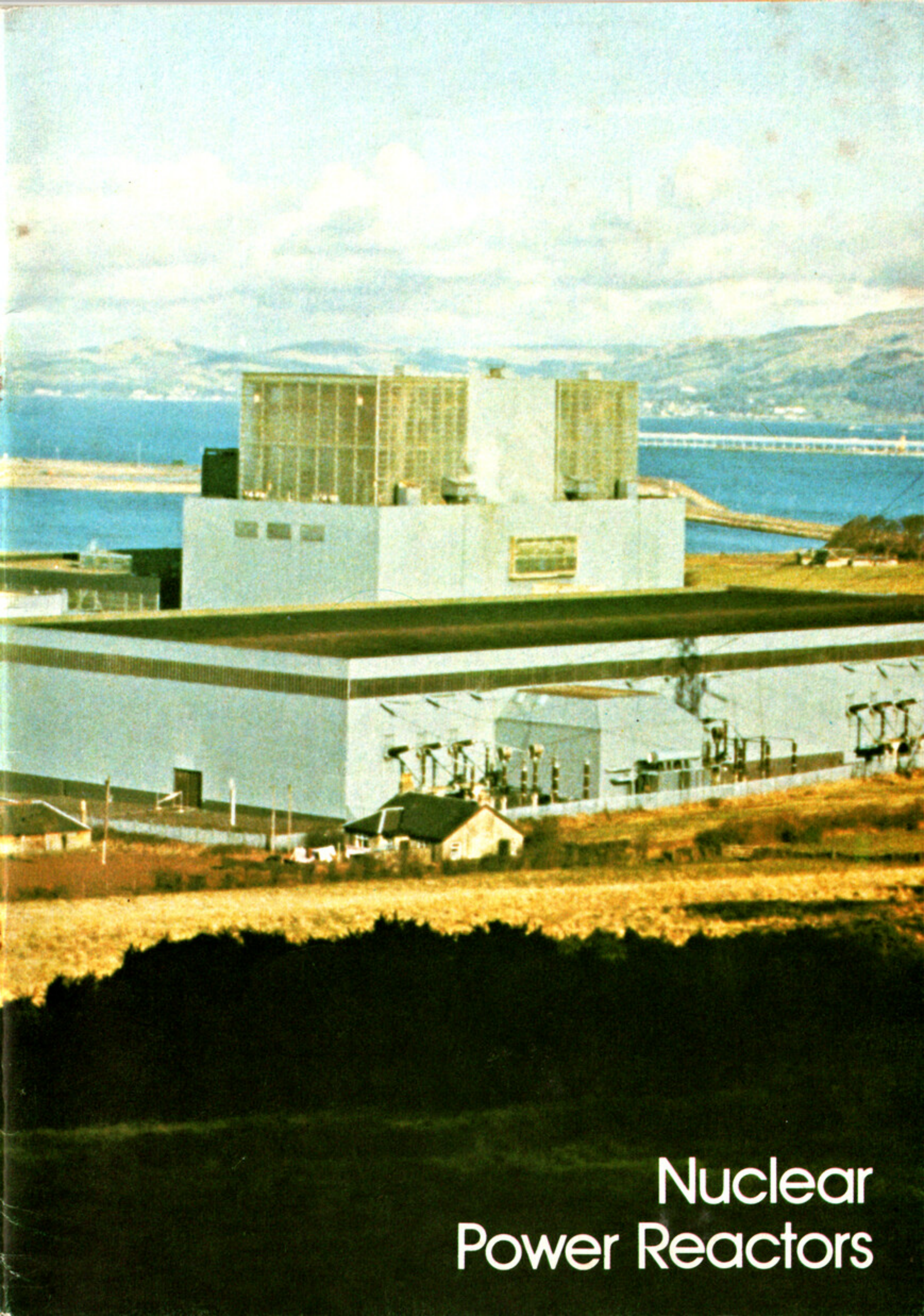
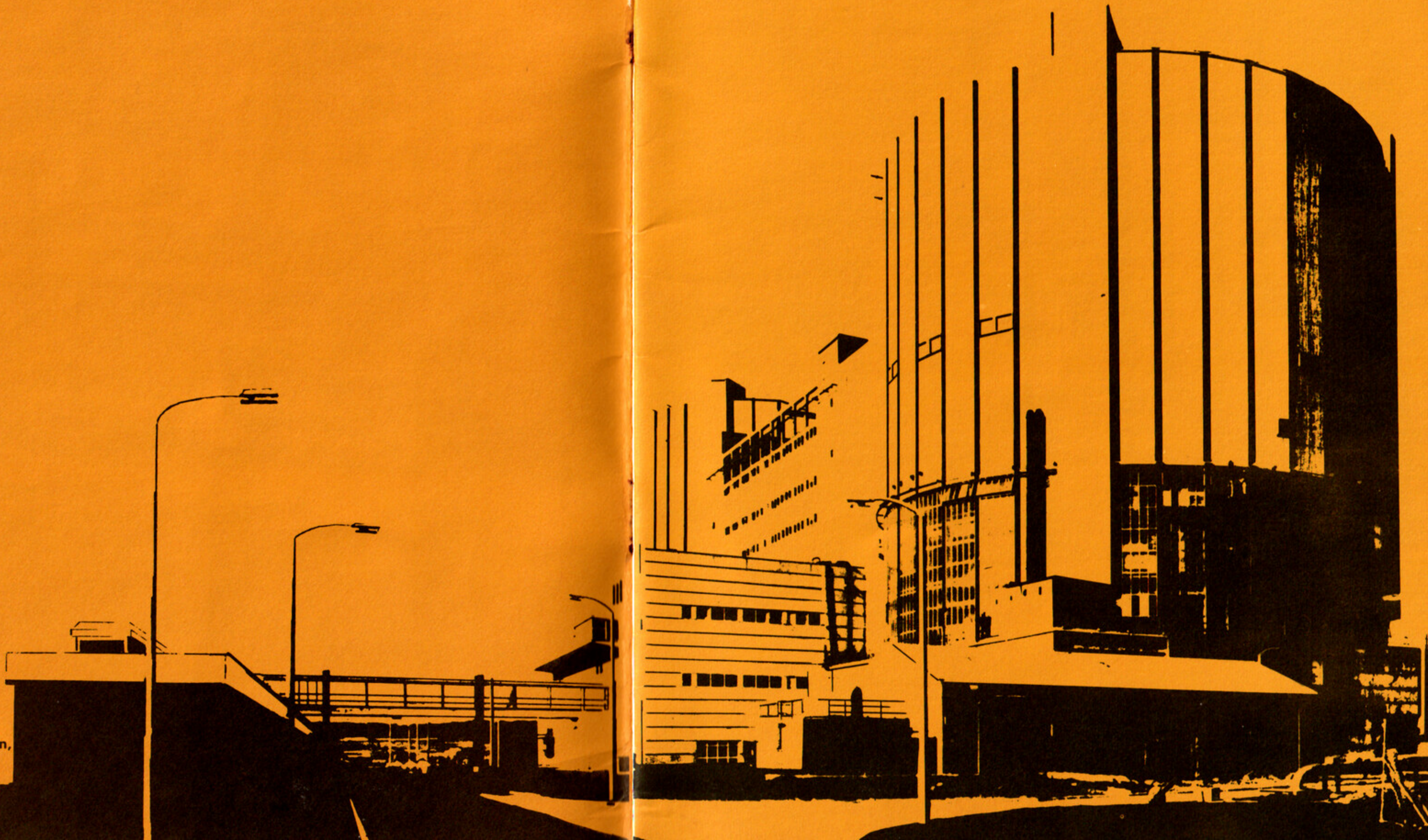
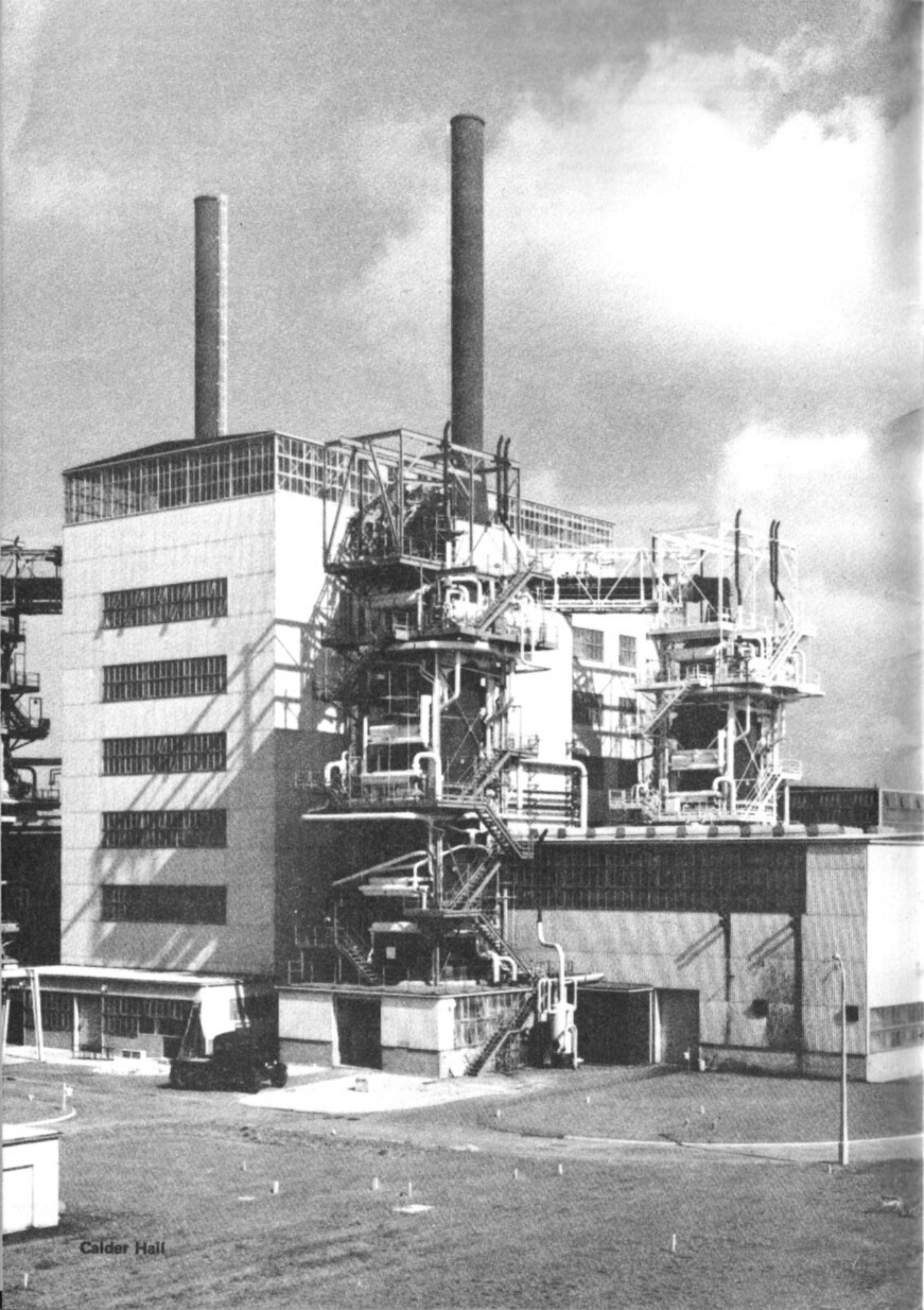


Nuclear Power Reactors

Nuclear Power Reactors



Cover
Hunterston 'B'
Nuclear Power Station,
Ayrshire.



Calder Hall

Introduction

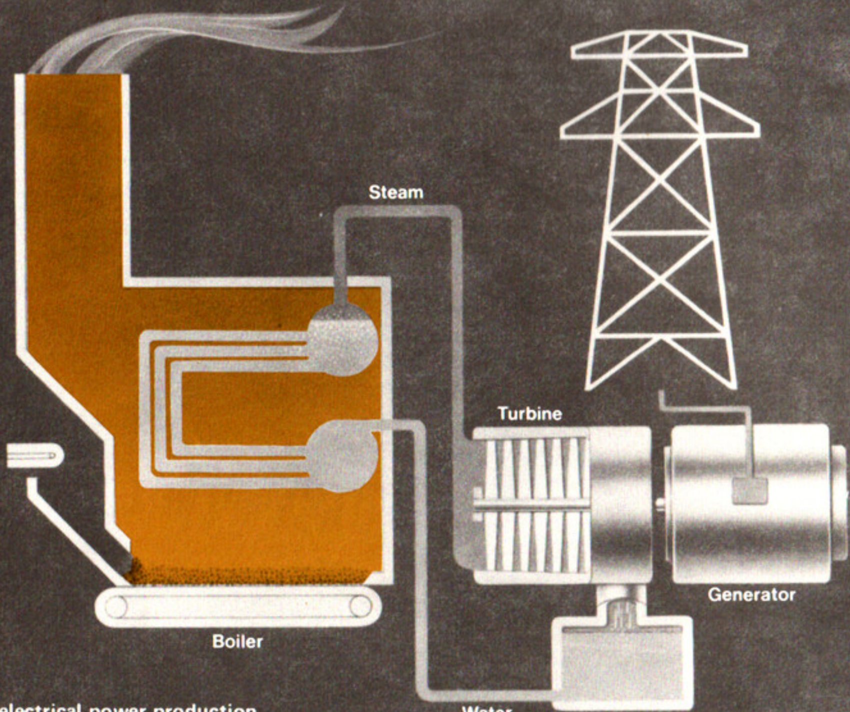
Since the discovery of fission in 1938, work to harness the energy of the atom for peaceful purposes has been carried out in many industrial countries. With growing realisation of the finite nature of traditional fuels, the importance of nuclear power as an assured method of generating electricity has become widely appreciated.

Few countries are as well endowed as Britain with fossil fuels. However North Sea oil reserves are expected to decline in the 1990's. Further, it is important to use a greater proportion of the oil for highly refined products like gasoline and chemical feedstocks. UK coal reserves are substantial but rates of extraction can only be increased gradually. These considerations point to nuclear power as a growing source of electricity generation.

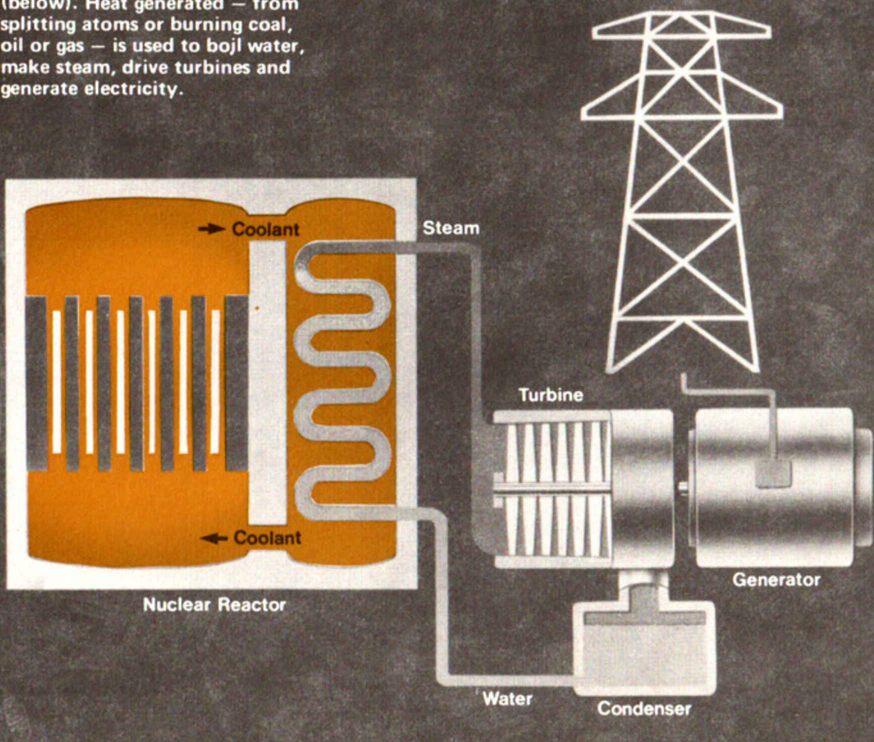
Today in several countries, including Britain, France and the United States nuclear reactors are used to produce more than 10% of the total electrical power required.

In Britain the present figure of 12% is expected to reach 20% when stations now under construction are finished. With a further 10 stations due to be built from 1982 onwards, subject to electricity demand and the performance of the industry, the amount of electricity generated by nuclear power will increase steadily over the next twenty years.

Since 1956 when the Queen opened the first nuclear power station at Calder Hall, many hundreds of reactors have been built all over the world in a range of sizes and designs. This booklet provides a brief introduction to the basic types and highlights those of particular interest to Great Britain.



In electrical power production, there is no fundamental difference between fossil fuel systems (above) and nuclear (below). Heat generated — from splitting atoms or burning coal, oil or gas — is used to bojl water, make steam, drive turbines and generate electricity.



Nuclear Power

The main difference between coal and oil-fired power stations and nuclear ones is the source of heat.

With coal and oil the heat is produced by burning the fuel – a chemical reaction. In nuclear stations the heat comes from energy released when the nucleus of a heavy atom (uranium or plutonium) is split – a nuclear reaction. This produces several million times the energy of a chemical reaction weight for weight. In practice, since present so-called 'thermal' reactors can only use a small percentage of their uranium fuel the figure is reduced to a few tens of thousand times. Even so, the volumes of nuclear fuel to be mined, processed and transported, and the waste products are all much smaller than in the case of fossil fuels.

Each person in Britain uses some 330 megawatt-hours of electricity during his lifetime. This requires the burning of 150 tonnes of coal – or six kilogrammes of uranium. After producing the electricity there are 30 tonnes of coal ash or a few kilogrammes of nuclear waste.

The amounts of uranium used may be small but like coal and oil the reserves are finite. Spent fuel from thermal reactors, however, contains a high proportion of unused uranium and a measure of plutonium actually created during operation. This fuel can, after reprocessing, be recycled in a fast reactor thus using the uranium 50 times more efficiently, and thereby greatly reducing Britain's need for imported stocks.

The depleted uranium already held from the operation of present thermal reactors is about 20,000 tonnes which, used in fast reactors, is equivalent to 40,000 million tonnes of coal, say 400 years of mining at present extraction rates.

The first 25 years of nuclear power have seen considerable developments in reactor design. The early stations in Britain, the 'Magnox' type were improved versions of Calder Hall. All are still operational. The Magnox design has been superseded by the Advanced Gas-Cooled Reactor (AGR) which, with higher steam temperature and pressure, operates at much higher efficiency. Parallel development of water cooled reactors, mainly in the United States, has produced the Pressurised Water Reactor (PWR) which is being considered for adoption for some future British stations.

Despite improvements in overall thermal efficiency the percentage burn-up of uranium remains low in all these 'thermal' reactors. Much research and development has gone into the 'fast' reactor which can use uranium far more effectively. This work has reached the stage where several countries are building, or have the capability to build commercial fast reactors.

Reactor Types

In a nuclear reactor, the atoms of uranium or plutonium are split by neutrons, releasing energy as heat and more neutrons to sustain a controlled chain reaction. The neutrons are released at high speed and some are absorbed in the uranium-238 atoms present, transforming them into plutonium. There are two basic types of nuclear power reactor: thermal reactors and 'fast' reactors, named after the speed of the neutrons.

Thermal neutrons have been slowed down to be in thermal equilibrium with the surrounding structure i.e. they are at a similar temperature. Fast neutrons are simply moving at the high speed with which they emerge from the fission reaction.

Prototype Fast Reactor at Dounreay

Thermal Reactors

Natural uranium consists mainly of the isotope U-238 with less than one percent of the isotope U-235. Nevertheless the probability of the fission of U-235 by slow neutrons is so much higher than that of U-238 by fast neutrons that it is worth deliberately slowing down the neutrons, to give U-235 fission.

Thermal Reactors therefore have a moderator to slow down the neutrons so that a sufficient number react with the particularly fissile uranium-235. The choice of moderator leads to two families of thermal reactors: graphite moderated reactors, (e.g. Magnox, AGR) in which the heat is transferred by gas; and water moderated reactors such as PWR in which water also transfers the heat.

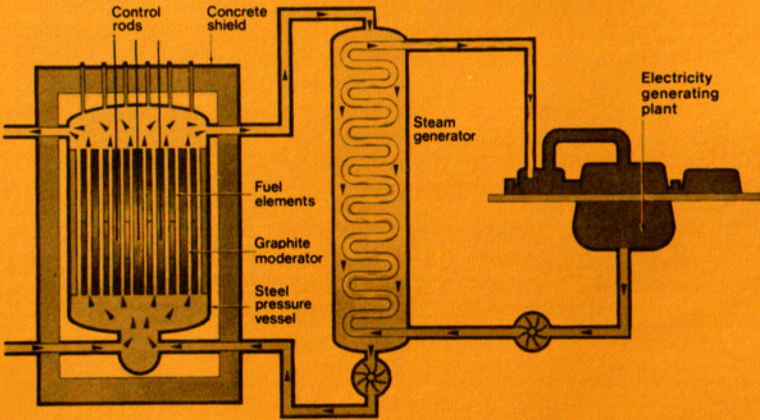
Most thermal reactors use as fuel enriched uranium in which the amount of U-235 has been artifically raised to 2–3%.

Fast Reactors

Fast Reactors currently use plutonium fuel, produced initially as a by-product from thermal reactors. The plutonium is sufficiently concentrated for the fission reaction to be sustained by fast neutrons and no moderator is necessary. Without a moderator, the core of the reactor can be compact and have a high heat rating provided an efficient coolant is used to transfer the heat. Liquid sodium is used.

In addition, the core can be surrounded by a uranium blanket and thus 'breed' more plutonium. Hence 'Breeder Fast Reactor' often incorrectly referred to as 'Fast Breeder Reactor' since thermal power reactors produce as much or more as a fast reactor of the same power.

Magnox Thermal Reactor
Graphite Moderated



The first nuclear power station in the world, Calder Hall, is a 200 MW(e) Magnox type. Besides Calder and its sister station Chapelcross, built as UKAEA experimental power reactors, Britain has nine twin reactor stations of this type built by British industry, on the basis of UKAEA designs, for the Generating Boards to supply electricity commercially to the National Grid. Two further stations were built overseas, one in Italy, and one in Japan. Magnox is being superseded by AGR. Total Magnox capacity in the UK is 4000 MW(e).

MAGNOX stations	**Date of commissioning**	**Nett capability** MW sent out
Calder Hall	1956	200
Chapelcross	1958	200
Berkeley	1962	276
Bradwell	1962	250
Dungeness 'A'	1965	410
Hinkley Point 'A'	1965	430
Hunterston 'A'	1964	300
Oldbury on Severn	1967	416
Sizewell 'A'	1966	420
Trawsfynydd	1965	390
Wylfa	1971	840

Fuel Uranium metal. To conserve neutrons and allow natural uranium to be used, the fuel is clad in a magnesium alloy (Magnox) with low neutron absorption.

Moderator Graphite.

Heat extraction Carbon dioxide gas is heated by passing it over the fuel in the core and transfers its heat to water in a steam generator; the steam drives a turbine coupled to an electric generator.

Indicative data for a reactor of 600 MW(e) size:

Uranium enrichment (% U.235)
0.7% (natural)

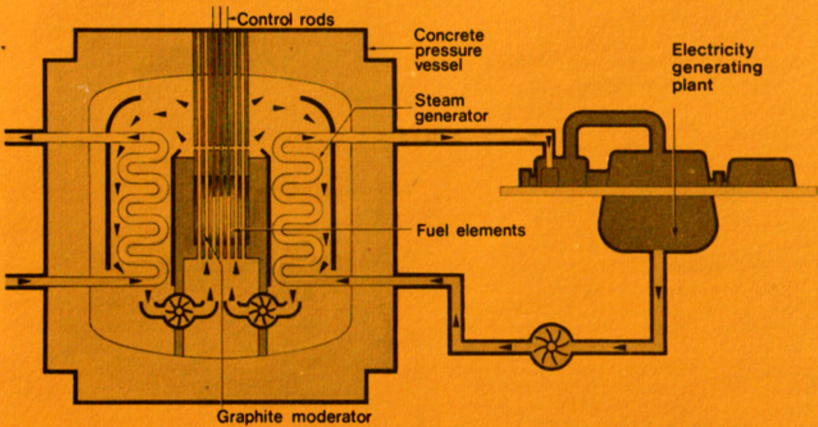
Coolant outlet temperature
400°C

Coolant pressure
300 psia

Steam cycle efficiency
31%

Core dimensions
14 m dia. x 8 m high

Advanced Gas-cooled Reactor (AGR)
Thermal Reactor - Graphite Moderated



AGR's are the second phase in Britain's own nuclear development programme. Seven twin reactor stations are involved. Two are in use and five are under construction making a total capacity of 9000 MW(e).

AGR stations	Date of commissioning	Nominal capacity MW
Hinkley Point 'B'	1976	1320
Hunterston 'B'	1976	1320
Dungeness 'B'	1981	1200
Hartlepool	1981	1320
Heysham 'A'	1982	1320
Heysham 'B'	Late 1980s	1320
Torness	Late 1980s	1320

Indicative data for a reactor of 600 MW(e) size:

Uranium enrichment (% U.235)
2.3%

Coolant outlet temperature
650°C

Coolant pressure
600 psia

Steam cycle efficiency
42%

Core dimensions
9.1 m dia. x 8.5 m high

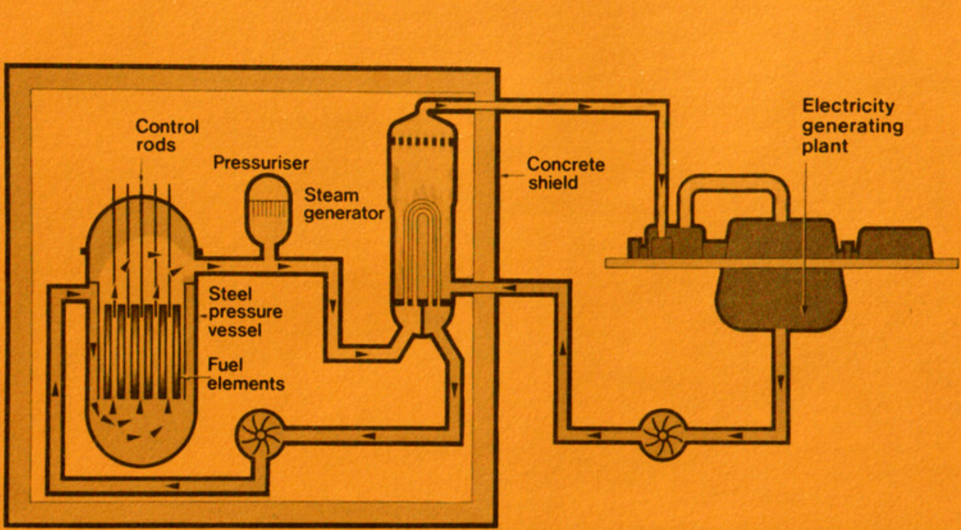
Fuel Uranium dioxide in stainless steel cladding. The fuel can operate at higher temperatures and heat output rates than Magnox reactor fuel, giving a smaller size of reactor core and a more efficient steam cycle. To achieve these advantages and a greater heat rating, the proportion of U.235 in the fuel has to be increased (enriched uranium).

Moderator Graphite.

Core layout Clusters of fuel elements are joined together end-to-end in a stringer, placed in vertical holes in the graphite.

Heat extraction Carbon dioxide gas is heated by passing over the fuel in the core and transfers its heat to water in a steam generator; the steam drives a turbine coupled to an electric generator.

Pressurised Water Reactor (PWR)
Thermal Reactor - Water Moderated



Developed originally by America and Russia as a compact reactor for marine propulsion this is now the most widely used type of reactor in the world. The version developed in the USA is now also built under licence for export by France and Germany. More than 20 countries have PWR's and Britain is considering adopting this system.

Fuel Uranium dioxide clad in an alloy of zirconium (Zircaloy).

Moderator Light water (ordinary water, H_2O).

Core layout Fuel pins, arranged in clusters, are placed inside a pressure vessel containing the light water moderator, which also is the coolant.

Heat extraction The light water in the pressure vessel at high pressure is heated by the core. It is pumped to a steam generator where it boils water in a separate circuit; the steam drives a turbine coupled to an electric generator.

Indicative data for a reactor of 700 MW(e) size:

Uranium enrichment (% U.235)
3.2%

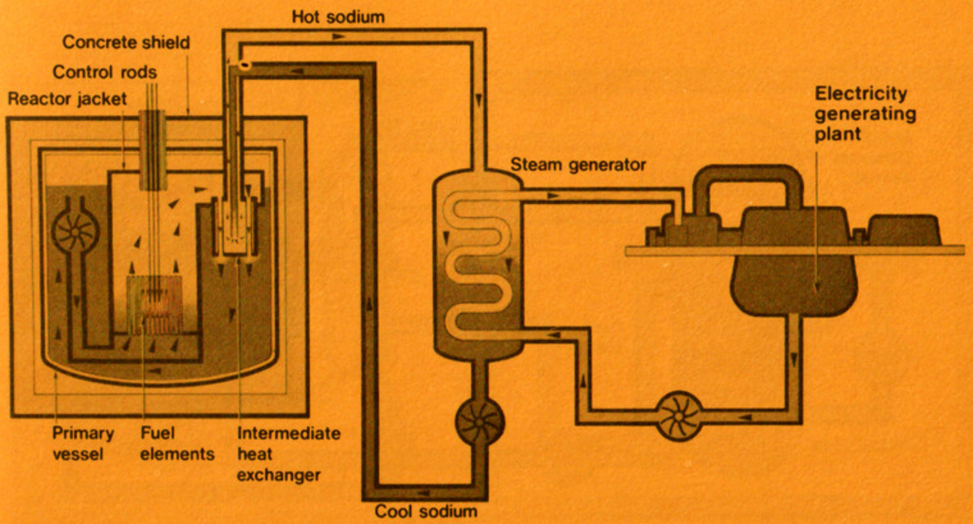
Coolant outlet temperature
317°C

Coolant pressure
2235 psia

Steam cycle efficiency
32%

Core dimensions
3.0 m dia. x 3.7 m high

Fast Reactors
Sodium Cooled



The most efficient users of uranium, fast reactors have been under development for many years. Britain's Dounreay Fast Reactor in Caithness was closed in 1977 after 18 years of operation; its successor the Prototype Fast Reactor (PFR) is designed to produce 250 MW(e) of electricity for the North of Scotland Hydro Electric Board. It is hoped to start building a commercial size fast reactor of about 1250 MW(e) capacity in the next few years, subject to a public inquiry. France is building a 1200 MW(e) commercial size reactor called Super Phenix. Russia has a 600 MW(e) station in and prototypes are also under study in other countries.

Fuel A mixture of plutonium and uranium dioxides in stainless steel cans.

Moderator None.

Core layout Assemblies of fuel elements are placed inside a tank containing the liquid sodium coolant. The core is surrounded by a "blanket" of uranium carbide in stainless steel cans.

Heat extraction The sodium is heated by the core and pumped through an intermediate heat exchanger where it heats sodium in a separate secondary circuit. The sodium in the secondary circuit transfers its heat to water in a steam generator; the steam drives a turbine coupled to an electric generator.

Indicative data for a reactor of 1300 MW(e) size:

Fuel enrichment (% Pu)
20%

Coolant outlet temperature
620°C

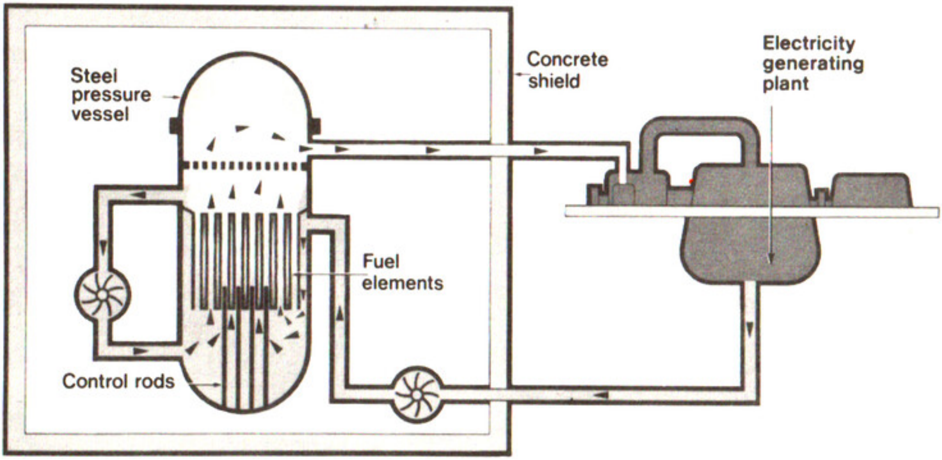
Coolant pressure
5 psia

Steam cycle efficiency
44%

Core dimensions
2.3 m dia. x 1.1 m high

Core and blanket dimensions
3.1 m dia. x 2.1 m high

Boiling Water Reactor (BWR)
Thermal Reactor - Water Moderated



Light Water Reactors (BWR & PWR) account for 90% of World Exports. BWR's are in use in a dozen countries.

Fuel Uranium dioxide in Zircaloy cans.

Moderator Light water (ordinary water, $H_2 0$).

Core layout Fuel pins, arranged in clusters, are placed inside a pressure vessel containing the light water moderator, which also is the coolant.

Heat extraction The light water in the pressure vessel is heated by the core and allowed to boil at pressure. The steam from the boiling coolant drives a turbine coupled to an electric generator.

Indicative data for a reactor of 600 MW(e) size:

Uranium enrichment (% U.235)
2.6%

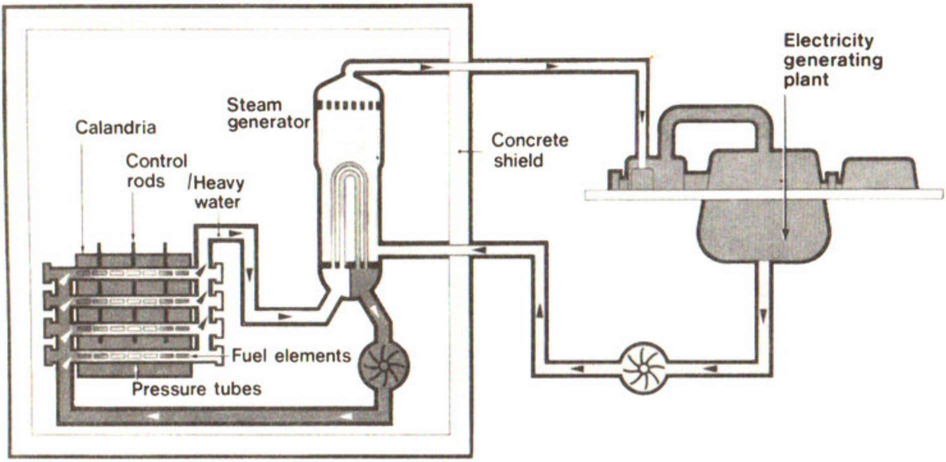
Coolant outlet temperature
286° C

Coolant pressure
1050 psia

Steam cycle efficiency
32%

Core dimensions
3.7 m dia. x 3.7 m high

CANDU Thermal Reactor
Water Moderated



To avoid the need for enriched uranium (a higher than normal amount of U235), Canada designed this heavy water reactor. CANDUs have been exported to India, Pakistan, Argentina, Korea and Romania.

Fuel Uranium dioxide in Zircaloy cans.

Moderator Heavy water (D_2O) which allows natural uranium fuel to be used.

Core layout Each cluster of fuel elements is in a separate pressure tube; the pressure tubes are in a tank of heavy water.

Heat extraction Heavy water (D_2O) at high pressure is heated by passing over the fuel in the pressure tubes. It is pumped to a steam generator where it boils light water (H_2O) in a separate circuit; the steam drives a turbine coupled to an electric generator.

Indicative data for a reactor of 600 MW(e) size:

Uranium enrichment
(% U.235)
0.7% (natural)

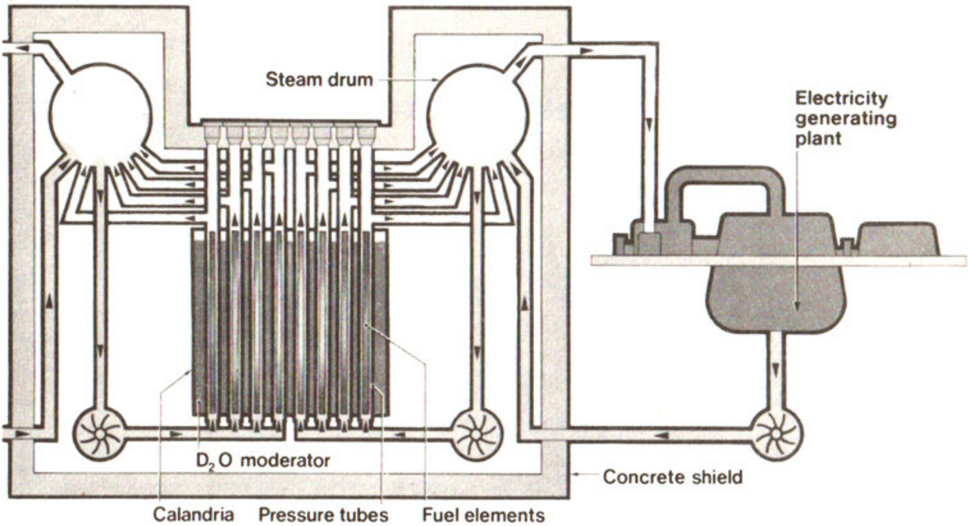
Coolant outlet temperature
305°C

Coolant pressure
1285 psia

Steam cycle efficiency
30%

Core dimensions
7.1 m dia. x 5.9 m high

Steam Generating Heavy Water Reactor (SGHWR) Thermal Reactor - Water Moderated



Many countries have developed reactors similar to CANDU using heavy water as moderator, but with light water as the coolant (for example FUGEN (Japan), CIRENE (Italy). A 100 MW(e) British version has been running for many years at the UK Atomic Energy Authority's Winfrith establishment. Experience with this water-cooled reactor and its associated test facilities will be related to the design work on PWR's.

Fuel Uranium dioxide in Zircaloy cans.

Moderator Heavy water (D_20).

Core layout Each cluster of fuel elements is in a separate pressure tube; the pressure tubes are in a tank of heavy water. Heavy water is the most efficient moderator and compensates for the neutron absorption in the pressure tubes.

Heat extraction Light water (ordinary water, H_20) at pressure is heated by passing over the fuel in the pressure tubes and allowed to boil; the steam from the boiling coolant drives a turbine coupled to an electric generator.

Indicative data for a reactor of 600 MW(e) size:

Uranium enrichment
(% U.235)
2.24%

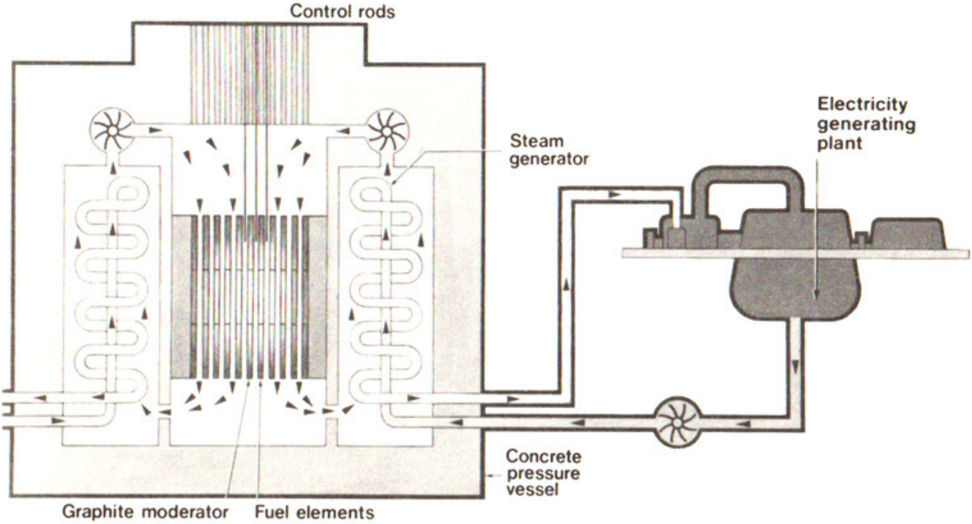
Coolant outlet temperature
272°C

Coolant pressure
900 psia

Steam cycle efficiency
32%

Core dimensions
6.5 m dia. x 3.7 m high

High Temperature Reactor (HTR)
Thermal Reactor - Graphite Moderated



The inherent high temperature of this type of reactor makes it a potential source of process heat. However, only experimental versions have been built, in the UK, USA and Germany.

Fuel Small spheres (about 800 um diameter) of uranium dioxide with a coating of silicon carbide, bonded in a graphite matrix and assembled with graphite into a fuel element. The fuel can operate at higher temperatures than metal clad fuel and a larger proportion can be "burned-up" in each cycle in the reactor.

Moderator Graphite, replaced with the fuel at each fuel change.

Core layout Fuel elements are arranged with vertical coolant passages in the graphite moderator.

Heat extraction Graphite would be corroded by carbon dioxide to an unacceptable extent at HTR temperatures so that Helium gas is heated by passing over the fuel in the core and transfers its heat to water in a steam generator; the steam drives a turbine coupled to an electric generator. Potential developments are to replace the steam generator and turbine by a gas turbine; and to use the heat directly in chemical processes.

Indicative data for a reactor of 1300 MW(e) size:

Uranium enrichment
(% U.235)
10%

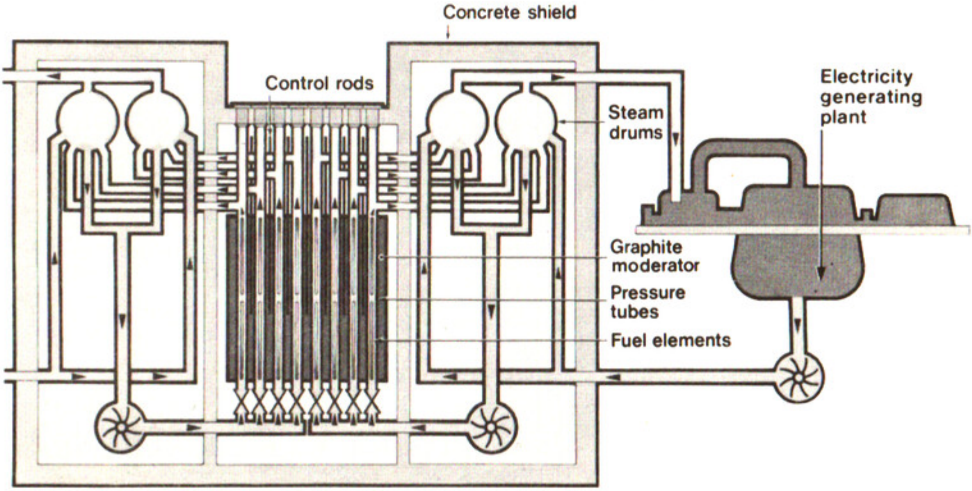
Coolant outlet temperature
720°C

Coolant pressure
715 psia

Steam cycle efficiency
39%

Core dimensions
9.8 m dia. x 6 m high

Leningrad (RMBK) Type Water-cooled Graphite Moderated



The first Russian power station, the 5 MW(e) plant at Obninsk, built in 1954 was of a hybrid type, being graphite moderated but water cooled. Subsequently this design has been enlarged to a unit size of 1000 MW(e) and many stations of this size are now under construction.

Fuel Uranium Dioxide.

Moderator Graphite.

Core layout Approximately 1700 channels each containing 36 fuel elements passing through graphite moderator assembly.

Heat extraction Light water at pressure is heated by passing over the fuel in the channels, and allowed to boil. The resulting steam/water mixture passes to a separator, and the saturated steam is passed to the turbine.

Indicative data for a reactor of 1000 MW(e) size:

Uranium enrichment
1.8%

Coolant outlet temperature
284°C

Coolant pressure
1000 psia

Steam cycle efficiency
31.3

Core dimensions
11.8 m dia. x 7 m high

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