Factfiles

The Institution of Engineering and Technology

Nuclear **Reactor Types**

A Factfile provided by the Institution of **Engineering and Technology**

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Cover image
Nuclear power plant at night

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Contents

Nuclear Reactor Types

Many different reactor systems have been proposed and some of these have been developed to prototype and commercial scale. Six types of reactor (**Magnox**, **AGR**, **PWR**, **BWR**, **CANDU** and **RBMK**) have emerged as the designs used to produce commercial electricity around the world. A further reactor type, the so-called fast reactor, has been developed to full-scale demonstration stage. These various reactor types will now be described, together with current developments and some prototype designs.

Gas Cooled, Graphite Moderated

Of the six main commercial reactor types, two (Magnox and AGR) owe much to the very earliest reactor designs in that they are graphite moderated and gas cooled. **Magnox** reactors (see **Fig 1**) were built in the UK from 1956 to 1971 but have now been superseded. The Magnox reactor is named after the magnesium alloy used to encase the fuel, which is natural uranium metal. Fuel elements consisting of fuel rods encased in Magnox cans are loaded into vertical channels in a core constructed of graphite blocks. Further vertical channels contain control rods (strong neutron absorbers) which can be inserted or withdrawn from the core to adjust the rate of the fission process and, therefore, the heat output. The whole assembly is cooled by blowing carbon dioxide gas past the fuel cans, which are specially designed to enhance heat transfer. The hot gas then converts water to steam in a steam generator. Early designs used a steel pressure vessel, which was surrounded by a thick concrete radiation shield. In later designs, a dual-purpose concrete pressure vessel and radiation shield was used.

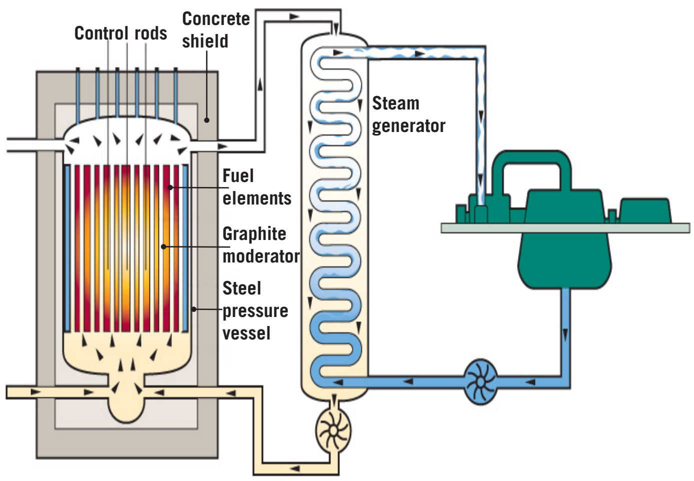

Figure 1 Schematic: Basic Gas-Cooled Reactor (MAGNOX)

In order to improve the cost effectiveness of this type of reactor, it was necessary to go to higher temperatures to achieve higher thermal efficiencies and higher power densities to reduce capital costs. This entailed increases in cooling gas pressure and changing from Magnox to stainless steel cladding and from uranium metal to uranium dioxide fuel. This in turn led to the need for an increase in the proportion of U^{235} in the fuel. The resulting design, known as the **Advanced Gas-Cooled Reactor (AGR)** (see **Fig 2**), still uses graphite as the moderator and, as in the later Magnox designs, the steam generators and gas circulators are placed within a combined concrete pressure-vessel/radiation-shield.

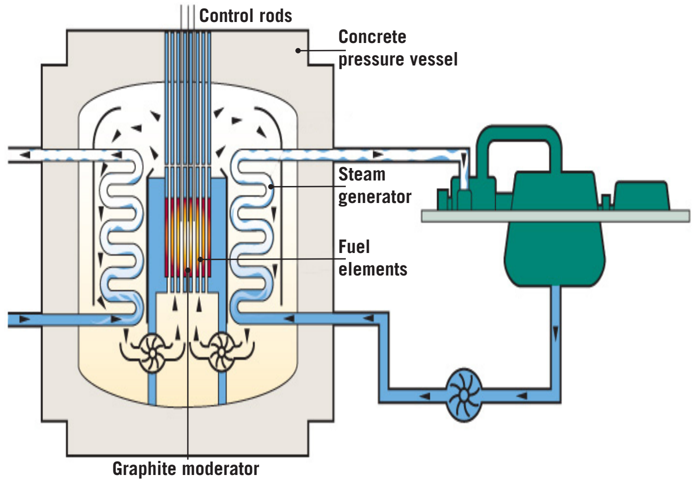

Figure 2 Schematic: Advanced Gas-Cooled Reactor (AGR)

Heavy Water Cooled and Moderated

The only design of heavy water moderated reactor in commercial use is the **CANDU**, designed in Canada and subsequently exported to several countries. In the CANDU reactor, (see **Fig 3**) un-enriched uranium dioxide is held in zirconium alloy cans loaded into horizontal zirconium alloy tubes. The fuel is cooled by pumping heavy water through the tubes (under high pressure to prevent boiling) and then to a steam generator to raise steam from ordinary water (also known as natural or light water) in the normal way.
The necessary additional moderation is achieved by immersing the zirconium alloy tubes in an un-pressurised container (called a **callandria**) containing more heavy water. Control is effected by inserting or withdrawing cadmium rods from the callandria. The whole assembly is contained inside the concrete shield and containment vessel.

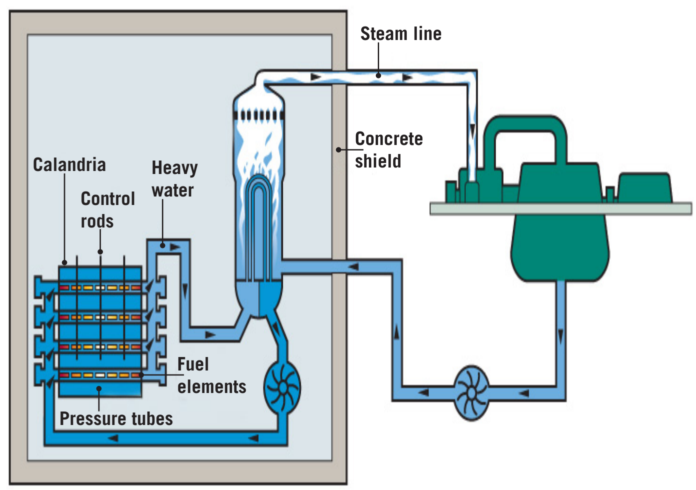

Figure 3 Schematic: Pressurised Heavy Water Reactor (CANDU)

Water Cooled and Moderated

By moving to greater levels of enrichment of U^{235}, it is possible to tolerate a greater level of neutron absorption in the core (that is, absorption by non-fissile, non-fertile materials) and thus use ordinary water as both a moderator and a coolant. The two commercial reactor types based on this principle are both

American designs, but are widely used in over 20 countries.

The most widely used reactor type in the world is the **Pressurised Water Reactor (PWR)** (see **Fig 4**) which uses enriched (about 3.2% U^{235}) uranium dioxide as a fuel in zirconium alloy cans. The fuel, which is arranged in arrays of fuel "pins" and interspersed with the movable control rods, is held in a steel vessel through which water at high pressure (to suppress boiling) is pumped to act as both a coolant and a moderator. The high-pressure water is then passed through a steam generator, which raises steam in the usual way. As in the CANDU design, the whole assembly is contained inside the concrete shield and containment vessel.

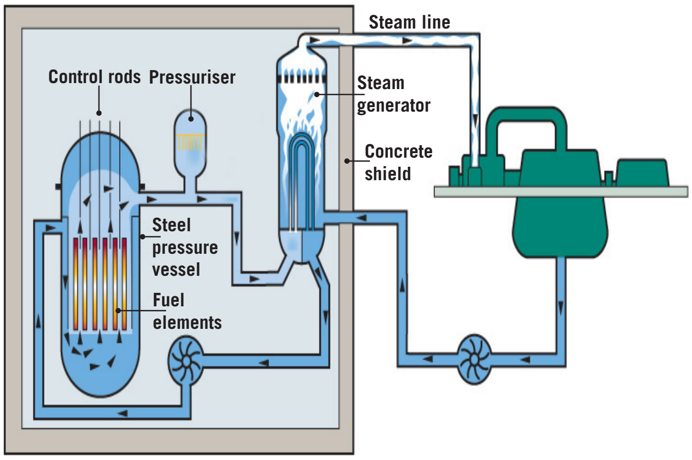

Figure 4 Schematic: Pressurised Water Reactor (PWR)

The second type of water cooled and moderated reactor does away with the steam generator and, by allowing the water within the reactor circuit to boil, it raises steam directly for electrical power generation. This, however, leads to some radioactive contamination of the steam circuit and turbine, which then requires shielding of these components in addition to that surrounding the reactor.

Such reactors, known as **Boiling Water Reactors (BWRs)**, (see **Fig. 5**) are in use in some ten countries throughout the world.

Water Cooled, Graphite Moderated

At about the same time as the British gas cooled, graphite moderated Magnox design was being commissioned at Calder Hall in 1956, the Russians were testing a water cooled, graphite moderated plant at Obninsk. The design, known as the **RBMK Reactor** (see **Fig 6**), has been developed and enlarged, and many reactors of this type have been constructed in the USSR, including the ill-fated Chernobyl plant. The layout consists of a large graphite core containing some 1700 vertical channels, each containing enriched uranium dioxide fuel (1.8% U^{235}). Heat is removed from the fuel by pumping water under pressure up through the channels where it is allowed to boil, to steam drums, thence driving electrical turbo-generators. Many of the major components, including pumps and steam drums, are located within a concrete shield to protect operators against the radioactivity of the steam.

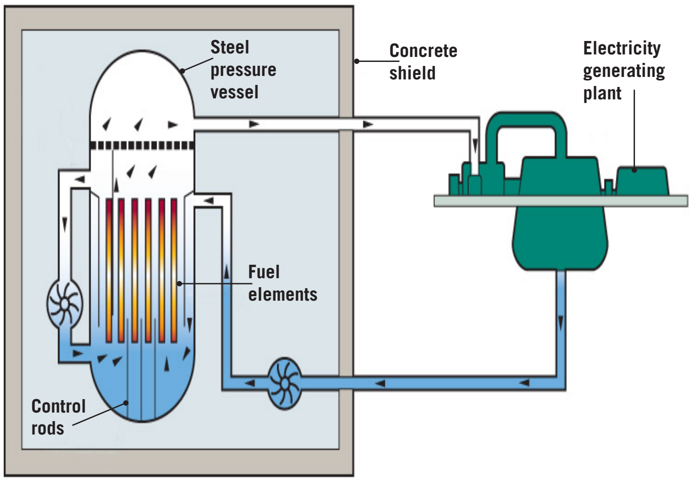

Figure 5 Schematic: Boiling Water Reactor (BWR)

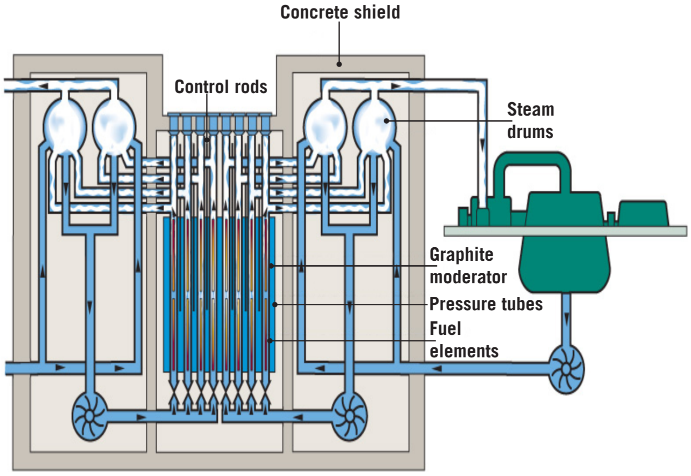

Figure 6 Schematic: RBMK Reactor - Boiling Light Water, Graphite Moderated Reactor

A Summary of Main Thermal Reactor Types Table 1.1 gives the technical details and the main economic and safety characteristics of each of the thermal reactor types.

Table 1.1: Summary of the main thermal reactor types

	Fuel	Moderator	Coolant			Spent Fuel Reprocessing	Steam Cycle Efficiency	Main Economic and Safety Characteristics
			Heat extraction	Outlet temp	Pressure			
Magnox	Natural uranium metal (0.7% U^{235}) Magnesium alloy cladding	Graphite	Carbon dioxide gas heated by fuel raises steam in steam generator	360°C	300 psia	Typically within one year, for operational reasons	31%	Safety benefit that coolant cannot undergo a change of phase. Also ability to refuel whilst running gives potential for high availability
AGR	Uranium dioxide enriched to 2.3% U^{235} Stainless steel cladding	Graphite	Carbon dioxide gas heated by fuel raises steam in steam generator	650°C	600 psia	Can be stored under water for tens of years, but storage could be longer in dry atmosphere	42%	Same operational and safety advantages as Magnox but with higher operating temperatures and pressures., leading to reduced capital costs and higher steam cycle efficiencies
PWR	Uranium dioxide enriched to 3.2% U^{235} Zirconium alloy cladding	Light Water	Pressurised light water pumped to steam generator which raises steam in a separate circuit	317°C	2235 psia	Can be stored for long periods under water giving flexibility in waste management	32%	Low construction costs resulting from design being amenable to fabrication in factory-built sub-assemblies. Wealth of operating experience now accumulated world wide. Off load refuelling necessary
BWR	Uranium dioxide enriched to 2.4% U^{235} Zirconium alloy cladding	Light Water	Pressurised light water boiling in the pressure vessel produces steam which directly drives a turbine	286°C	1050 psia	As for PWR	32%	Similar construction cost advantages to PWR enhanced by design not requiring a heat exchanger, but offset by need for some shielding of steam circuit and turbine. Off load refuelling necessary
CANDU	Unenriched uranium dioxide (0.7% U^{235}) Zirconium alloy cladding	Heavy Water	Heavy water pumped at pressure over the fuel raises steam via a steam generator in a separate circuit.	305°C	1285 psia	As for PWR	30%	Good operational record but requires infrastructure to provide significant quantities of heavy water at reasonable costs
RBMK	Uranium dioxide enriched to 1.8% U^{235}	Graphite	Light water boiled at pressure, steam used to drive a turbine directly	284°C	1000 psia	Information not available	31%	Information not available but operated in considerable numbers in the former USSR. Believed in the West to be inherently less safe

Current Developments

Next-Generation (NG) CANDU

NG CANDU is based on the standard proven CANDU design. It introduces new features:

- Light water reactor coolant system instead of heavy water
- Use of slightly enriched uranium oxide fuel in bundles rather than natural uranium fuel
- Compact reactor core design: core size is reduced by half for same power output
- Extended fuel life with reduced volume of irradiated fuel
- Improved thermal efficiency through higher steam pressure steam turbines.

The NG CANDU retains the standard CANDU features of on-power fuelling, simple fuel design and flexible fuel cycles. The steam and turbine generator systems are similar to those in advanced pressurised water reactor systems.

For safety, NG CANDU design includes two totally independent safety shutdown systems and an inherent passive emergency fuel cooling capability in which the moderator absorbs excess heat. The whole of the primary system and the steam generators are housed in a robust containment to withstand all internal and external events. (See **Fig 7**)

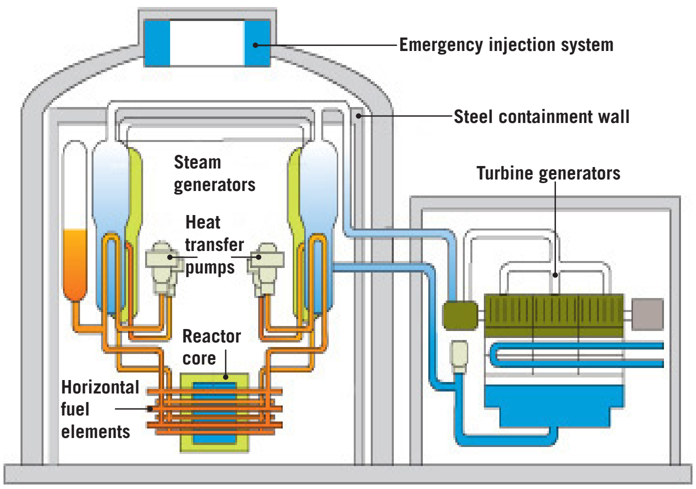

Figure 7 Schematic: NG CANDU Flow Diagram

British Energy have been involved in a feasibility study of the NG CANDU with the vendor AECL (Atomic Energy of Canada Limited). This included the feasibility of the design against UK criteria and in particular licensability of the design.

Advanced Pressurised Water Reactor AP1000

As part of a co-operative programme with the US Department of Energy, the Westinghouse Company have developed an Advanced PWR with predominantly passive safety systems. Termed the AP600 (600MWe) it is the most up-to-date design licensed in the United States. Westinghouse have also developed the AP1000 (1000MWe) with similar safety features to the smaller version but gaining in economies of scale. The advanced passive design is a development of the PWR design at Sizewell B.

Key design features of the AP designs are:

- Simplification of standard PWR designs with less piping, fewer valves, less control cabling and reduced seismic building volumes.
- Modular manufacturing techniques giving a shorter construction schedule (for the AP600 plant 36 months from first concrete to fuel loading.)
- Passive safety systems using only natural forces such as gravity, natural circulation and compressed gas. Fans, pumps, diesels and chillers are not required for safety, nor is operator intervention. A few simple valves are used to align the passive safety systems when required, in most instances the valves are 'fail safe' in that on loss of power they move to the safety position.
- The passive cooling systems include core cooling, providing residual heat removal, reactor coolant make-up and safety-injection, and containment cooling which provides the safety related ultimate heat sink for the plant.
- Operating lifetime of 60 years with a design plant availability of 90%+.
- Probabilistic risk assessment has been used as an integral part of the design process with numerous fine design changes being made as a result of the PRA studies. The net effect of the overall design approach is that the predicted core damage frequency is about a factor of 100 better than current plant designs.

British Energy have been involved in a feasibility study with Westinghouse covering:

- The feasibility of the design against UK criteria and, in particular, the licensability of the design.
- The technical suitability of AP1000 reactors on existing sites.
- The economic case for the plant and potential funding models.

In May 2007, the AP1000 design was certified for compliance with European Utilities Requirements confirming that the design can be deployed in Europe.

The AP1000 design has been ordered for 4 units in China, the first to be operational in 2013. In the US, 12 new projected plants have identified the AP1000 design as the technology of choice.

Evolutionary Power Reactor/European Pressurised-Water Reactor (EPR)

The EPR is a large advanced Pressurised Water Reactor. It was developed by French-German collaboration involving the power plant vendors Framatome and Siemens KWU, with EDF (Electricité de France) and the major German utilities.

The EPR is a 1600 MWe PWR with an overall efficiency of 36%. Its design is developed from the latest well proven reactor technologies from France and Germany and builds on world wide experience in the operation of light water reactors.

Main design features of the EPR are:

- The reactor containment building has two walls: an inner pressurised concrete housing covered internally with a

leak tight metallic liner and an outer reinforced concrete shell both 1.3 metres thick
- The containment houses the reactor coolant system: the reactor vessel, four steam generators, a pressuriser and four reactor coolant pumps. The larger volumes of the main components, as compared to previous designs, gives additional benefits in terms of operating and safety margins
- The nuclear island, covering the reactor building, the fuel building, the four safeguard buildings, the nuclear auxiliary building and the waste building, stands on a single thick reinforced concrete basemat. This provides protection against a major earthquake
- EPR is designed to achieve 92% availability averaged over the entire 60 years of its design lifetime, with long irradiation cycles, shorter refuelling outages and in-operation maintenance
- EPR is designed to be permanently operable at any power level between 20 and 100% in fully automatic mode
- Modular manufacturing and prefabrication techniques lead to a reduced timescale for its construction: the target is commercial operation four years from pouring first concrete
- Optimised core design and higher overall efficiency with savings on uranium consumption. Costs are therefore reduced for the entire fuel cycle.

Key nuclear safety aspects are:
- The EPR complies with the safety objectives set jointly by the French and German authorities for future PWR power plants as well as meeting the "European Utilities Requirements"
- Increased protection against accidents including core meltdown and their radiological consequences. Within the containment there is a special area where, in the very unlikely event of core meltdown, any of the molten fuel escaping from the reactor vessel would be collected, retained and cooled
- Robust against external hazards including commercial plane impact and severe earthquake
- Enhanced radiological protection of the public and operating and maintenance personnel
- Fourfold redundant safety systems, and their supporting systems, with independent and physically separated 'trains' or subsystems to minimise the consequences of internal and external hazards. The different trains of the safety systems are located in four different buildings with strict physical separation. Each train is capable of performing the entire safety function independently
- The EPR approach is based mainly on the 'defence in depth' deterministic approach backed up by probabilistic risk assessment studies of all faults and hazards.

EPR Construction Projects

The first EPR is being constructed at Olkiluoto in Finland. Construction work commenced in February 2005 with the start of electricity generation in 2011. The plant will be operated by the Finnish utility Teollisuuden Voima Oy (TVO).

In France, in 2004, EDF proposed a demonstration EPR at Flamanville in Normandy. This 1600 MWe project, costing around €3.3 billion, is scheduled to begin in 2007 with completion in 2012. EDF plans to construct at least one EPR a year from 2015 progressively replacing its existing nuclear fleet of 58 commercial reactor units.

Economic Simplified Boiling Water Reactor (ES BWR)

The GE-Hitachi ESBWR is a passively safe generation III reactor design which has evolved from the ABWR (Advanced Boiling Water Reactor) and the standard BWR design which has been deployed worldwide.

The ESBWR core has 1132 fuel bundles and generates 4500 MWth or 1550 MWe. Design temperature and pressure are 302°c and 1250 psig. Design life is 60 years.

A major design feature of the ESBWR is that it has a taller vessel, 27m inside height, compared to the ABWR, at 21m, and a shorter core. This is to promote natural circulation flow so that the ESBWR has no external recirculation loops, no main pumps and no large pipe nozzles below the top of the core region.

Principal design safety features of the ESBWR are:
- Four division passive Emergency Core Cooling System (ECCS) - driven solely by gravity drain without the need for pumps, water is sourced from tanks located high in the containment
- Automatic Depressurisation System (ADS) - consists of 10 safety relief valves and 8 depressurisation valves. In the event of a loss of coolant accident, the ADS depressurises the vessel in sufficient time for the gravity driven cooling system injection flow to replenish core coolant to maintain core temperatures below design limits
- Reinforced concrete containment, similar to an ABWR but with an elevated suppression pool and a slightly large volume to accomodate the passive ECCS water tanks
- Passive Containment Cooling System - this has low pressure loops with heat exchangers/steam condensers located above and immediately outside the containment, the system has no active components and is independent of AC power
- Basemat Internal Melt Arrest Coolability Core Catcher - in a hypothesised very severe accident, the molten fuel is contained and cooled
- All front line safety functions are passive - in the event of a fault no operator actions ar required for 72 hours, nor are diesels or AC power supplies.

With these safety systems, the probability of a radioactive release to the atmosphere is significantly lower compared with standard nuclear plants. The ESBWR safety case is based on deterministic and probabilistic studies.

Currently, the GE-Hitachi ESBWR design is proceeding through the US Nuclear Regulatory Commission Reactor Design Certification process. Final Design Approval is expected late 2008 and Design Certification late in 2009.

Prototype Designs

Designs now being considered for the longer term (ie 2020 - 2030) include:

IRIS - International Reactor, Innovative, Secure
This is based on a small LWR concept with secure safety aspects built in. The design will be modular and flexible and achieve economic competitiveness.

PBMR - Pebble Bed Modular Reactor
The reactor is a helium-cooled graphite moderated unit of 100MWe which drives a gas turbine linked to a generator giving up to 50% thermal efficiency. Key design features:

- Fuel elements are spherical 'pebbles' 60mm in diameter of graphite containing tiny spheres of uranium dioxide coated with carbon and silicon carbide. This coating retains the gaseous and volatile fission products generated in operation.
- The reactor consists of a vertical steel pressure vessel, 6m in diameter and about 20m high. It is lined with graphite bricks drilled with vertical holes to house the control rods.
- Helium is used as the coolant and transfers heat to a closed cycle gas turbine and generator.
- When fully loaded the core contains 310,000 fuel spheres; re-fuelling is done on-line with irradiated spheres being withdrawn at the base of the reactor and fresh fuel elements being added at the top.
- The PBMR has inherent passive safety features that require no operator intervention. Removal of decay heat is achieved by radiation, conduction and convection. The combination of very low power density of the core and temperature resistance of the fuel in millions of independent particles underpins the safety assurance of the design. (See **Fig 8**)

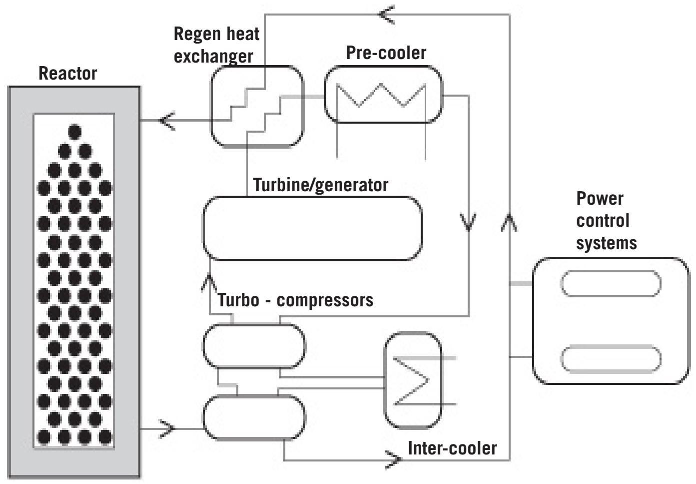

Figure 8 Schematic: Circuit of Pebble Bed Modular Reactor

This design takes forward the approach originally developed in Germany (AVR 15MW experimental pebble bed reactor and Thorium High-Temperature Reactor THTR 300MWe) and is being developed by Eskom, the South African electrical utility, for application in South Africa initially through a demonstration plant. Exelon (the major US utility) is supporting this venture to develop and commercialise the PBMR.

Fast Reactors

All of today's commercially successful reactor systems are "thermal" reactors, using slow or thermal neutrons to maintain the fission chain reaction in the U^{235} fuel. Even with the enrichment levels used in the fuel for such reactors, however, by far the largest numbers of atoms present are U^{238}, which are not fissile.

Consequently, when these atoms absorb an extra neutron, their nuclei do not split but are converted into another element, Plutonium. Plutonium is fissile and some of it is consumed in situ, while some remains in the spent fuel together with unused U^{235}. These fissile components can be separated from the fission product wastes and recycled to reduce the consumption of uranium in thermal reactors by up to 40%, although clearly thermal reactors still require a substantial net feed of natural uranium.

It is possible, however, to design a reactor which overall produces more fissile material in the form of Plutonium than it consumes. This is the **fast reactor** in which the neutrons are unmoderated, hence the term "fast". The physics of this type of reactor dictates a core with a high fissile concentration, typically around 20%, and made of Plutonium. In order to make it breed, the active core is surrounded by material largely U^{238}) left over from the thermal reactor enrichment process. This material is referred to as **fertile**, because it converts to fissile material when irradiated during operation of the reactor.

Due to the absence of a moderator, and the high fissile content of the core, heat removal requires the use of a high conductivity coolant, such as liquid sodium. Sodium circulated through the core heats a secondary loop of sodium coolant, which then heats water in a steam generator to raise steam. Otherwise, design practice follows established lines, with fuel assemblies of clad pins arranged together in the core, interspersed with movable control rods. The core is either immersed in a pool of coolant, or coolant is pumped through the core and thence to a heat exchanger. The reactor is largely un-pressurised since sodium does not boil at the temperatures experienced, and is contained within steel and concrete shields (See **Fig 9**).

The successful development of fast reactors has considerable appeal in principle. This is because they have the potential to increase the energy available from a given quantity of uranium by a factor of fifty or more, and can utilise the existing stocks of depleted uranium, which would otherwise have no value.

Fast reactors, however, are still currently at the prototype or demonstration stage. They would be more expensive to build than other types of nuclear power station and will therefore become commercial only if uranium or other energy prices substantially increase.

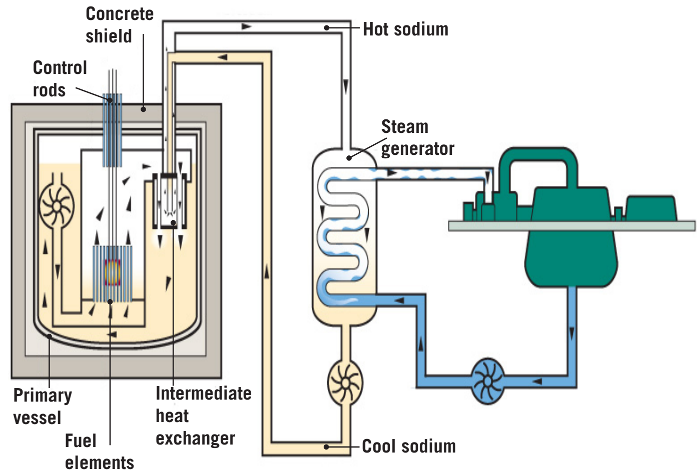

Figure 9 Schematic: Sodium-Cooled Fast Reactor

The British prototype reactor was at Dounreay in Scotland, but has now been closed on cost grounds. In 1992 the Government announced that all UK research into fast reactors would cease. The justification for these decisions was the belief that commercial fast reactors would not be needed in the UK for 30 to 40 years.

Fusion

All the reactors outlined before are fission reactors. Energy can also be produced by fusing together the nuclei of light elements. This is the process which provides the energy source in the sun and other stars. The idea of releasing large amounts of energy by the controlled fusion of the nuclei of atoms such as deuterium and tritium is very attractive because deuterium occurs naturally in seawater.

Unfortunately, controlled fusion has turned out to be an extraordinarily difficult process to achieve. For the reaction to proceed, temperatures in excess of one hundred million degrees must be obtained and high densities of deuterium and tritium must be achieved and retained for a sufficient length of time. So far, it has not proved possible to sustain these requirements simultaneously in a controlled way. A large number of major projects, including a European collaboration which has built the Joint European Torus (JET) at Culham in Oxfordshire, have gradually got closer to reaching the combination of temperature, density and containment time required for success. Even if this can be achieved eventually, the process must be capable of being developed in a form which will allow power to be generated cost effectively and continuously over a long period. The next phase is the construction of the ITER international tokamak experiment. This will be built at Cadarache in southern France. It should demonstrate the technological feasibility of fusion as an energy source and is expected to begin operating in 2016.

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Further Reading

- Wood, J. **Nuclear Power** (IET Power and Energy Series 52); Institution of Engineering and Technology (2007) ISBN 0863416683

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