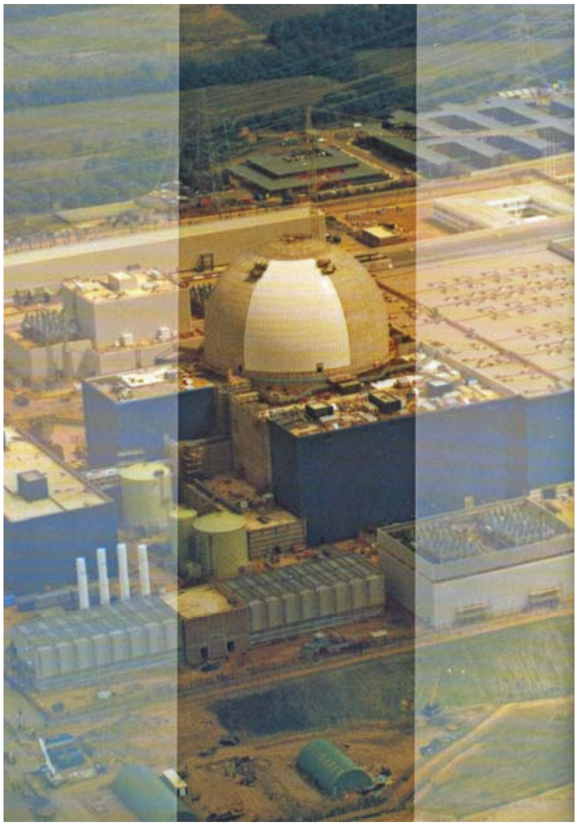

Nuclear Reactor Types

An Environment & Energy FactFile
provided by the IEE

Published by
The Institution of Electrical Engineers
Savoy Place
London
WC2R 0BL
November 1993
This edition November 2005
ISBN 0 85296 581 8
The IEE is grateful to the following organisations for permitting their material to be reproduced:
Nuclear Electric
The cover photograph shows Sizewell B Nuclear Power Station under construction

Nuclear Reactor Types

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 **Magnox** reactors (see **Fig 1.1(a)**) were built in the UK from 1956 to 1971 but have now been superseded.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 Further vertical channels contain control rods (strong neutron absorbers) which can be inserted or withdrawn from the core to adjust the rate of the fission process and, therefore, the heat output.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.

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**, or **AGR** (see **Fig 1.1(b)**), 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.

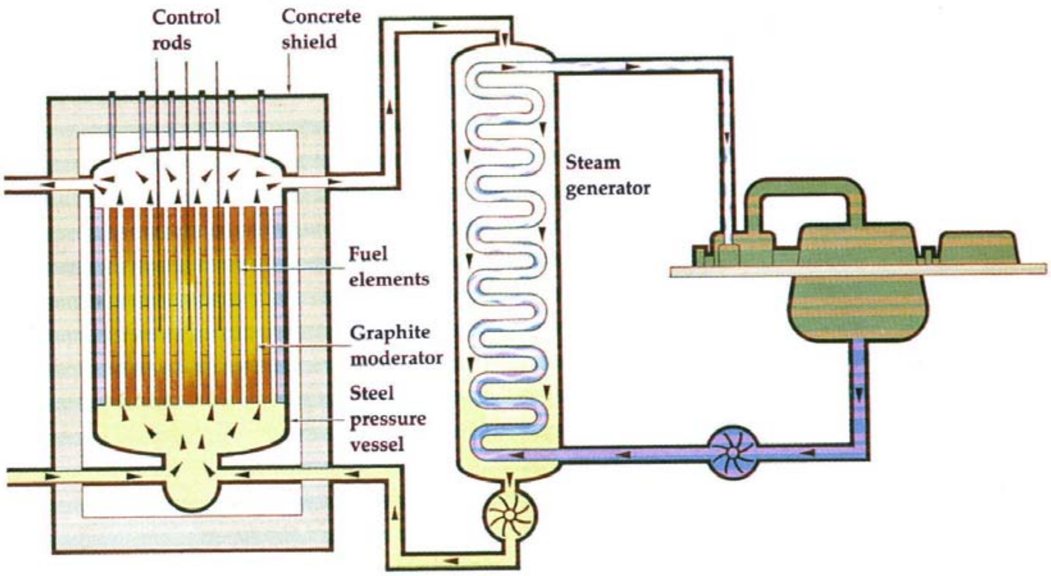

Figure 1.1(a) Schematic: Basic Gas-Cooled Reactor (MAGNOX)

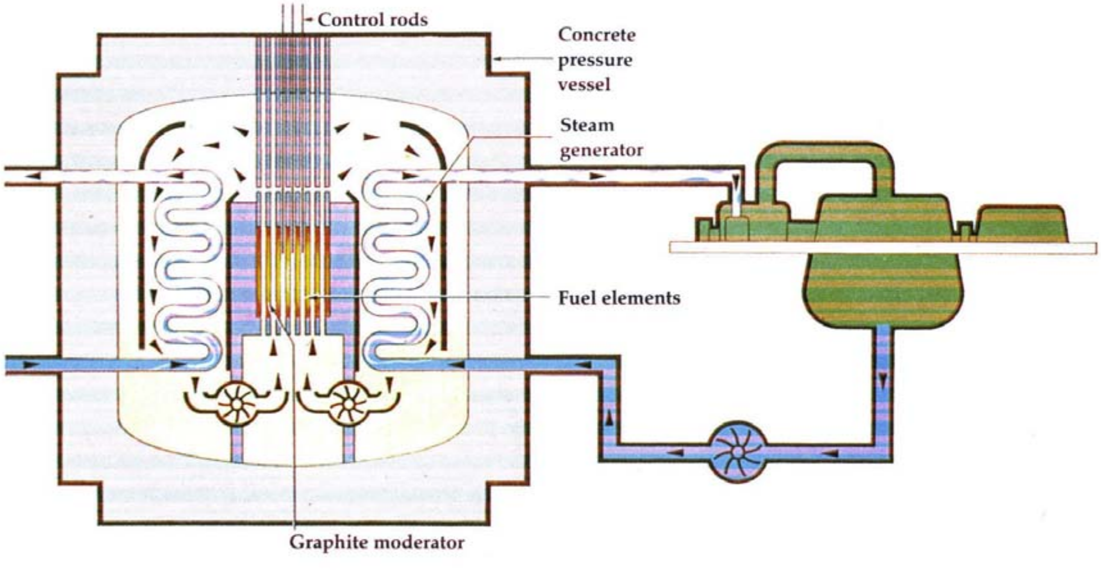

Figure 1.1(b) Schematic: Advanced Gas-Cooled Reactor (AGR)

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 1.2**) unenriched 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 unpressurised 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.

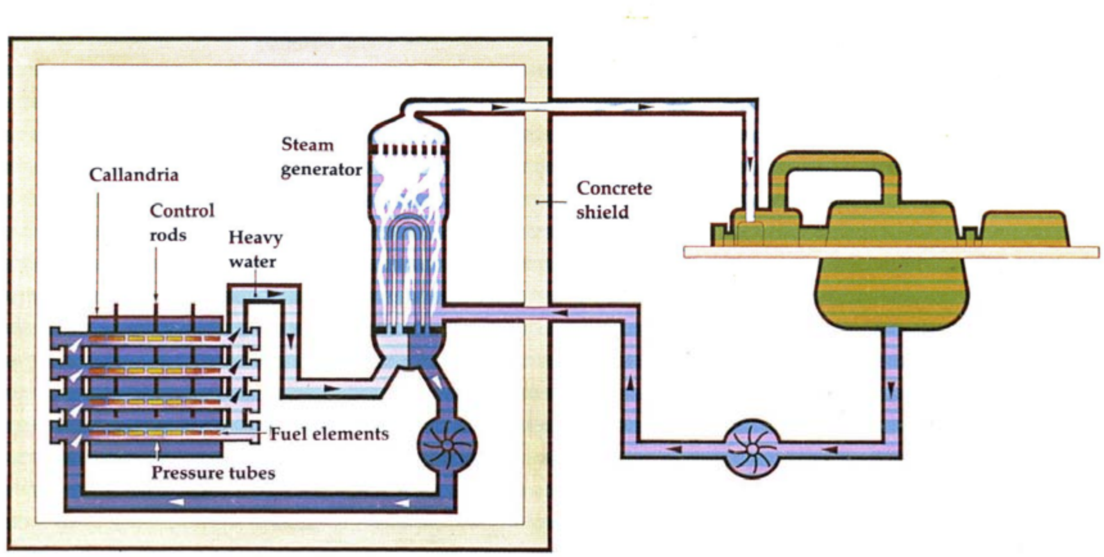

Figure 1.2 Schematic: Pressurised Heavy Water Reactor (CANDU)

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 1.3a**) 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.

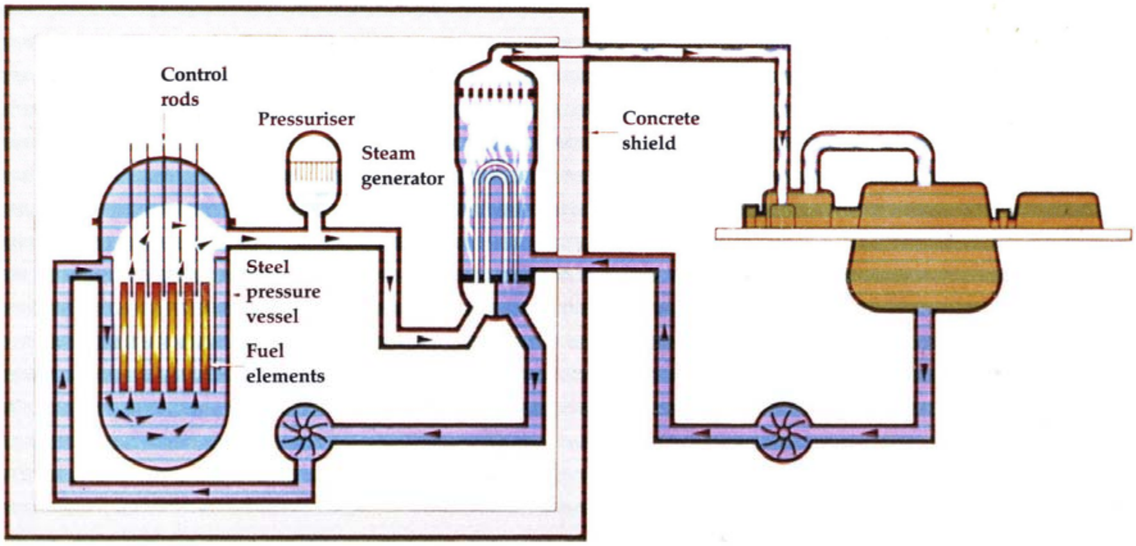

Figure 1.3a Schematic: Pressurised Water Reactor (PWR)

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. 1.3b) are in use in some ten countries throughout the world.

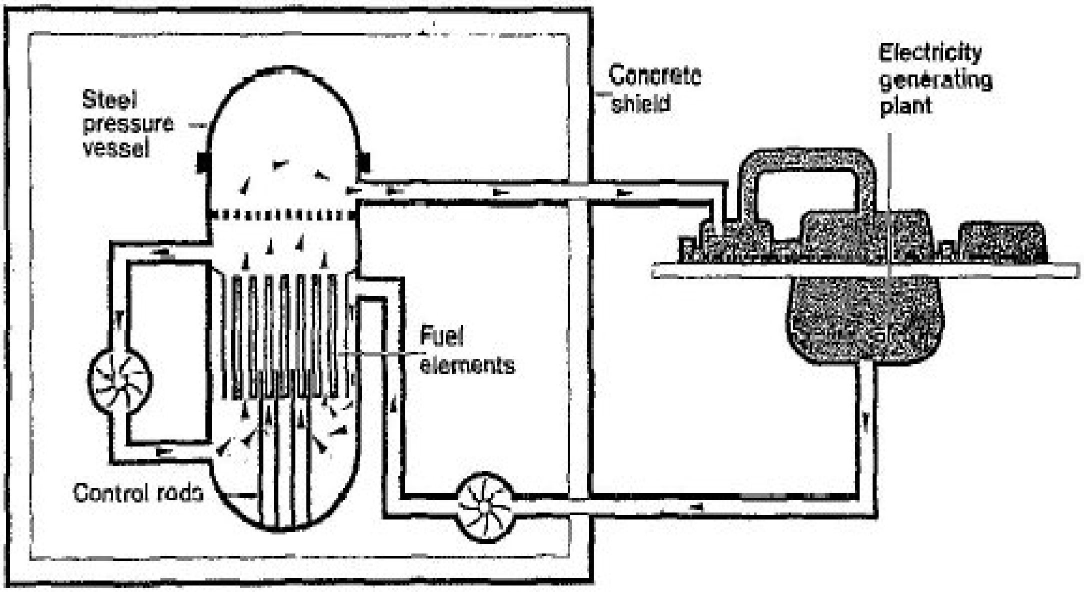

Figure 1.3b Schematic: Boiling Water Reactor (BWR)

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 1.4**), 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% U235). 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.

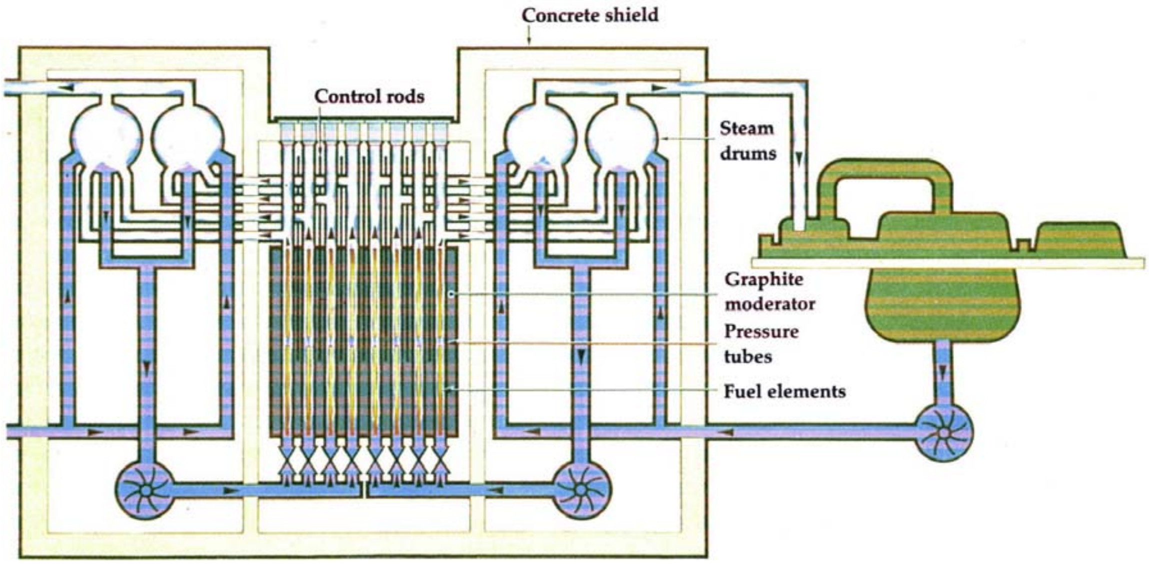

Figure 1.4 Schematic: RBMK REACTOR Boiling Light Water, Graphite Moderated Reactor

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 **Figure 1.5**)

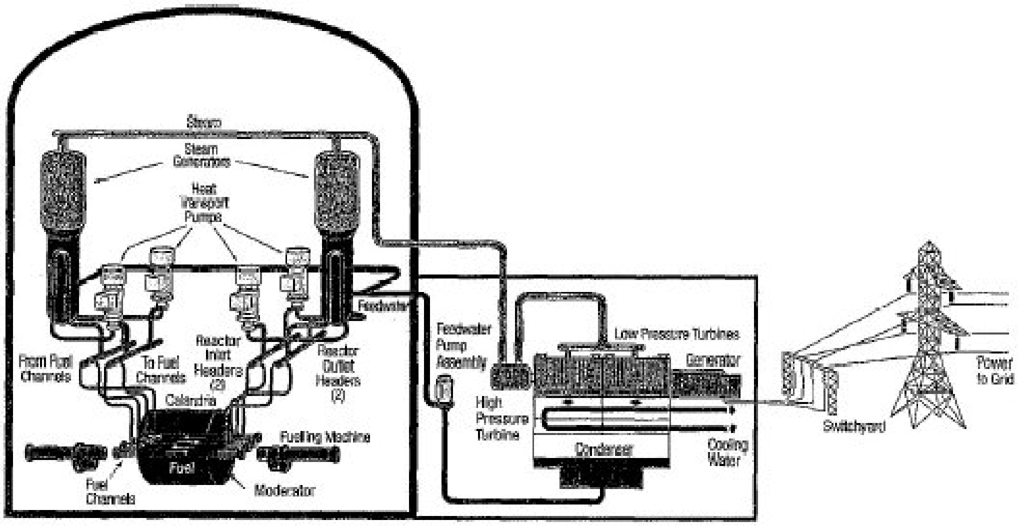

Figure 1.5 Schematic: NG CANDU Flow Diagram

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, which is owned by BNFL, 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. BNFL 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 BNFL/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.

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% 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 **Figure 1.6**)

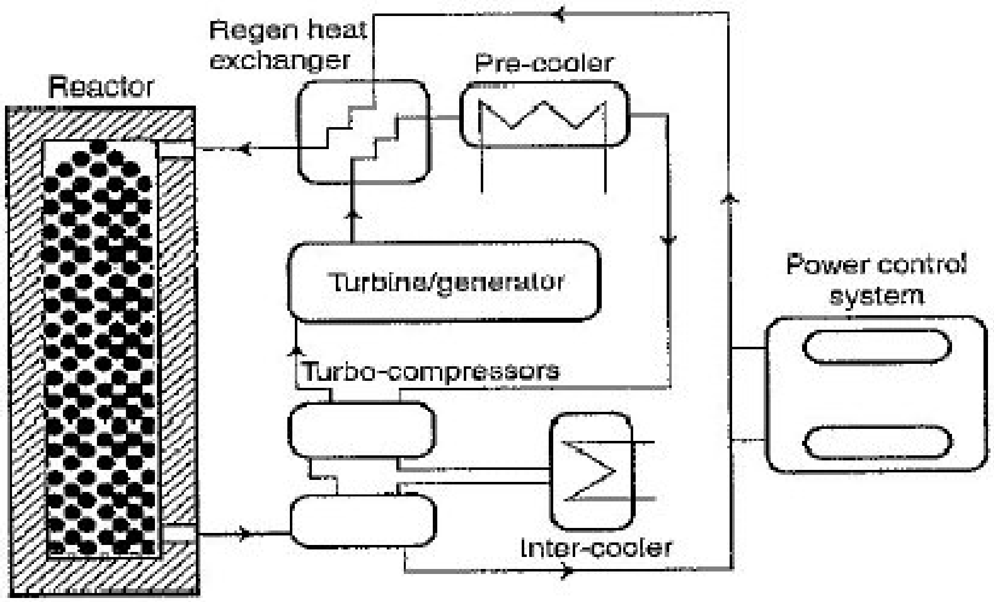

Figure 1.6 Schematic: Circuit of Pebble Bed Modular Reactor

The PBMR 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) and BNFL are 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 clad in cans and 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 unpressurised since sodium does not boil at the temperatures experienced, and is contained within steel and concrete shields (See **Figure 1.7).**

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.

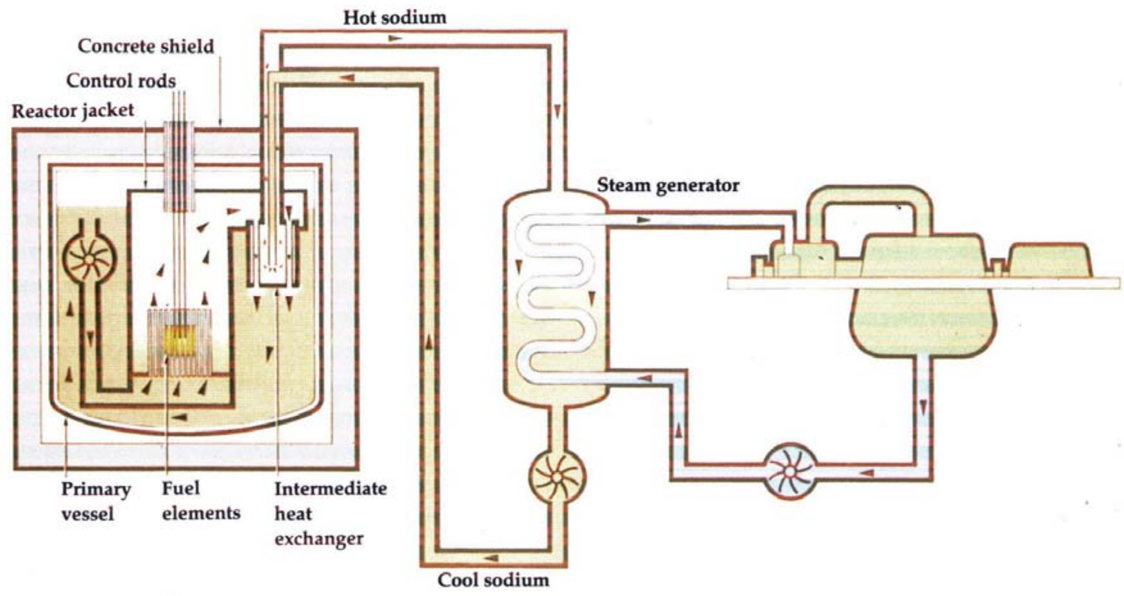

Figure 1.7: Sodium-Cooled Fast Reactor

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.

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. It is very unlikely that this could be achieved until well into the twenty-first century.