Parliamentary Office of Science and Technology

postnote

November 2008 Number 317

FUTURE NUCLEAR TECHNOLOGIES

The 2008 Energy White Paper announced the government's intention to allow private companies to propose the building of new nuclear power plants[1]. This POSTnote provides an assessment of nuclear power generation technologies. It looks at the designs of any new UK reactors and outlines details of the regulatory design assessment process, with an emphasis on safety, security and waste. It also looks at longer term research into reactor design and waste management.

Background

Nuclear reactors work by harnessing the energy released when a heavy atom, like uranium, is split (see POST Report 222). Reactor designs may vary in their:

- *fuel* (various forms of uranium are used).
- *moderator* (used to maintain the nuclear reaction, e.g. graphite or water).
- *coolant* (used to take heat from the reactor and drive turbines to generate electricity, usually water or gas).

Generations of Nuclear Power

Since the first commercial nuclear power plants in the 1950s, reactors world-wide can be thought of as evolving through several 'generations' as follows:

- Gen I were the early prototype reactors built in the 1950s. These include the UK's Magnox reactors that were built from 1956 through 1971; eleven power stations were built, only two are now operational.
- Gen II developed from these prototypes and were built from the 1960s-1980s. Most operational reactors are Gen II. UK examples include the seven Advanced Gas Reactor (AGR) stations first operational in 1976.
- Gen III, the latest generation of operational reactors. Four advanced Boiling Water Reactors (BWR) have been built in Japan. Sizewell B, the UK's Pressurised Water Reactor (PWR), operational in 1995, also falls into this classification.
- Gen III+ designs evolved from Gen III (any new nuclear power plants in the UK would be of this type).
- Gen IV are advanced reactor designs expected to be available for construction beyond 2030

The UK currently has nineteen nuclear reactors (at ten power stations) generating 18.4% of the country's electricity[2]. They are all scheduled to be closed by 2023, apart from Sizewell B PWR.

While nuclear technologies are being developed around the world, this report will focus on reactors and designs likely to be relevant to the UK.

Nuclear Reactor Issues

Safety

The International Atomic Energy Agency identifies three fundamental safety objectives that reactor safety systems must meet[3]:

- The reactor can be shut down under any credible circumstances.
- Radioactivity must be kept confined behind barriers.
- The reactor can be kept cool (radioactivity continues to generate heat after the reactor is shut down).

The Health and Safety Executive (HSE) regulates the safety of the UK nuclear industry through the Nuclear Directorate (ND) (Box 2).

Security

Civil nuclear security is regulated by the Office of Civil Nuclear Security (Box 1), part of the HSE's ND. POST Report 222 discussed the three categories of nuclear security threats that have some relevance to nuclear power plants[4], and that nuclear security regulation addresses:

- Attacks on nuclear power plants, facilities and transport that could lead to a release of radiation.
- The dispersal of radiation through the construction of a 'dirty bomb' or radiation dispersal device (RDD).
- Manufacture of a nuclear weapon from stolen material.

Waste

The UK has a nuclear waste legacy from its previous civilian and military nuclear programmes. Spent fuel from Gen I Magnox and Gen II AGR stations is transported to Sellafield to await reprocessing (where re-useable fuel is extracted). Spent fuel from Sizewell B PWR is currently kept on site. It has been determined that the best way to deal with this legacy is to store it underground in a Geological Disposal Facility (GDF)[5].The public sector will provide funds for a GDF capable of housing the current amount of legacy waste.

Box 1. Office of Civil Nuclear Security (OCNS)
While reactor safety systems can contribute towards security, the OCNS states that nuclear security is also a set of procedures that reduce dangers originating outside a reactor. For example, in 2004, the OCNS directed that Authorised Firearms Officers of the Civil Nuclear Constabulary should be permanently deployed at all the UK's nuclear reactors[6].

The key statutory instrument for security in the civil nuclear industry is *The Nuclear Industries Security Regulations (NISR) 2003*. Since its inception it has been complemented by similar instruments covering lower risk nuclear materials and uranium enrichment technology. The *Terrorist Act 2006* includes provisions for prosecuting those who trespass on licensed nuclear sites.

As a division of the HSE's Nuclear Directorate, OCNS is contributing to the Generic Design Assessment process. It is important that security measures are included in the designs for new reactors to avoid costly retro-fitting.

New Nuclear Build

The 2008 Energy White Paper introduced plans to facilitate private investment in new nuclear power plants. These are branded by vendors as 'Gen III+'. Private construction of nuclear power plants would involve vendors (who design and build reactors), operators (utilities who will own and run the power plants) and regulatory bodies and associated agencies (see Box 2).

Box 2. Nuclear Agencies and Nuclear Regulators
- HSE (Health and Safety Executive) regulates the nuclear industry through its Nuclear Directorate (ND).
- ND regulates the safety of all nuclear facilities, and the security of civilian nuclear facilities through the OCNS.
- OCNS (Office for Civil Nuclear Security) is charged with regulating the UK's nuclear security at non-military sites.
- UKSO (UK Safeguards Office), also part of the ND, ensures international compliance with nuclear safeguards.
- EA (Environment Agency) oversees the management of nuclear waste and monitors the environmental impact.
- JPO (Joint Programme Office) was setup by the HSE and EA specifically for the assessment of new reactor designs.
- DfT-DGD (Department for Transport – Dangerous Goods Division) regulates the safety of nuclear material transport.

Generic Design Assessment (GDA)

The GDA process enables nuclear power plant vendors to submit reactor designs for 'pre-licensing' - initial evaluation and assessment of safety, security and environmental aspects of the design before an application is made to build a reactor at a particular site[7]. Provision for this was made in the 2006 Energy Act, with the aim of making the licensing process more efficient. The Joint Programme Office, set up to administer the GDA process, is comprised of nuclear safety and security regulators as well as officers of the Environment Agency.

Assessment of New Designs
In the UK, initially there were four reactor designs under consideration (Box 3). They all passed GDA Step 2, which involved comparing vendors' claims about their designs to what is expected from a modern nuclear reactor. Following step 2, Atomic Energy of Canada Ltd and General Electric-Hitachi temporarily withdrew support for their GDA applications in order to concentrate on their domestic markets. The remaining reactors (EPR and AP1000) are currently undergoing the more thorough design examination of Step 3.

Step 4 will involve an exacting assessment of the detailed technical documents (Safety Cases) of the reactors passing Step 3. Successful designs will be ready for construction should private investment and a suitable site be available. However, site specific applications will have to be made in order to obtain a Nuclear Site Licence.

Box 3. Generation III+ Reactors for the UK
All the reactors under consideration in the UK Generic Design Assessment are designed to last for 60+ years, and have construction times ranging from 36-42 months.

Advanced CANDU Reactor (ACR-1000)
Designed by Atomic Energy of Canada Ltd (AECL), this is an evolutionary development of their existing CANDU reactor. AECL has suspended their involvement in the current GDA process to concentrate on their domestic market.

Advanced Passive (AP-1000)
The AP-1000 is a Pressurised Water Reactor designed by the US company Westinghouse. Its safety systems rely on passive processes such as gravity and natural circulation to keep the reactor core cool and safe. Four units are currently under construction in China.

Economic Simplified BWR (ESBWR)
The ESBWR is General Electric–Hitachi (GE-H) collaboration. This design is an evolution of the advanced BWR (Boiling Water Reactor), operating in Japan. GE-H have paused their support for the GDA to focus on the USA.

European/Evolutionary Pressurised Reactor (EPR)
The EPR is a PWR developed by Areva NP, Siemens AG of Germany and Electricite de France (EDF - who are currently taking over British Energy). Units are under construction in Finland and France.

Gen III+ Characteristics

Reactors currently in operation rely on multiple safety systems (mechanical, chemical or electrical) to meet the IAEA requirements outlined earlier. Such reactors have high levels of redundancy (multiple copies of the same safety feature) and diversity (different types of system). These safety systems may be either 'active' or 'passive'.

Active Safety
The operation of active systems relies on power (usually electrical or steam driven). Vendors describe the Gen III+ EPR as having four-fold redundancy (two or three-fold being more common in Gen II) and diversity: safety features such as emergency backup power and its active-cooling systems are replicated four times.

Passive Safety
To some extent, passive safety is a feature of all modern reactors. Such systems take advantage of natural

processes such as gravity, convection and condensation to keep the reactor safe. After initiation, they do not require human or machine intervention to maintain correct operation. Both the AP1000 and ESBWR (Box 3) are designed to rely on such passive safety features. The reduction in complexity also simplifies the construction.

Security

The ND says the specifications of a reactor design focus on safety rather than security. Many safety features also contribute to security e.g. redundant safety systems protect against accidents but also against sabotage. If attackers disabled one safety system there would still be multiple backups. Additionally, utilities point out that new reactor buildings are engineered to withstand intentional as well as random aircraft crashes.

Fuel and Waste

Gen III+ reactors are designed to extract as much energy from their fuel as possible. This is known as "increased burn-up" and will decrease the volume of nuclear waste (spent fuel) generated. However, it will increase the radioactivity and initial temperature of the waste, which may increase the amount of storage space required in a GDF (Box 4).

Box 4. Geological Disposal Facility Expansion

Expansion of a GDF to accommodate any additional waste generated from new reactors will have to be financed by private operators. These operators will also have to satisfy the regulators that they are capable of storing the spent fuel on their reactor sites until a long-term GDF is built.

The radioactivity and temperature of spent fuel falls with time. Increasing the duration of temporary storage may decrease the amount of storage space required for 'increased burn-up' waste. However, an extended period of on-site storage may cause the material encasing the fuel to weaken, making it difficult to transport. The Department of Transport's Dangerous Goods Division says that it may be necessary for a new type of cask to be designed to transport this waste.

Uranium Resources

The 2008 White Paper on nuclear power concludes that, on the basis of known reserves, there are sufficient uranium resources available to meet future global demand, and that any new nuclear plant in the UK would have a small impact on the total reserve. However, a global resurgence in nuclear power may put pressure on prices. Canada and Australia are the biggest uranium producers, while the largest resources lie in Australia and Kazakhstan[8].

Reprocessing

Spent nuclear fuel can be reprocessed to extract plutonium and unused uranium. The uranium can be used to make new fuel, which would extend the lifetime of resources. However, reprocessing technology increases costs and leads to higher volumes of waste. Also, plutonium is used in some types of nuclear weapon. Overall, the government has decided that any new reactors should be built on the basis that their fuel will not be reprocessed.

Engineering Skills

The UK nuclear industry is concerned about the shortage of engineers, especially if new reactors are to be built. In Finland, the lack of engineers with the experience and qualifications necessary to meet the standards of the nuclear industry has set back the construction of their EPR. In the UK, the "National Skills Academy for Nuclear" has been set up by the Government to address the skills and training issues affecting the industry. As part of a major inquiry into UK engineering, the Commons Innovation, Universities, Science and Skills Parliamentary Select Committee is conducting a case study on nuclear skills.

Beyond Gen III+

New Fuels

Testing new fuels is a lengthy process, requiring many experiments in order to determine fuel behaviour reliably. The entire fuel cycle has to be analysed, taking into account the environmental impacts of extraction, fuel fabrication and waste management. Reactors are expensive assets, so operators are conservative about the type of fuel used. Another consideration is whether the fuel cycle leads to proliferation of materials that could be used in weapons.

MOX Fuel

As a result of the UK's spent fuel reprocessing activities, there is over 100 tonnes of plutonium in storage at Sellafield in Cumbria[9]. This plutonium could be mixed with uranium to make MOX (mixed oxide) fuel, which behaves similarly to the uranium fuel used commonly (POSTnote 137). In this way plutonium that would pose a proliferation risk and be classified as nuclear waste can be utilised. The Sellafield MOX Plant was supposed to produce MOX fuel for outside the UK. However, in seven years of operation it has yet to demonstrate its ability to manufacture fuel on a commercially viable scale.

Thorium

Thorium is a heavy metal suitable for nuclear fuel that, though currently not in commercial use, is under investigation in India and Russia (with US cooperation). It is three times more abundant than uranium, with large resources in Australia, USA and Turkey. Research is underway in Norway to assess whether thorium can be mixed with plutonium (as with MOX fuel) to produce fuel that could be used in existing and Gen III+ reactors[10]. Thorium spent fuel would be difficult to use for a nuclear weapon, being harder to handle and easier to detect than uranium spent fuel. Thorium is also a candidate for use in advanced reactors (see below).

Future Waste Management

Transmutation

Transmutation is a means of reducing the long-term hazard of radioactive waste. It involves subjecting the waste to sub-atomic particles in order to transform it in to material that loses its radioactivity more quickly[11]. The particles required could come from a nuclear reactor (such as a fast reactor - Box 5), an accelerator driven system (see below) or a particle accelerator.

Partitioning
Before transmutation can take place the components of the nuclear waste have to be partitioned (chemically separated) in to their different types. This is also a stage in spent fuel reprocessing. Partitioning could reduce the volume, temperature and radioactivity of the residual nuclear waste. Research into partitioning and transmutation is underway in Japan, France and the USA as well as other countries. The UK monitors this research to maintain awareness of the progress, but is not actively involved.

Advanced Reactors

Pebble Bed Reactors
In Pebble Bed Reactors the fuel and moderator are contained in balls, or 'pebbles', that feed in through the top of the reactor and pass out through the bottom[12]. They are smaller than traditional types, with the electricity output of Chinese and South African prototypes around a tenth of the Gen III+ designs. Instead of operating as a base-load plant (generating continuous minimum supply) they could provide electricity for peak demand (which current reactors do not for economic reasons).They could also provide electricity directly to a town or an industrial complex, operating independently of an electricity grid.

Box 5. Generation IV Reactors
The Generation IV International Forum[13] was established in 2000 and is made up of thirteen countries, three of which are currently non-active members, including the UK. Six reactor technologies are under development (although fourth-generation equivalent designs exist outside of the Forum). The following three are the most closely aligned with UK expertise:

- **Very High Temperature Gas-cooled Reactor (VHTR).** Like the UK Magnox and AGRs, this design uses graphite to maintain the nuclear reaction, and gas (in this case helium) to cool the core. The high reactor temperatures would enable electricity to be generated more efficiently. Such heat could also be put to industrial uses, such as hydrogen production.
- **Sodium Cooled Fast Reactor (SFR).** Fast reactors use fuel more efficiently, and do not use a moderator. Liquid metal coolants such as sodium are used due to the high temperatures. Fast reactors can also be used to change nuclear waste into a less hazardous form. The UK operated two prototypes at Dounreay between 1959 and 1994.
- **Gas-cooled Fast Reactor.** A variant of the SFR, using helium gas coolant. Gas coolant reactors can operate at higher temperatures than liquids, making them more thermally efficient. Such a design could take advantage of the skills gained during the UK Magnox and AGR programmes.

Generation IV (Gen IV) Reactors
Gen IV reactors are advanced designs expected to become available beyond 2030 (see Box 5). These designs aim to have "sustainable and proliferation resistant" fuel cycles. International research into these designs is steered by the Generation IV International Forum (GIF). Although a founder of GIF, the UK is currently a non-active member.

The Engineering & Physical Sciences Research Council (EPSRC) funding into nuclear power is focussed on waste management and decommissioning, rather than new reactor designs. In its 2007 'Strategy Options for the UK's Separated Plutonium' the Royal Society advised that the UK should renew its involvement in GIF to have the ability to monitor technological developments that may make use of separated plutonium.

Accelerator Driven Systems (ADS)
ADS devices require an external source of sub-atomic particles, such as a particle accelerator, to keep the nuclear reaction going, so cannot be described as a 'reactor'. Turning off this source would stop the nuclear reaction. However, decay heat from radioactivity would still be present, which would necessitate cooling. The 'Energy Amplifier' concept, developed by a group at the CERN facility in Switzerland, is a thorium fuelled ADS.

Nuclear Fusion

Nuclear Fusion (POSTnote 192) involves the joining together of hydrogen nuclei at temperatures hotter than the Sun. International research into the commercial potential of fusion – the ITER project – is underway at Cadarache, France. The first reaction is scheduled to take place in 2018. The UK Atomic Energy Authority says that fusion safety does not rely upon an additional set of systems. In the event of an attack on a fusion facility, the nature of the attack itself (e.g. the bomb) would likely pose a greater threat than any damage to the device.

Overview

- The Government's 2008 Energy White Paper provides a framework under which industry can bring forward proposals for new nuclear plants.
- New reactor designs that could be built in the UK are being assessed by the safety and security regulators.
- Generation III+ designs have more sophisticated safety systems than previous reactors.
- Advanced technologies offer the possibility of recycling fuel and reducing the radio-toxicity of waste, but are currently at the research stage.

Endnotes

1 *The Future of Nuclear Power*, BERR, January 2008.
2 *Nuclear Energy Statistics*, HoC Library, 2008.
3 *Safety of Nuclear Power Plants: Design NS-R-1*, IAEA 2000.
4 *The Four Faces of Nuclear Terrorism*, Ferguson and Potter, 2005.
5 *Managing Radioactive Waste Safely*, DEFRA, June 2008.
6 *The State of Security in the Civil Nuclear Industry*, OCNS, 2004-8.
7 *The Civil Nuclear Reactor New Build Programme -GDA*, HSE, 2008.
8 *Supply of Uranium*, World Nuclear Association, June 2008.
9 *Strategy for the UK's separated plutonium*, Royal Society, 2007.
10 *The Norwegian Thorium Initiative*, Thor Energy AS, 2008.
11 *Partitioning and Transmutation*, Euratom, 2001.
12 *Nuclear Renaissance*, WJ Nuttall, 2005.
13 *A Technology Roadmap for Gen IV Systems,* GIF 2002.

POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of public policy issues that have a basis in science and technology. POST is grateful to Dr Barnali Ghosh for assisting in the research for this briefing, to the Royal Commission for the Exhibition of 1851 for funding her parliamentary fellowship, and to all contributors and reviewers. For further information on this subject, please contact Dr Michael O'Brien at POST.

The Parliamentary Office of Science and Technology, 7 Millbank, London, SW1P 3JA; Tel: 020 7219 2840; email: post@parliament.uk
www.parliament.uk/parliamentary_offices/post/pubs.cfm