Japan's Fukushima Dai-ichi nuclear power site. Reactors 1-3 were operational on 11 March 2011 when Japan was struck by its worst recorded earthquake, shortly followed by a 13m tsunami. Reactors 1-3 shut down safely on detection of the earthquake, but power to the nuclear site, required to cool the reactors down, was cut. Initially, emergency diesel generators provided backup power, but when the tsunami swamped the 10m seawall protecting the site, they were flooded and stopped working. Finally, a further backup, a battery-run cooling system, ran out of power on 12 March 2011. The failure of all the backup power to maintain cooling systems led to reactors 1-3 overheating, resulting in several explosions and major releases of radioactive material.

Price of Nuclear Electricity
Historically, the price of nuclear electricity has been cheaper than other low carbon alternatives. However, the price of electricity from new nuclear power stations is likely to be more than that of old nuclear (the price of electricity from the new reactor Hinkley Point C will be £92.50 per megawatt-hour).[7] Consequently nuclear may face more competition from other low carbon alternatives. Government and industry say the increase in price is because:
- new reactors (Box 3) are 'first-of-a-kind' in the UK, which have been shown to be more expensive to build
- funding available from non-UK Government sources is more expensive than previous UK Government funding
- labour and material costs in the building phase have risen
- new regulation requires more safety measures.

The House of Commons Environmental Audit Committee and European Commission have raised concerns that the price for Hinkley Point C may constitute a subsidy.[8]

UK Engineering Skills and Supply Chain
By 2025, over half of the current UK nuclear workforce will have retired. In 2011, the House of Lords Science and Technology Committee expressed concerns about the lack of engineers attracted to and retained by the nuclear industry. A similar skills shortage has left Finland's EPR reactor (Box 3) five years behind schedule. This issue is being addressed by several UK bodies, which are trying to identify skills gaps, deliver subject specific courses and set up research centres.
- The Nuclear Energy Skills Alliance was set up by a group of interested bodies in 2012.
- The National Nuclear Laboratory was set up by the Government in 2006.
- The Nuclear Technology Education Consortium was set up in 2005 and provides over 90% of the UK's nuclear postgraduate teaching.
- The Department of Energy and Climate Change (DECC) has put £12.5m towards international collaborations.

The House of Commons Energy and Climate Change Committee also noted that the UK has lost most of its nuclear supply chain and recommended measures to encourage its redevelopment.[9] The Government's Office for Nuclear Development is supporting the UK supply chain and has published a Nuclear Supply Chain Action Plan.

Involvement of Overseas Companies

Following privatisation from 1996-2009, overseas state-owned companies may build and operate UK nuclear power stations. For example, EDF Energy (85% French state-owned) operates eight UK reactors and two Chinese companies (both 100% Chinese state-owned) may be involved in the construction and running of Hinkley Point C. Some concerns have been raised about the safety implications of involving Chinese companies. For example, in the 1980s-90s there were serious errors by Chinese Nuclear Energy Group interpreting EDF's building plans.[10] However, IAEA inspections have shown improvements in the standard of Chinese nuclear build and all operators will be subject to ONR regulation.[11]

Beyond New Nuclear Build

Beyond 2014, alternative fuels, waste management and alternative and Gen IV reactors may be considered.

Alternative Fuel Sources

Introducing new fuels is a lengthy process, requiring analysis of the entire fuel cycle. Reactors are also costly assets, so operators are conservative about the type of fuel used. There are three alternative fuels of interest to the UK.

- **Thorium** has advantages over uranium, including greater abundance and lower volumes of radioactive waste. Although thorium is not in commercial use, it is being researched in Europe, China, India, Japan and the USA. Thorium is unable to wholly substitute uranium in existing reactors; a thorium-only reactor would require significant development.
- **Plutonium** is a by-product of used uranium fuel. There are over 100 tonnes of plutonium stored at Sellafield (POSTnote 237). Plutonium could be used in fast reactors (see Gen IV below), which may make the UK's plutonium stockpile a valuable fuel asset.[12]
- **Mixed Oxide (MOX)** fuels contain a mix of nuclear fuels, including uranium and plutonium. DECC currently prefers to use its plutonium stockpile in MOX. However, the Sellafield MOX Plant will close after a drop in demand following the Fukushima accident (Box 4). DECC is reviewing whether a new MOX plant should be built.[12]

Alternative and Future Reactor Designs

Small Modular Reactors (SMRs)

SMRs have *small* power outputs of less than 0.5 gigawatts (GW) and are *modular* (manufactured off-site). The UK has 50 years experience of 0.5 GW non-modular Gen I reactors and of modular build from its nuclear submarines. SMRs benefit from enhanced safety and security, flexibility on fuel used and site location, being easier to find investment for (due to their size) and greater potential for cost savings (from serial production).[13] Several Gen III+ SMRs are being developed globally for commercial use within 10 years.

Gen IV Designs

Gen IV reactors are not expected to be available before 2030. These intend to be more fuel and waste efficient.[14] Six designs are being researched globally (Table 1). They could use a range of fuels, moderators and coolants (Box 1) and are either **thermal** (include a moderator) or **fast** (do not have a moderator). The UK has experience of gas-cooled reactors, from its Gen I reactors and sodium-cooled fast reactors, from two reactors operated at Dounreay from 1959-1994. GE-Hitachi is designing *PRISM*, a sodium-cooled fast 'breeder' reactor (it can produce fuel as well as burn fuel), which can be fuelled by MOX fuel that contains plutonium. The Gen IV Forum leads international research on Gen IV designs, but the UK is a non-active member. The House of Lords Science and Technology Committee has suggested the UK becomes an active member again.

Table 1. Gen IV reactor designs being researched.

Reactor Name	Design Variation
Molten salt reactors (thermal or fast reactor)	**Fuel** – uranium, thorium, MOX **Moderator** – graphite or none **Coolant** – molten salt*
Supercritical water-cooled reactors (thermal or fast reactor)	**Fuel** – uranium, MOX **Moderator** – water or none **Coolant** – water
Very high temperature reactors (thermal reactor)	**Fuel** – uranium or thorium **Moderator** – graphite **Coolant** – helium or molten salt*
Gas-cooled fast reactors (fast reactor)	**Fuel** – uranium, plutonium, MOX **Coolant** – helium, carbon dioxide
Lead-cooled fast reactors (fast reactor)	**Fuel** – uranium, plutonium, MOX **Coolant** – lead and lead alloys
Sodium-cooled fast reactors (fast reactor)	**Fuel** – uranium, plutonium, MOX **Coolant** – molten salt*

*Coolants (Box 1) are only cooler than the reactor fuel, rather than 'cold'.

Improved Waste Management

Producing less high level waste could reduce the burden on costly waste storage and disposal facilities. Lowering the volume of radioactive waste is being researched world-wide. One method is partitioning and transmutation. Waste is separated into different chemical types (partitioning), which could reduce the volume, temperature and radioactivity of waste. This waste is then bombarded with particles (which could come from a fast reactor) to change it into material that loses its radioactivity faster (transmutation).

Endnotes

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POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of policy issues that have a basis in science and technology. POST is grateful to Jodie Symington for researching this briefing, to the Institution of Chemical Engineers and Croda Ltd. for funding her parliamentary fellowship, and to all contributors and reviewers. POSTnote 457 updates POSTnote 317. For further information on this subject, please contact the co-author, Dr Aaron Goater.