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Description of the Advanced Gas Cooled Type of Reactor (AGR)

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Abstract

The present report comprises a technical description of the Advanced Gas cooled Reactor (AGR), a reactor type which has only been built in Great Britain 14 AGR reactors have been built, located at 6 different sites and each station is supplied with twin-reactors

The Torness AGR plant on the Lothian coastline of Scotland, 60 km east of Edinburgh, has been chosen as the reference plant and is described in some detail. Data on the other 6 stations, Dungeness B, Hinkley Point B, Hunterston B, Hartlepool, Heysham I and Heysham II, are given only in tables with a summary of design data

Where specific data for Torness AGR has not been available, corresponding data from other AGR plants has been used, primarily from Heysham II, which belongs to the same generation of AGR reactors The information presented is based on the open literature

The report is written as a part of the NKS/RAK-2 subproject 3. "Reactors in Nordic Surroundings", which comprises a description of nuclear power plants neighbouring the Nordic countries

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1 Introduction

A new four-year nuclear research program within the framework of NKS, Nordic Committee for Nuclear Safety Research, was started in 1994 as a follow-on to several preceding Nordic programmes. Joint research in this field is of interest for the five Nordic countries who have similar needs for maintaining their nuclear competence in the field of reactor safety and waste management, and who are exposed to the same outside risks from reactors in neighbouring countries, from nuclear powered vessels, and from risks of contamination of terrestrial and aquatic areas.

This report is written as a part of the NKS/RAK-2 subproject 3: "Reactors in Nordic Surroundings", which comprises a description of nuclear power plants neighbouring the Nordic countries.

The main objective of the project has been to investigate, collect, arrange and evaluate data of reactors in the Nordic neighbourhood to be used by the Nordic nuclear preparedness and safety authorities.

In the former NKS project, SIK-3, reactors within 150 km from the border of a Nordic country were treated, but it was decided to add a description of the British reactors, although the minimum distance to a Nordic border, the Norwegian, is about 500 km.

The present report comprises a technical description of the **A**dvanced **G**as cooled **R**eactor (**AGR**), a reactor type which has only been built in Great Britain. 14 AGR reactors have been built, located at 6 different sites and seven stations, Figure 1.1. and Table 1.1. Each station is supplied with twin-reactors, the site of Heysham has two stations Heysham I and Heysham II.

Dungeness B was the first commercial AGR plant to be ordered and it represents together with Hinkley Point B and Hunterston B the first generation of AGR's. All three stations are almost identically and are therefore called sister plants.

Hartlepool and Heysham I represent a modified version of first generation AGR's with a so-called multi-cavity pressure vessel, while Torness and Heysham II constitute second generation of AGR type of reactor with improved safety features.

The Torness AGR plant on the Lothian coastline of Scotland, 60 km east of Edinburgh, has been chosen as the reference plant and is described in some detail. Data on the other 6 stations are given only in tables with a summary of design data in appendix A-E.

Where specific data for Torness AGR has been unavailable, corresponding data from other AGR plants has been used, primarily from Heysham II, which belongs to the same generation of AGR reactor. The information presented is based on the open literature and the content of the report follows the format agreed on in the SIK-3 project (*Ref. 1*).

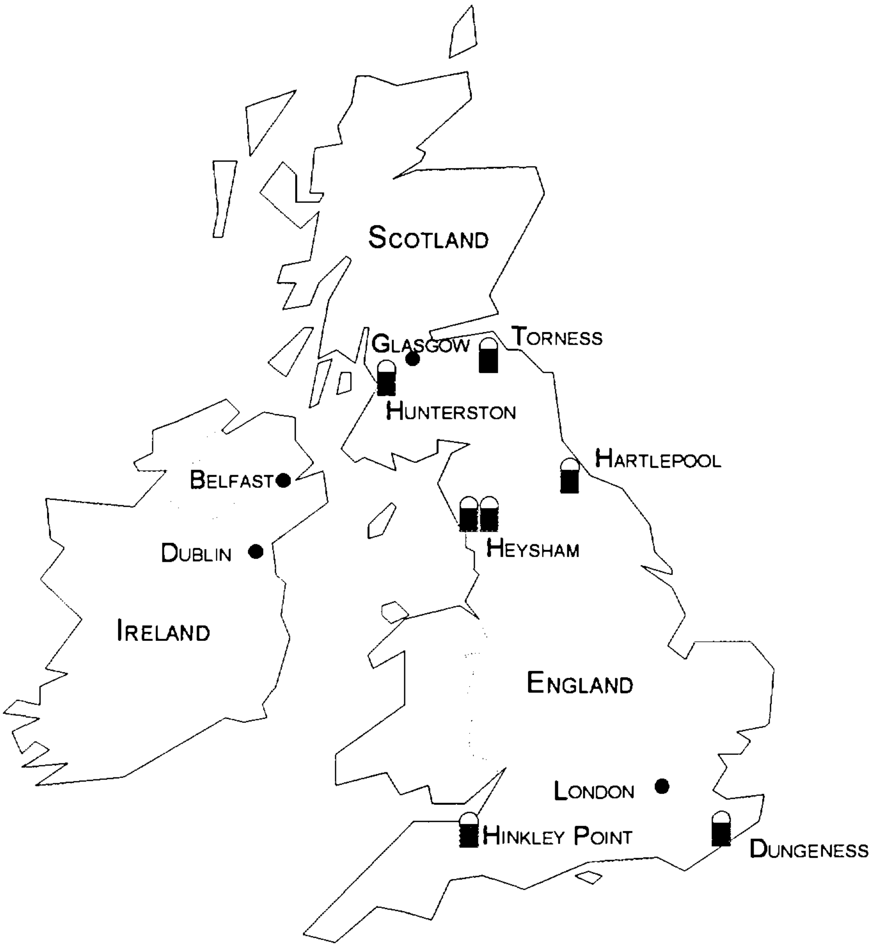


Figure 1.1. AGR stations in Great Britain

Table 1.1. AGR stations in operation.

Station unit	MWe	Generation of AGR	Sister plant	Start of operation
Dungeness B	2 x 660	first	a	1983-85
Hinkley Point B	2 x 660	first	a	1976
Hunterston B	2 x 660	first	a	1976-77
Hartlepool	2 x 660	first*	b	1983-84
Heysham I	2 x 660	first*	b	1983-84
Heysham II	2 x 660	second	c	1988
Torness	2 x 660	second	c	1988
Total number of AGR units : 14 at 6 sites and 7 stations				

2 Summary of design data

In Table 2.1 a summary of the main design data for Torness AGR nuclear power station is shown. All data applies to a single unit of the twin-reactor station.

Table 2.1. Summary of design data for Torness AGR nuclear power station

Station design		
Reactor type	AGR	Advanced Gas Cooled
Electrical output (gross)	2 x 660	MWe
Thermal output (gross)	2 x 1623	MWt
Efficiency	40.7	%
Heat balance		
Power to turbine	1649	MW
Power loss to vessel liner cooling system	8.5	MW
Power loss to circulator cooling system	4.5	MW
Power loss to gas treatment plant	3.0	MW
Total heat to gas	1665	MW
Pumping power	42	MW
Power from reactor	1623	MW
Reactor		
Moderator	Graphite	
Coolant gas	CO_2	
Number of fuel channels	332	
Lattice pitch (square)	460	mm
Active core diameter	9.5	m
Active core height	8.3	m
Number of control rod channels	89	
Diameter of control rod channels	127	
Mean gas pressure	41	bar
Mean inlet gas temperature	339	°C
Mean outlet gas temperature	639	°C
Peak channel outlet temperature	661	°C
Total gas flow	4067	kg/s
Peak channel flow	14	kg/s
Average channel flow	12	kg/s

Table 2.1 continued

Fuel elements		
Material	UO_2	
Type	36 pin cluster	in graphite sleeve
Pellet diameter	14.5	mm
Inner graphite sleeve diameter	190	mm
Channel diameter	264	mm
Cladding material	Stainless steel	
Cladding thickness	0.38	mm
Element length	1036	mm
Number of elements per channel	8	
Enrichment	2.2 - 2.7	%
Power density	3	kW/litre
Mass of uranium per reactor	123	tonnes
Average fuel rating	13.65	MWt/tU
Average fuel burn-up	18,000	MWd/tU
Pressure vessel		
Material	Pre-stressed	concrete
Inner liner	Stainless steel	
Internal diameter	20.3	m
Internal height	21.9	m
External diameter	31.9	m
Top slap thickness	5.4	m
Bottom slap thickness	7.5	m
Design pressure	45.7	bar
Gas circulators		
Type	Centrifugal	
Regulation	Constant speed	variable inlet vanes
Number circulators	8	
Power consumption per reactor	42	MWe
Boilers		
Number of boilers	4	
Number of units per boiler	3	
Feedwater temperature	158	°C
Gas inlet temperature to reheater	619	°C
Gas outlet temperature	293	°C
Superheater outlet pressure	173	bar
Superheater outlet temperature	541	°C
Steam generation	525	kg/s
Reheater outlet pressure	42	bar
Reheater outlet temperature	539	°C

Table 2.1 continued

Turbine plant		
High pressure turbine:		
Number of flows	1	
Inlet pressure	167	bar
Inlet temperature	538	°C
Outlet temperature	344	°C
Intermediate pressure turbine:		
Number of flows	2	
Inlet pressure	41	bar
Inlet temperature	538	°C
Low pressure turbine:		
Number of flows	4	
Number of feedwater heaters	4	
Feedwater pump driven by steam		
Generator:		
Stator coolant	Water	
Rotor coolant	Hydrogen	
Voltage	23500	V

3 Site and region

3.1 Selection of the site

Torness is on the Lothian coastline, about 60 km east of Edinburgh, Figure 3.1. The site has good ground conditions capable of supporting heavy loads, ample supplies of sea water for cooling purposes, good road and rail access and is supplied with fresh water from Lothian Regional Council.

The location of this base load plant in the east of the County provides a good geographical match between generating capacity and demand, and minimises the need for additional transmission.

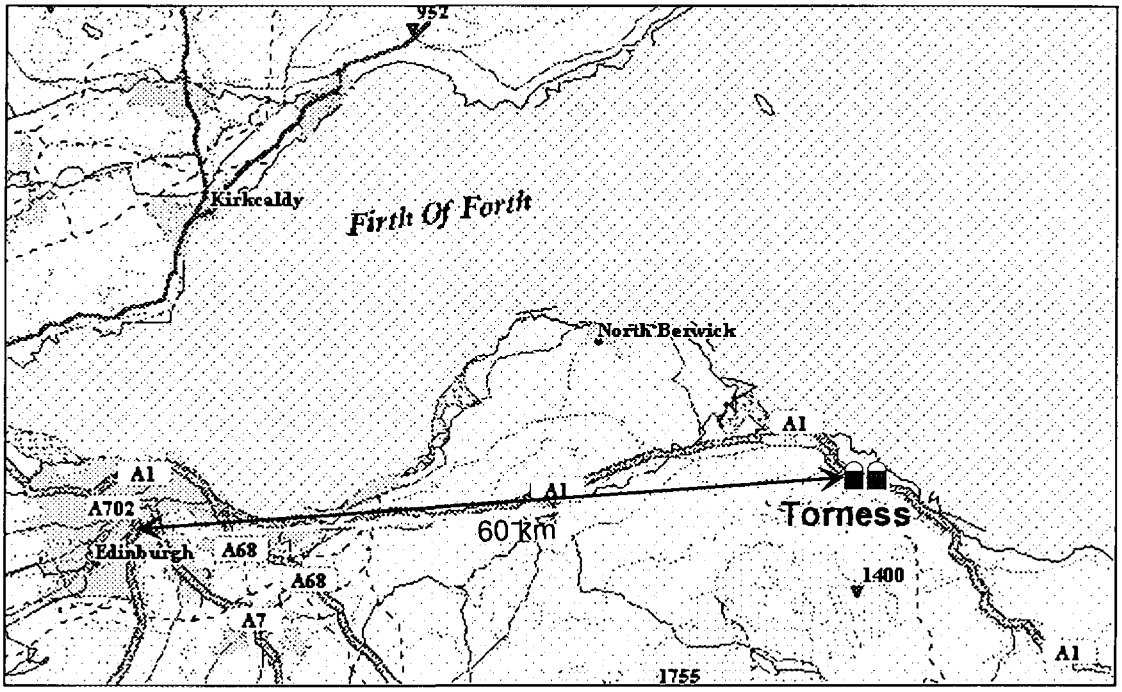


Figure 3.1. Site of Torness Nuclear Power Station.

Site work on Torness power station started in February 1977, with main construction following in 1980. The first of the twin-station units was synchronised to the Scottish grid in May 1988 and the second in February 1989, giving a total generating capacity of 1320 MWe.

4 Safety criteria

A primary concern for the UK nuclear programme has been to assure, that neither the public or the personnel at nuclear power stations are exposed to harmful radiation. The policy for achieving these objectives embodies certain fundamental principles, of which some of the main features are:

- As the result of normal operation of a power station, no person shall receive doses of radiation in excess of the appropriate limits.
- The exposure of individuals shall be kept as low as reasonable practicable.
- The collective dose-equivalent to operators and the general public as a result of the operation of a nuclear installation shall be kept as low as reasonably practicable.
- All reasonably practical steps shall be taken to prevent accidents.
- All reasonably practical steps shall be taken to minimize the radiological consequences of any accident.

Safety requirements are an important factor in the design, manufacture, construction and operation of the nuclear power plants and they shall assure defence in depth.

The first line of defence is high quality in design and manufacture of components and equipment so that the plant will operate reliably, and operation of the plant by highly trained staff.

The second line of defence is a reactor design which assumes that if faults occur, then instrumentation and control systems will automatically bring the reactor to a safe shutdown condition. Duplication or triplication of safety equipment is provided where appropriate, and it is designed to "fail safe", so that if faults develop, the reactor is shut down automatically.

The third line of defence is the examination of a whole range of extreme accidents or unlikely faults, which could point to the need of additional safety features. These safety features could be extra emergency cooling systems, or additional electricity supplies.

5 Technical description and design evaluation

5.1 Plant arrangement

In an AGR nuclear power station, there are two reactor units and one turbine house combined in a single complex with a central block for fuel handling, instrumentation and control, a so-called twin-station. The reactors are served by one refuelling machine operating within a common charge hall. The principle components of a typically AGR system are shown in Figure 5.1.

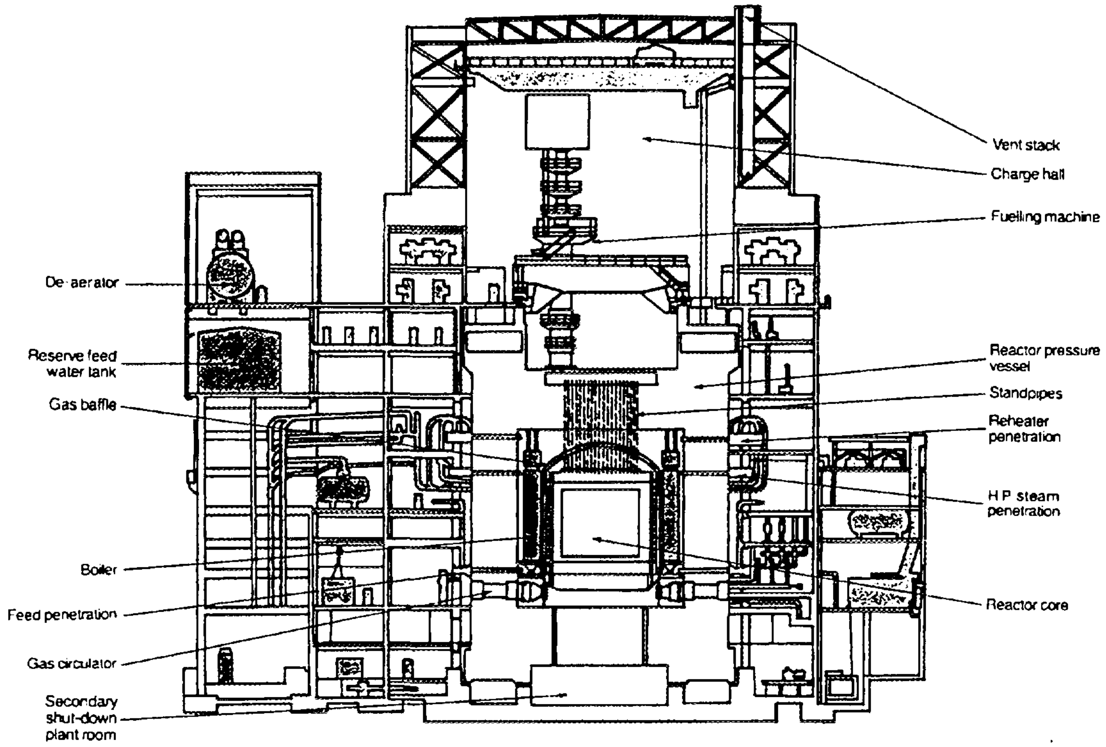


Figure 5.1. Components of a typically AGR nuclear power station.

5.2 Buildings and structures

In Figure 5.2 is shown the site layout of buildings and structures of the Torness Plant. The reactor building is a reinforced concrete construction topped by the charge hall superstructure of steel portal frames to a height of 74 metres above ground level.

There are four supplies buildings, housing diesel generators and switchgear. These buildings together with the reactor building are designed to withstand seismic loads. The four buildings are located close to but separate from the reactor building to provide maximum segregation.

The reactor building also houses the high level de-aerators, reserve feed water tanks and the high pressure steam and feed pipework. The station control room is also within the reactor building, and turbine hall is a continuation of this building but with a lower roof

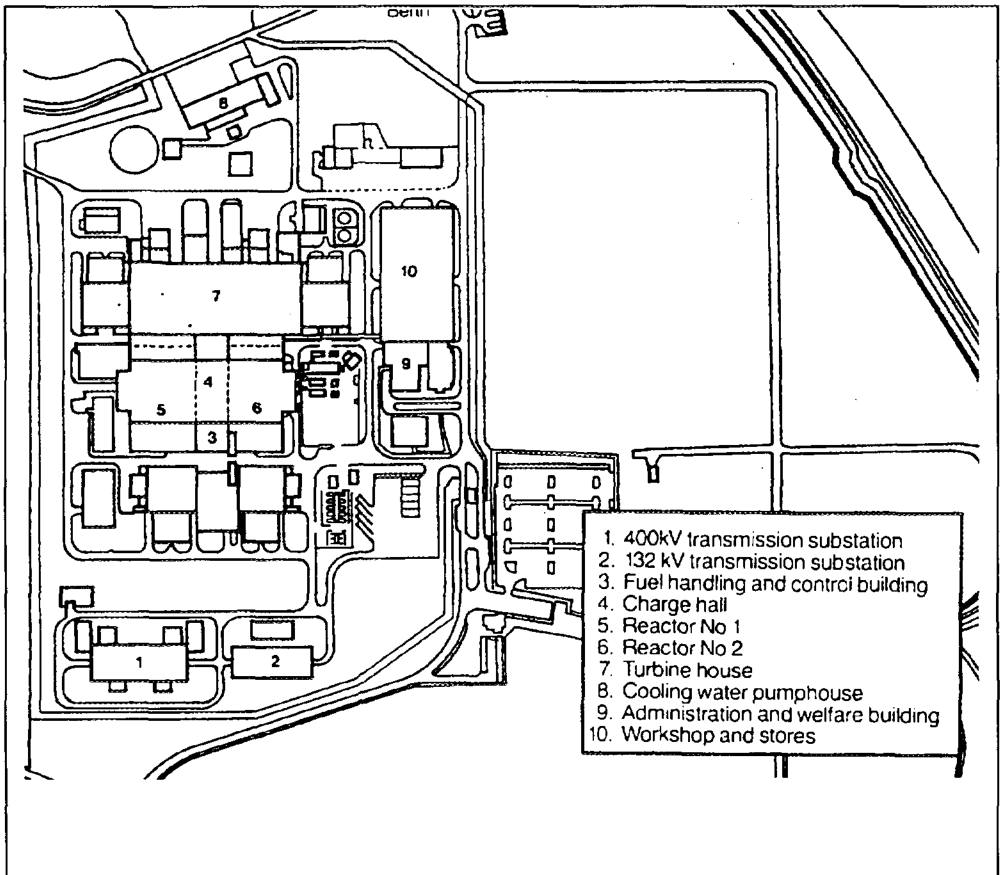


Figure 5.2. Layout of building structures

level. It contains the turbine generators and associated auxiliary plant, and the condensate and feedwater treatment plant. The circulating water pump house is a reinforced concrete and steel structure located to the north of the reactor and turbine hall buildings. It houses the four main circulating water pumps and eight reactor cooling pumps. Between the pumphouse and the sea is an area containing four drums which filter the inlet sea water.

Major features of the plant construction include the lifting-in of the gas baffle enclosing the core and liner roof assembly, installing the reactor and boiler components and the two 700 MWe turbine generators, laying about 53 000 cables for power, control and instrumentation, and constructing a 400 kV transmission substation.

5.3 Reactor core and other reactor vessel internals

Figure 5.3 shows the main components of the reactor.

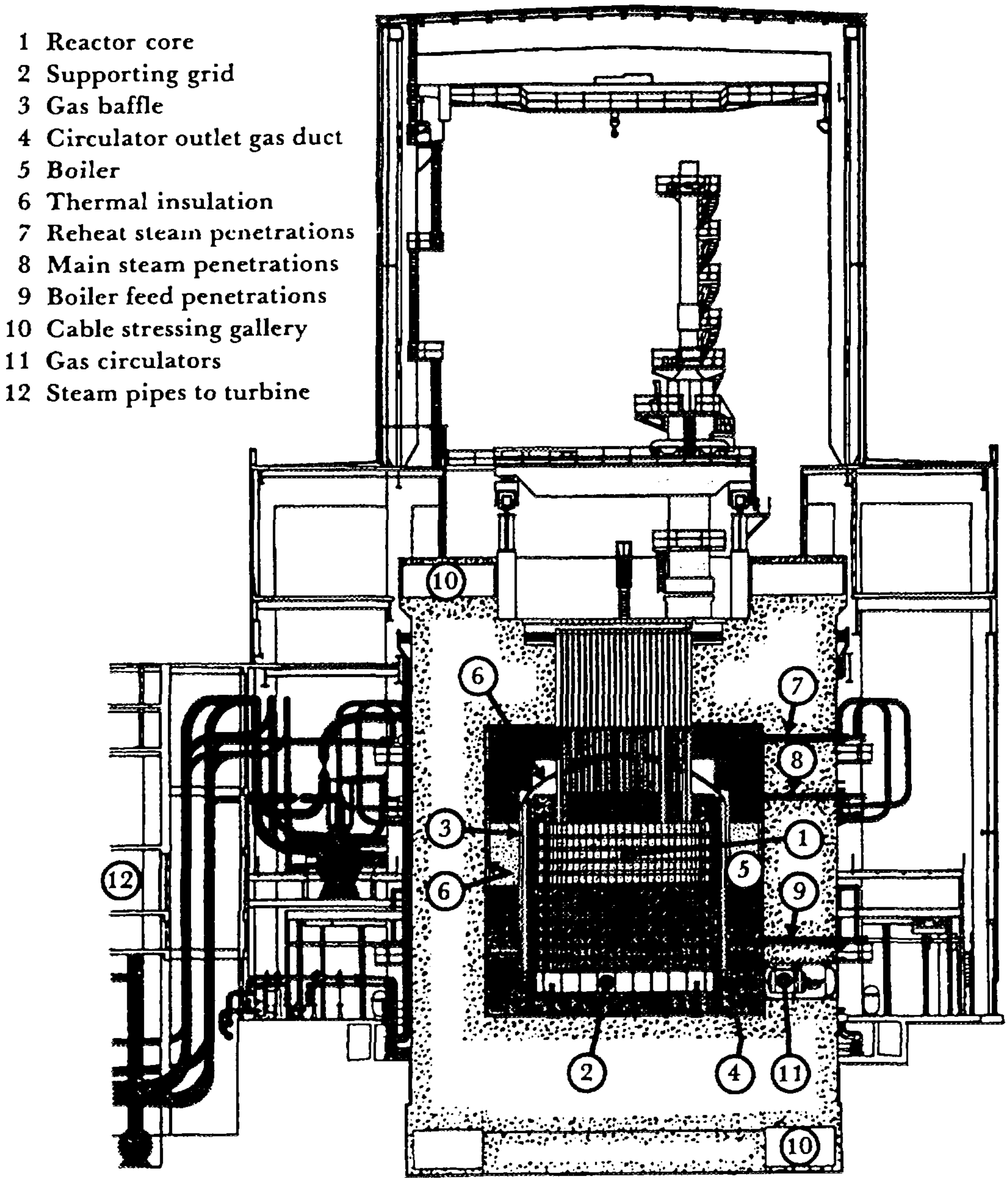


Figure 5.3. Main components of reactor.

5.3.1 Mechanical design

In a typical AGR system, the reactor core, boilers and gas circulators are housed in a single cavity, pre-stressed concrete pressure vessel. The reactor moderator is a sixteen-sided stack of graphite bricks. It is designed to act as a moderator and to provide individual channels for fuel assemblies, control devices and coolant flow (Figure 5.3 and Table 5.1).

Table 5.1. Design data for pressure vessel.

Material	Pre-stressed concrete
Inner liner	Stainless steel
Internal diameter	20.3 m
Internal height	21.9 m
External diameter	31.9 m
Top slap thickness	5.4 m
Bottom slap thickness	7.5 m
Design pressure	45.7 bar

The graphite is covered by an upper neutron shield of graphite and steel bricks and mounted on a lower neutron shield of graphite bricks, that rests on steel plates. Radial shielding is in the form of steel rods located in two outer rings of graphite bricks. The graphite structure is maintained in position by a steel restraint tank that surrounds the graphite and is supported on a system of steel plates.

The shielding reduces radiation levels outside the core, so that when the reactor is shut down and depressurized, access to the boilers is possible.

There are two main effects of irradiation of the graphite moderator. One is dimensional change and the other is radiolytic oxidation by the carbon dioxide coolant. There will also be a significant change in the thermal conductivity, which decreases with an increasing temperature. Because of the relatively high temperatures in the core, there will be little or no stored energy in the graphite (Wigner energy).

The dimensional change due to the anisotropic properties of graphite is reduced by manufacturing the graphite bricks by use of moulding rather than extrusion.

When CO_2 is radiolysed it breaks down giving CO and a very reactive chemical species which behaves like an oxygen atom

$$CO_2 \rightarrow CO + \text{“O”} \qquad \text{(radiolytic)}$$

Most of these species recombine in the gas phase

$$\text{“O”} + CO \rightarrow CO_2$$

However, some of them will escape recombination in this way - the mean distance that the active species can travel before undergoing reaction is slightly greater than the mean pore diameter of the graphite - and will reach the graphite surface where they will react:

$$\text{“O”} + C \rightarrow C(O) \qquad \text{(graphite surface reaction)}$$

where C(O) is a surface oxide. This will subsequently break loose to give gaseous CO. The consequences of the process is a weight loss of the graphite. However, only that gas contained in the pores of the graphite takes part in the reaction, the bulk of the gas in the reactor circuit is not involved.

The criterion adopted for the maximum permissible mean weight loss of graphite has been set to 5 % over a 30 years lifetime.

Radiolytic oxidation is inhibited by adding methane to the coolant. However, methane in high concentrations can lead to carbon depositions, in particular on the fuel assembly surfaces. Therefore, a compromise between protection of the moderator and deposition on the fuel must be made by a careful choice of the concentration of the inhibitor.

The core and the shield are completely enclosed by steel envelope called the gas baffle, the main function of which is to produce a downward flow of coolant gas (re-entrant flow) through paths in the graphite moderator to cool the graphite bricks and to separate the hot from the cold gas (Figure 5.4).

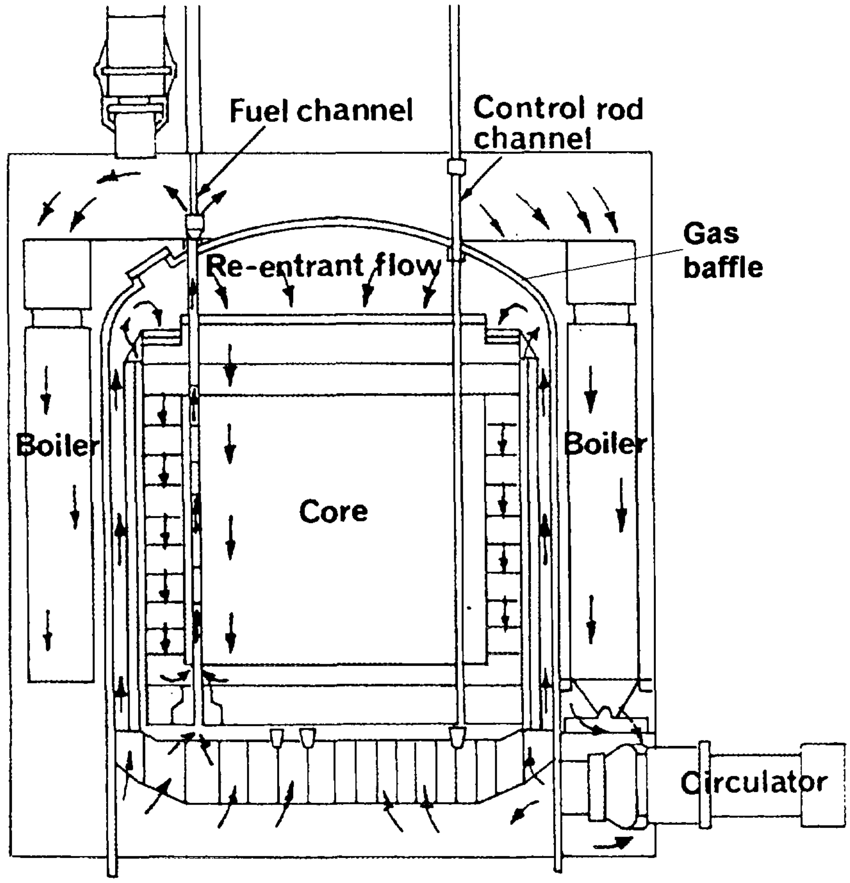


Figure 5.4. Gas baffle with gas flow paths.

The gas baffle has three main sections - the dome, the cylinder and the skirt. In the doom there are a number of penetrations - one for each of the fuel channels in the graphite moderator. Between the penetrations and the tops of the channels, system of guide tubes provide the paths for the fuel assemblies and the control rods. The skirt forms the lower part of the gas baffle cylinder.

The core and the radiation shields are supported on a structure called the diagrid, which itself forms an integral part of the gas baffle. This diagrid is designed to carry the weight of the reactor core and to accommodate the thermal movements which arise from coolant temperature variations during normal operating and in the case of incidents.

5.3.2 Nuclear design

Reactor core
The main design data for the reactor core is shown in Table 5.2.

Table 5.2. Main design data for the core.

Moderator	Graphite
Coolant gas	CO_2
Number of fuel channels per reactor	332
Number of control rods	89
Lattice pitch (square)	460 mm
Active core diameter	9.5 m
Active core height	8.3 m
Power density	3.0 kW/litre
Mean inlet gas temperature	339 °C
Mean gas outlet temperature	639 °C
Peak channel outlet temperature	661 °C
Total gas flow	4067 kg/s
Peak channel flow	14 kg/s

The reactor moderator is a sixteen-sided stack of graphite bricks. The bricks are interconnected with graphite keys to give the moderator stability and to maintain the vertical channels on their correct pitch, despite dimensional changes due to irradiation, pressure loads and thermal stresses (Figure 5.5).

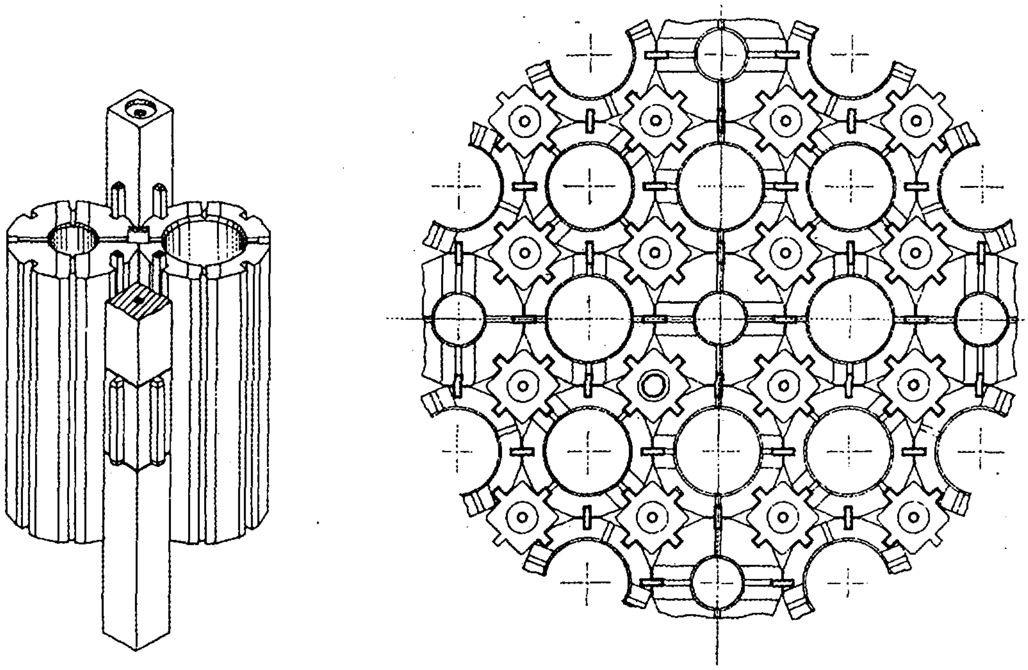


Figure 5.5. Interconnection of graphite bricks with keys.

The complete reactor core consists of an inner cylinder of graphite moderator containing 332 fuel channels. It is surrounded by a graphite reflector and a steel shield. The graphite structure is maintained in position by a steel restraint tank which surrounds the graphite and which is supported on a system of steel plates (Figure 5.3).

The primary system for control and shutdown of the reactor consists of 89 absorber rods and drives housed in standpipes in the top part of the reactor vessel. The control rods are located in interstitial positions, i.e. in off-lattice positions (Figure 5.6).

As a back up against the extremely remote possibility of a fault in the primary system which will prevent a substantial number of control rods from entering the core when required, a secondary shutdown and hold-down system is provided. The secondary shutdown system comprises 163 interstitial core channels into which nitrogen can be injected from beneath the core (Nitrogen absorbs neutrons to a much greater extent than carbon dioxide). Gradually the nitrogen flows from the interstitial channels into the re-entrant passages and through the fuel channels. Thus, a nitrogen concentration is building up in the coolant gas circuit until it is sufficient to hold the reactor in a shutdown condition.

The store of nitrogen, which consists of banks of high pressure cylinders, is common to both reactor units. It holds sufficient nitrogen gas for the shutdown and subsequent hold down one reactor, provided the reactor remains pressurized. Thus a fast shutdown is achieved.

Further more, a boron bead injection system is also provided in 32 of the 163 interstitial channels designed to give long-term-hold-down capabilities in the extremely unlikely situation where an insufficient number of control rods have been inserted into the core and depressurization of the core is required; in this case the pressure of the nitrogen injection system cannot be maintained.

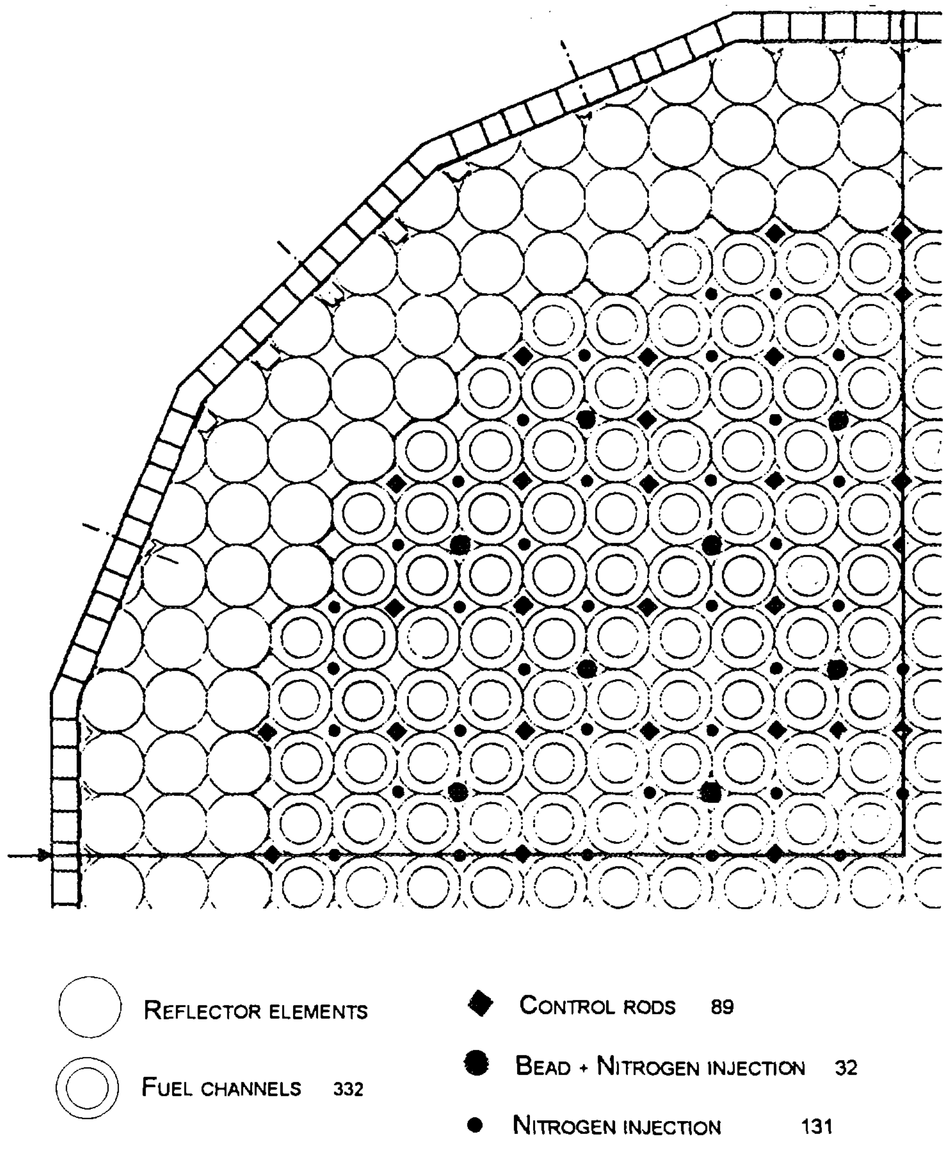


Figure 5.6. Core layout - nearly 1/4 core symmetry.

Fuel assemblies
The main design data for fuel assemblies are shown in Table 5.3.

The fuel in AGR's consists of slightly enriched UO_2 in the form of cylindrical pellets with a central hole. These are contained within stainless-steel cladding tubes, each of which is about 900 mm long. A fuel element consists of 36 fuel pins surrounded by two concentric graphite sleeves. The fuel pins are supported by top and bottom grids which are fixed to the outer graphite sleeve (Figure 5.8 and Figure 5.9). The possible bowing of the pins is limited by support braces. The support grids, braces, and inner sleeves are secured in position by a screwed graphite retaining ring at the top. The complete unit forms a fuel element (Figure 5.7). Eight of these fuel elements are linked together with a tie bar to form a fuel stringer assembly. Each of the 332 fuel channels is provided with a fuel stringer assembly.

Table 5.3. Main design data for fuel elements.

Material	UO_2	
Type	36 pin cluster	in graphite sleeve
Pellet diameter	14.5	mm
Inner graphite sleeve diameter	190	mm
Cladding material	Stainless steel	
Element length	1036	mm
Number of elements per channel	8	
Number of channels	332	
Enrichment	2.2 - 2.7	%
Mass of uranium per element	44	kg
Average fuel rating	13.65	MWt/tU
Average fuel burn-up	18,000	MWd/tU

The function of the double sleeve in the fuel element is to provide a static gas gab between inner and outer sleeve to reduce leakage of heat from the hot coolant to the graphite moderator.

The fuel stringer assembly and its associated plug unit form a composite fuel assembly that is handled by the fuelling machine and loaded into the reactor as one unit. Since it is important that the cladding exhibit good heat transfer properties, the cladding is provided with small transverse ribs on the outer surface (Figure 5.8), and is compressed onto the pellets during manufacture to minimize the clearance gab between pellet and cladding. The remaining space is filled with helium, an inert gas with good heat-conducting properties.

The reactor has to single channel access, i.e. each channel is extended upwards with its own separate opening in the concrete vessel. This permits the gas temperature in each channel to be measured and to adjust the flow of gas coolant remotely.

Finally it permits refuelling both when the reactor is on and off load and for any pressure from atmospheric to normal operating pressure, by a fuelling machine that handles complete fuel assemblies from the top of the vessel.

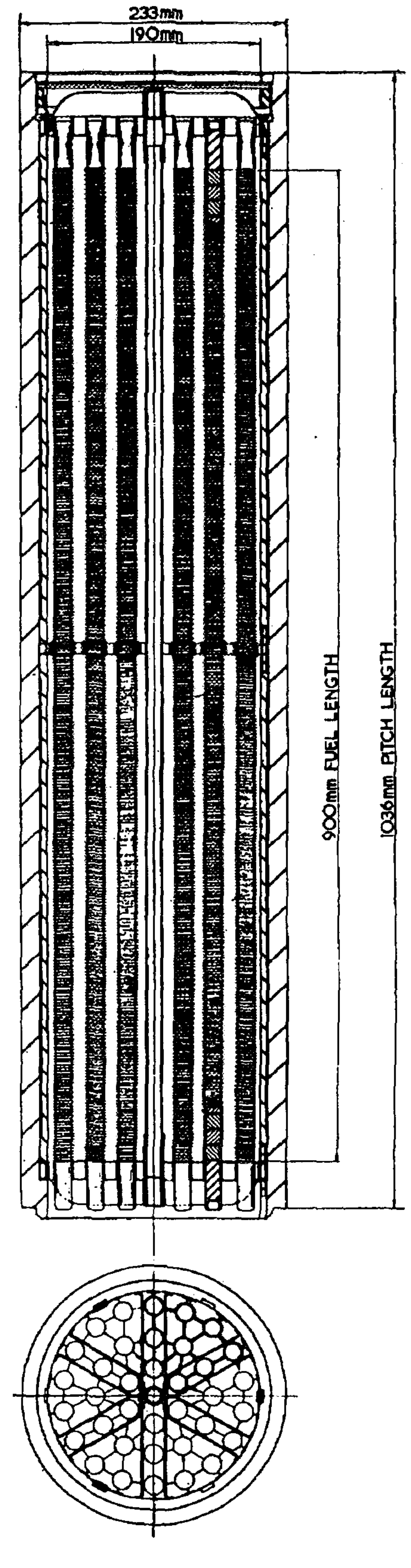


Figure 5.7. Dimensions of an AGR fuel element.

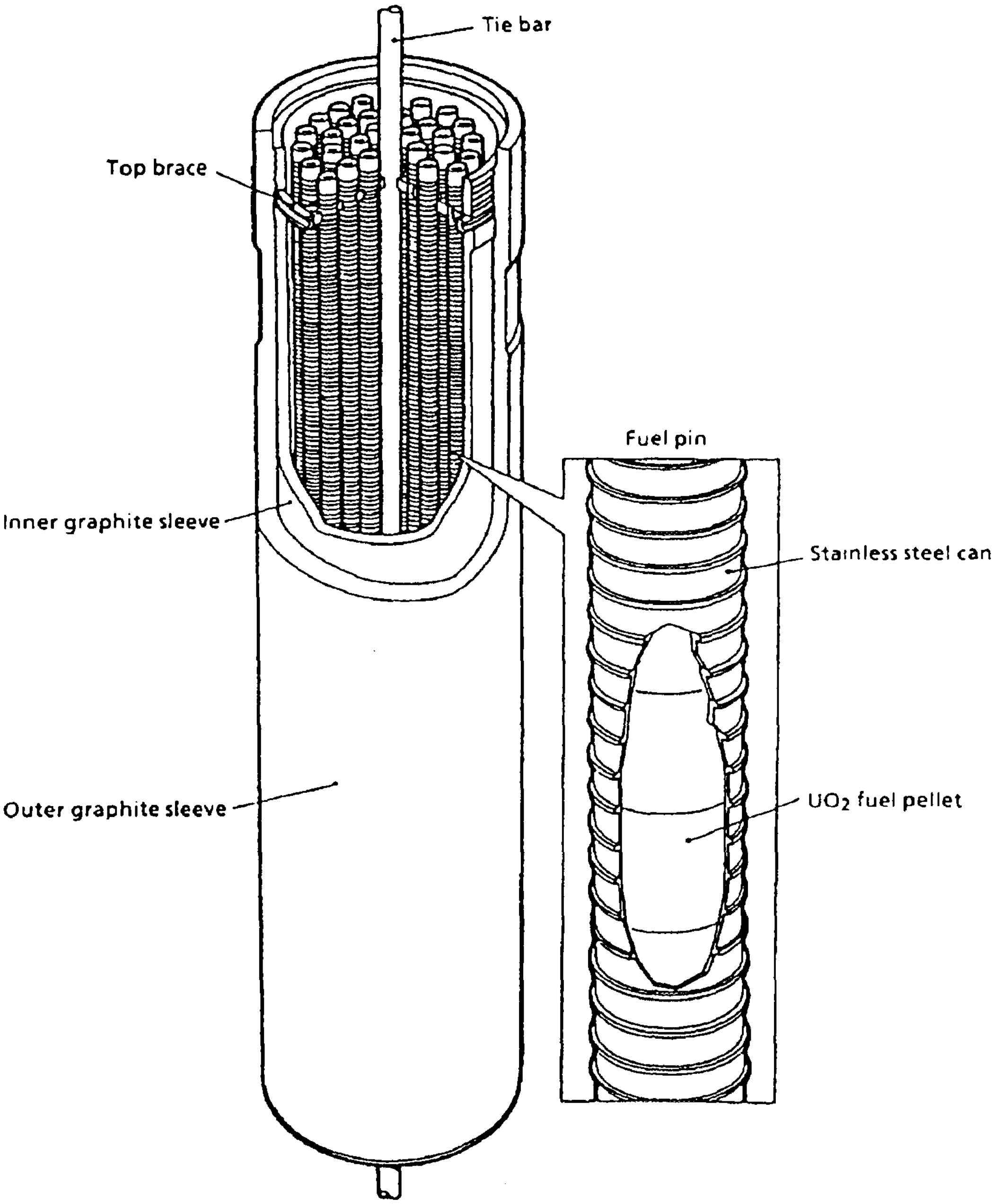


Figure 5.8 AGR fuel element.

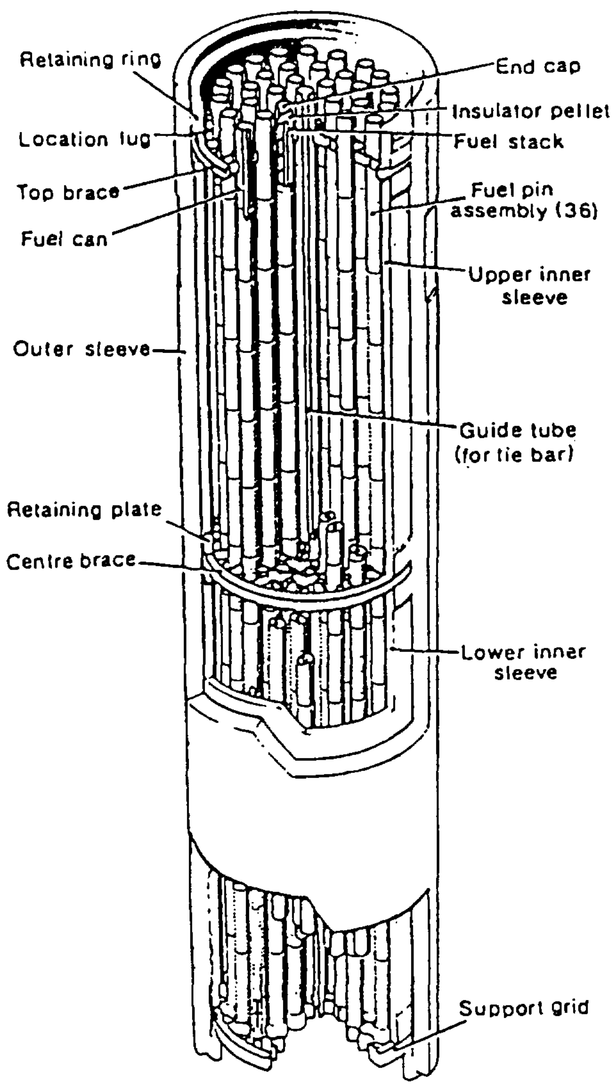


Figure 5.9 Detailed view of AGR fuel element

The fuel assembly plug consists of a closure unit, a biological shield plug, a valve (gag) unit and actuator and a neutron scatter plug. During normal operation, the fuel assembly plug unit acts as the seal of the reactor pressure vessel at each fuel standpipe. They are provided with closure/locking mechanisms, which are operated remotely.

The biological shield plug is designed primarily to limit neutron and gamma-radiation through the standpipe. It consists of two mild-steel blocks joined together by a mild-steel tube. A steel ring loosely mounted on the lower block reduces radiation streaming through the annular gab between the plug and the standpipe liner.

The valve unit is situated in the lower part of the fuel assembly plug. It contains a duct for the hot coolant gas between the fuel stringer assembly and the outlet ports above the gas baffle dome. It includes a flow control valve (gag) for adjustment of coolant flow through the individual channels. The valve is coupled by a shaft passing through the biological shield plug to a motor-driven valve actuator, the basic function of which is to set the valve position. The actuator is operated by remote control from the central control room.

Below the gag unit a neutron scatter plug is located to prevent neutrons streaming up the channel. The tie bar, attached to the top of the gag unit carry both that unit and the fuel stringer assembly during refuelling operations.

Fuel handling

Access to the reactor for refuelling is provided by standpipes located in the top cap of the reactor pressure vessel, one standpipe for each reactor channel.

One refuelling machine, designed to handle both fuel and control assemblies, serves both reactors. The machine runs on a travelling gantry that spans the width of the charge hall and is supported on rails which run along the full length of the hall, Figure 5.10. This gives the machine access to both reactors and to the central service block. In this block there are facilities for storage of new fuel elements and fuel stringer components and for their assembly into complete fuel assemblies. It also includes facilities for temporary storage and dismantling of irradiated fuel assemblies. The fuel storage pound, used for the longer term storage of irradiated fuel elements, is also located in the central block.

The refuelling machine - essentially a hoist contained within a shielded pressure vessel - is provided with a telescopic snout which can be extended to connect, seal and lock on to a short extension tube fitted to the standpipe being serviced. Within the refuelling machine pressure vessel a three-compartment turret can be rotated to align any of the compartments with the machine snout. One turret tube is for

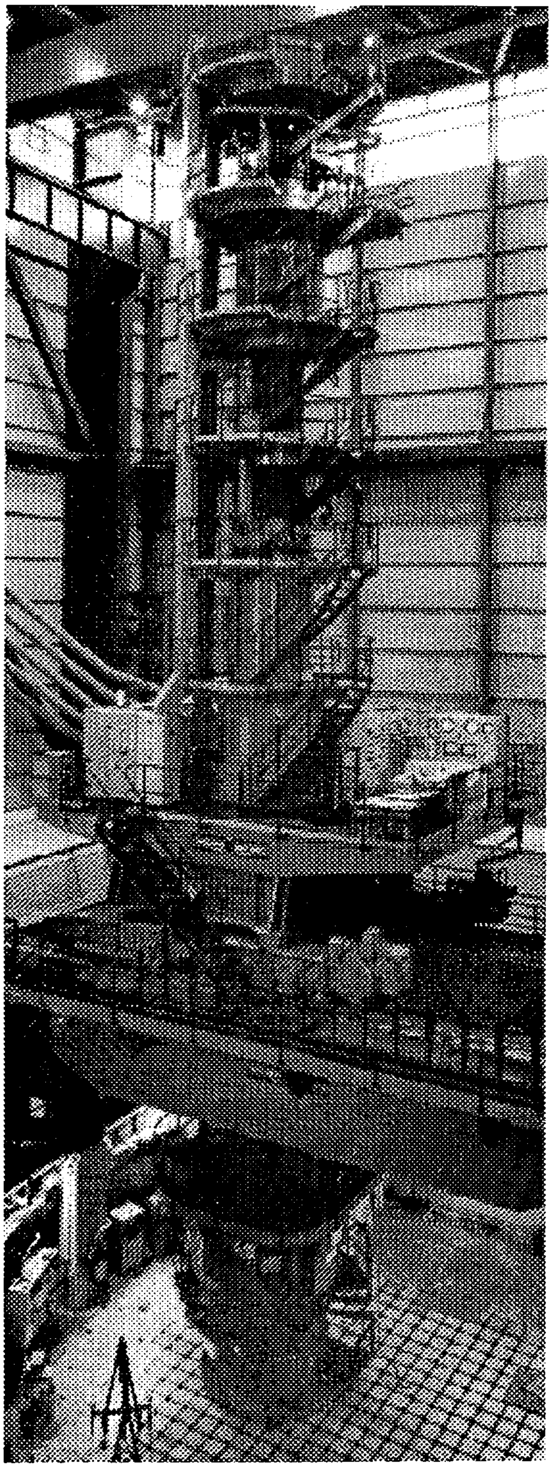


Figure 5.10. Refuelling machine.

withdrawing of used fuel, one carry the new fuel and the last carry a spare plug unit. The top section of the pressure vessel above the turret contains the hoist drive shaft, which passes through seals in the vessel. At the end of the shaft is located the machine grab, suspended in roller chains. The grab is operated electrically by solenoids, and it can be lowered through the turret tube aligned with the machine snout to pick up fuel assemblies.

The movements of the machine and the connections to the standpipes are controlled from a platform at the bottom of the machine, Figure 5.10. All other operations are controlled from a platform on the machine located just above the gantry. The refuelling programme requires about 5 fuel assemblies to be replaced per month.

5.3.3 Thermal and hydraulic design

Carbon dioxide gas is used to transfer the heat produced in the reactor to the boilers. The gas is pumped through the channels of the reactor at high pressure by gas circulators; its main flow paths are shown in Figure 5.11.

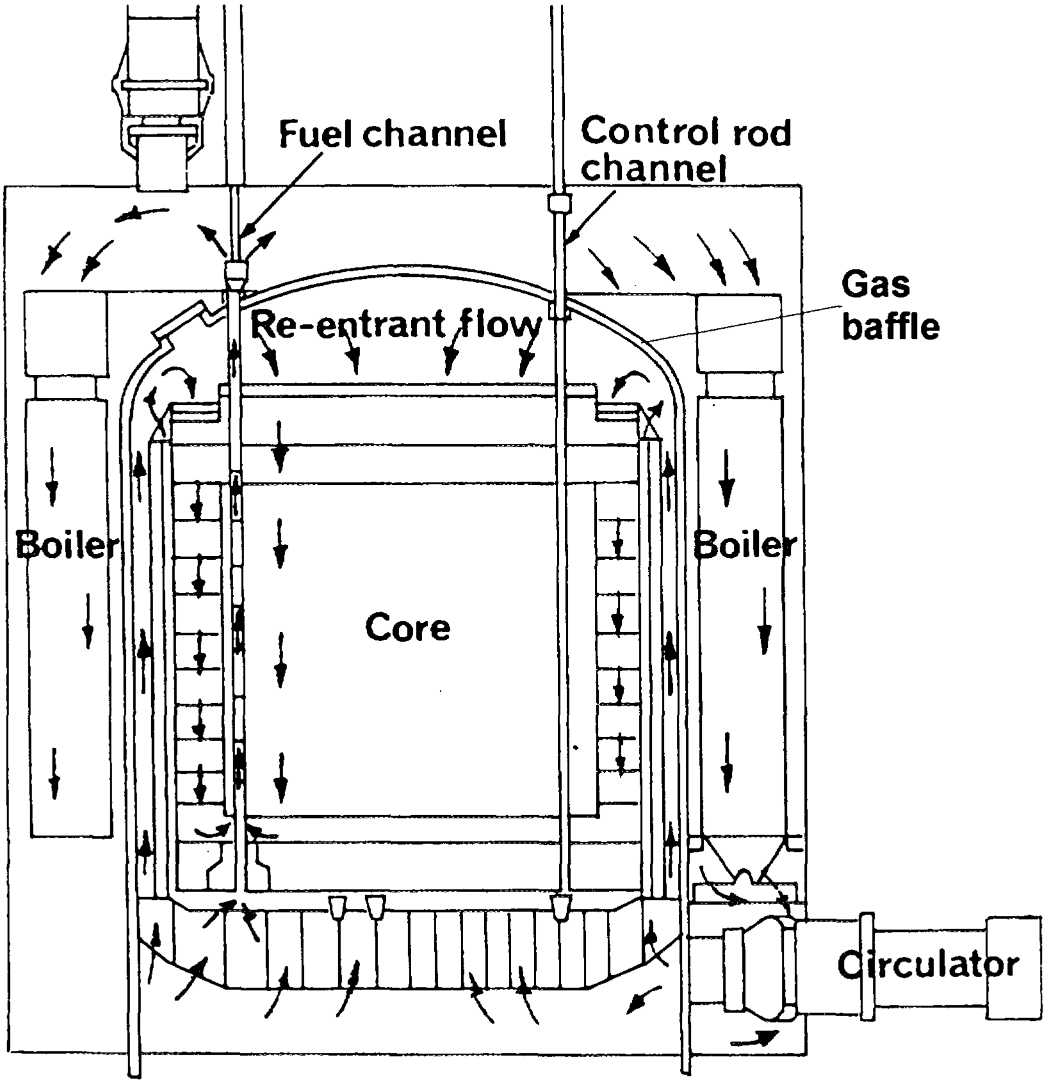


Figure 5.11. Gas flow distribution in the core and vessel.

The gas circulator pumps the cooled gas from the bottom of the boilers and into the space below the core. About half of this gas flows directly to the fuel channel inlets, while the remainder, known as the re-entrant flow, passes up through the annulus surrounding the core along the inner surface of the gas baffle to the top baffle. It returns downwards through passages between the graphite moderator and the graphite sleeves of the fuel elements to rejoin the main coolant flow at the bottom of the fuel channels. (Probable some kind of orifice is used at the bottom of the fuel channels to split the gas flow into the re-entrant flow and the fuel channel flow).

The re-entrant flow thus cools the graphite bricks, the core restraint system and the gas baffle. The combined flow passes up the fuel channels and through the guide tubes. Then the hot gas flows into the space above the gas baffle and down through the boilers, where it is cooled, before re-entering the gas circulators below the boilers.

The main reason for the re-entrant flow from the top of the core to the bottom is to keep the moderator temperature below 450° C to avoid excessive thermal oxidation of the graphite bricks, and to limit temperature gradients within a brick to about 50° C. This is most economically achieved by a re-entrant coolant flow, in which part of the coolant will pass downwards between the bricks before entering the bottom of the fuel channels. However, it does complicate the internal layout of the plant within the pressure vessel vault by necessitating a gas baffle around the core.

Fuel element guide tubes, located at the top of each channel, are used to duct the hot gas through the space below the gas baffle before it is discharged into the space above.

The core and the surrounding graphite reflector and shield are completely enclosed in the gas baffle which has a diameter of 13.7 and which is provided with a torispherical head. The baffle has to withstand the full core pressure differential of 1.9 kg/cm^2, and its temperature is kept down to 325° C by insulation on the topside so that mild steel can be used.

In Table 5.4 are shown a heat balance scheme for a typical AGR plant.

Table 5.4. Heat balance for an AGR plant.

Power to turbine	1649 MW
Power loss to vessel liner cooling system	8.5 MW
Power loss to circulator cooling system	4.5 MW
Power loss to gas treatment plant	3.0 MW
Total power to gas	1665 MW
Pumping power	42 MW
Power from reactor	1623 MW

5.4 Reactivity control system

The primary system for control and shutdown of the reactor consists of 89 absorber rods and drives housed in standpipes in the top cap of the reactor vessel. 44 of these are black rods (Figure 5.12) of which 7 act as sensor rods for detecting any guide tube misalignment that may occur between the graphite moderator and the steel structures above it. The remaining 45 absorber rods are grey regulating rods, of which 16 are used as a safety group. This safety group can be moved out of the core when the reactor is shut down so that it can be moved into the core in case of an inadvertent criticality.

Each black rod consists of eight cylindrical sections linked together by joints.

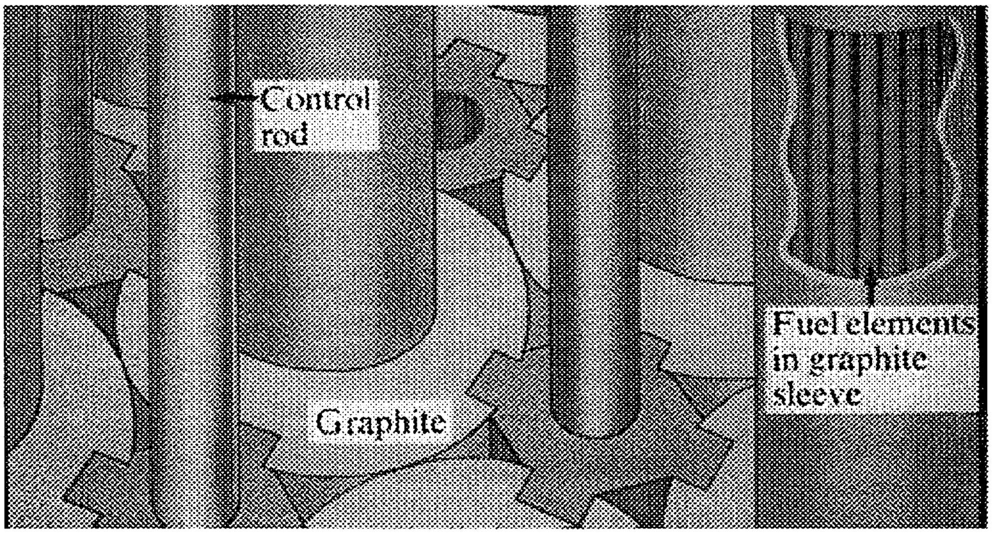


Figure 5.12. AGR control rod.

Each of the lower six sections consists of a 9 % Cr, 1 % Mo steel sheath containing four tubular inserts of stainless steel with a 4.4 % boron content to ensure blackness to thermal neutrons. Between the tubular inserts are two solid, cylindrical, graphite inserts to reduce neutron streaming.

The upper two sections, which form part of the top reflector when fully inserted, contain full-length, solid graphite inserts only.

The 45 grey regulating rods are of a design similar to the black rods. However, the lower six sections contain tubes of stainless steel without boron, but with graphite inserts arranged as in the black rods.

The control assembly consists of a control rod, a control plug unit, a control rod actuator and standpipe closure unit and its housing. The complete control assembly is designed for removal by the refuelling machine both when the reactor is operating and when it is shut down.

The control plug unit is designed to reduce to acceptable levels radiation streaming from the core through the standpipe penetrations in the vessel roof. It consists of a steel plug with a central hole through which passes the control rod suspension chain.

The control rod actuators raise or lower the control rods. Each actuator is provided with motor operated winding gear and suspension chain storage, electromagnetic clutch, hand winding drive to the clutch, rod position indicator and limit switches. The actuator and rod drive is designed for frequent small movements. The control rod speed is controlled by regulating the electricity supply to the induction motor. In the event of a reactor trip, the clutch is de-energized to allow rod insertion by gravity. The insertion rate is controlled by a carbon disc brake.

5.4.1 Secondary shutdown system

As a backup against the extremely remote possibility of a fault in the primary system preventing a substantial number of control rods from entering the core when required, two secondary shutdown and hold-down system are provided.

Fast shutdown is achieved by a system that automatically injects nitrogen from beneath the core into 163 interstitial core channels. Nitrogen absorbs neutrons to a much larger extent than carbon dioxide. The nitrogen storage arrangements is designed to provide nitrogen injection in two stages. When the trip valves are opened, a high initial nitrogen flow rate is provided by the first stage storage. This initial flow purges the 163 interstitial channels of carbon dioxide and fills them with nitrogen. Flow from the second stage provide make-up to each channel as the nitrogen flows from the channels into the re-entrant passages and through the fuel channels, thus gradually building up the nitrogen concentration in the coolant gas circuit until it is sufficient to hold the shutdown core in a sub-critical condition for several hours.

A boron bead injection system is also provided designed to give long-term hold-down in the extremely unlikely situation where an insufficient number of rods have been inserted into the core and when the reactor is depressurized, whereby the nitrogen pressure is reduced.

Boron glass beads with a diameter of 3 mm are injected into 32 of the 163 secondary shutdown channels. Each of these channels has an associated bead delivery pipe, with one end terminated at the top of the channel and other end connected to one of the bead storage hoppers. CO_2 gas is used to inject the beads pneumatically from the bottom of the hopper to the top of the channel. The beads run downwards into the channel from the open end of the delivery pipe until the channel is filled.

Bead delivery is initiated by the manual operation of valves situated adjacent to the hoppers. Key interlocks control the valve operation sequence, while additional locks prevent unauthorized release of the beads. This system holds the reactor in a shutdown condition indefinitely.

5.5 Reactor main coolant system

5.5.1 Reactor coolant piping

Carbon dioxide gas is used to transfer heat from the reactor to the boilers. The gas is pumped through the channels of the reactor by gas circulators at a pressure of about 40 bar; its main flow paths have been described in section 5.3.3.

5.5.2 Reactor coolant pumps

Gas circulators

Each reactor has 8 gas circulators driven by induction motors, Figure 5.13. Each circulator, complete with motor and control gear, is a totally closed unit located in a horizontal penetration at the bottom of the reactor pressure vessel.

In addition to its normal duties, the circulator unit, its mounting system and shaft labyrinth act as a secondary containment system, should the penetration closure fail. The mounting system is pre-tensioned to provide nominally constant loading of the motor stator frame under all operating and fault conditions leading to depressurization.

The motor is provided with a variable frequency power supply to enable operation at lower speeds especially at reactor trips. If a reactor trip occurs, the blower speed drops to 450 rev/min, but increases automatically to 3000 rev/min in the case of accidental de-pressurization of the reactor.

The normal regulation of the flow is via variable inlet guide vanes, which also control the reverse flow when the pump motor has stopped.

Table 5.5. Design data for gas circulators.

Type	Centrifugal
Regulation	Constant speed/variable inlet vanes
Number per reactor	8
Power consumption per reactor	42 MW

The reason for the use of a totally enclosed gas circulator design is partly to make swift removal and replacement of circulator units with a minimum loss of reactor output possible and partly to avoid the high pressure, rotating, oil-fed gas seal which has been used so far on circulators for Magnox reactors.

The complete gas circulator assembly with motor, impeller, and guide vanes (Figure 5.13), can be withdrawn and sealed off from the reactor circuit while the reactor is at pressure. After the internal seal is made operational, the outer pressure casing may be removed and the gas circulator replaced.

CO_2 supply
A carbon dioxide supply system is located on site. Its purpose is to provide storage capacity for liquid carbon dioxide and supplies of gaseous carbon dioxide for each reactor, the refuelling machine and auxiliary plant facilities during normal operation and fault conditions. The composition of the gas coolant is maintained within defined operational limits by the reactor coolant processing system. A fraction of the reactor coolant flow is passed continuously through the processing plant and after treatment is returned to the main coolant circuit at a circulator inlet, the circulator providing the driving force.

The plant is also provided with a reactor coolant discharge system for the controlled discharge of contaminated gas from the reactor and associated equipment. It comprises

- The reactor vessel blowdown and purge system - one per reactor
- The auxiliary blowdown system - one per station
- The reactor vessel safety relief-valve system - two per reactor

and will be described in section 5.8 of the report.

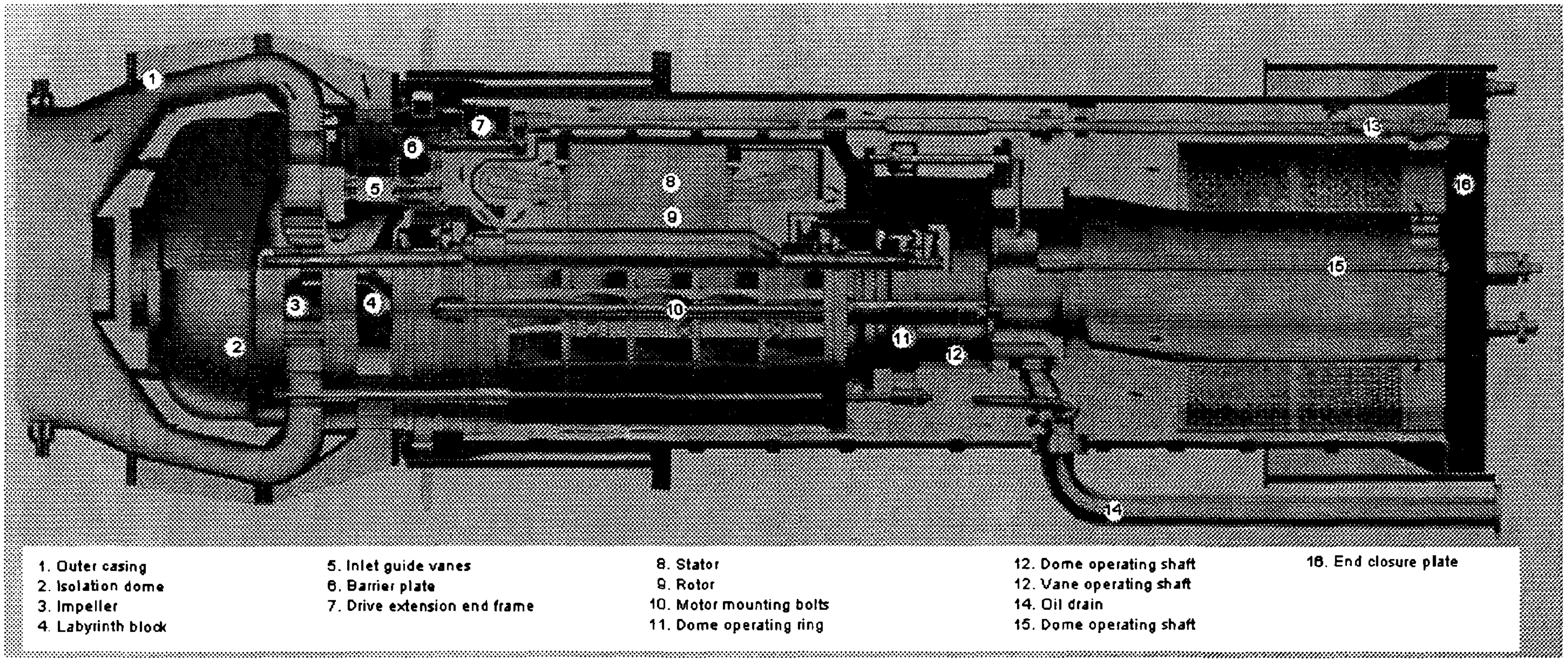


Figure 5.13. AGR gas circulator.

5.5.3 Steam generators

Steam side

The boiler annulus situated between the gas baffle and the reactor pressure vessel, Figure 5.11 and Figure 5.14, is partitioned into four quadrants, each containing one boiler and two gas circulators. The boiler consists of three main boiler units, each composed by an economiser, evaporator and superheater section within a single casing, and supported from below on beams anchored in the pressure vessel and the gas baffle skirt, Table 5.6. and Figure 5.15.

On top of each boiler a reheater unit is suspended from the pressure vessel roof with sliding joints between the boiler and the reheater casing to accommodate thermal movements between the two sections. Separate banks of tubes situated below the economiser sections in the boiler casing form the decay heat system (decay boiler), which is designed to provide cooling of the reactor during shut down.

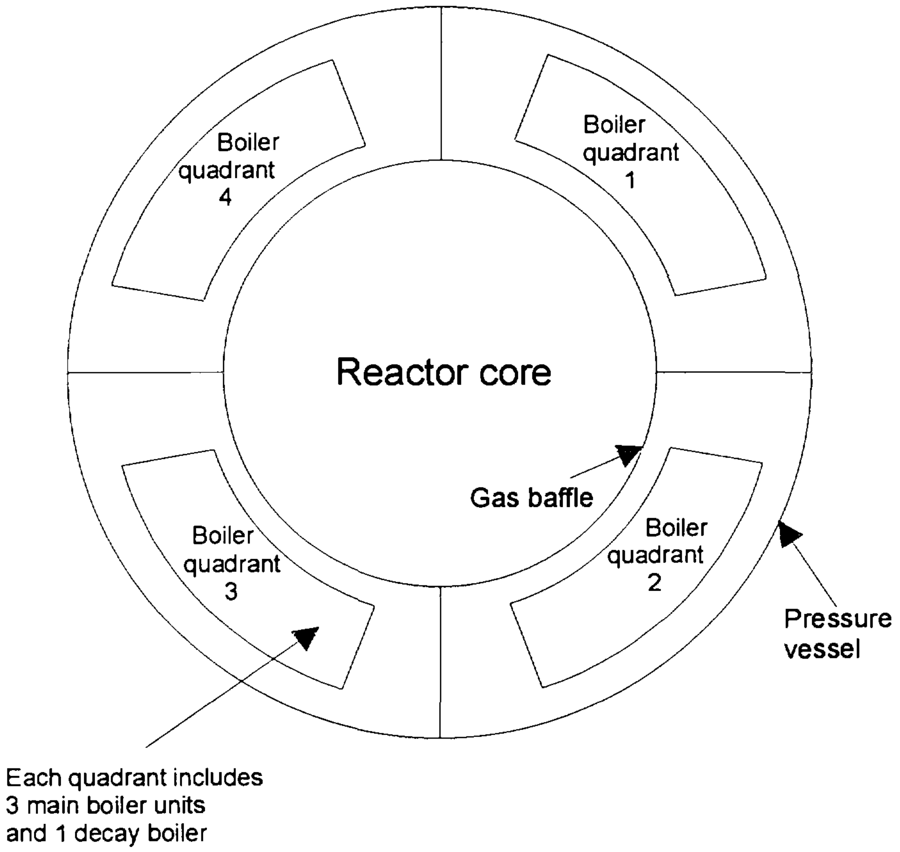


Figure 5.14. The four boiler quadrants in the AGR.

The boilers are of the once-through type to minimize the number of pressure vessel penetration required. Such boilers are characterized by the absence of steam-separating drums and fluid recirculation, and the working fluid is pumped continuously through the boiler. Heated feedwater is pumped via a manifold into the economiser at the bottom of the boiler and flows upwards through banks of tubes via the evaporator and superheater zones to emerge through an outlet at the top of the boiler as superheated steam.

Table 5.6. Design data for boilers.

Number of boilers	4	
Number of units per boiler	3	
Feedwater temperature	158	°C
Gas inlet temperature to reheater	619	°C
Gas outlet temperature	293	°C
Superheater outlet pressure	173	bar
Superheater outlet temperature	541	°C
Steam generation	525	kg/s
Reheater outlet pressure	42	bar
Reheater outlet temperature	539	°C

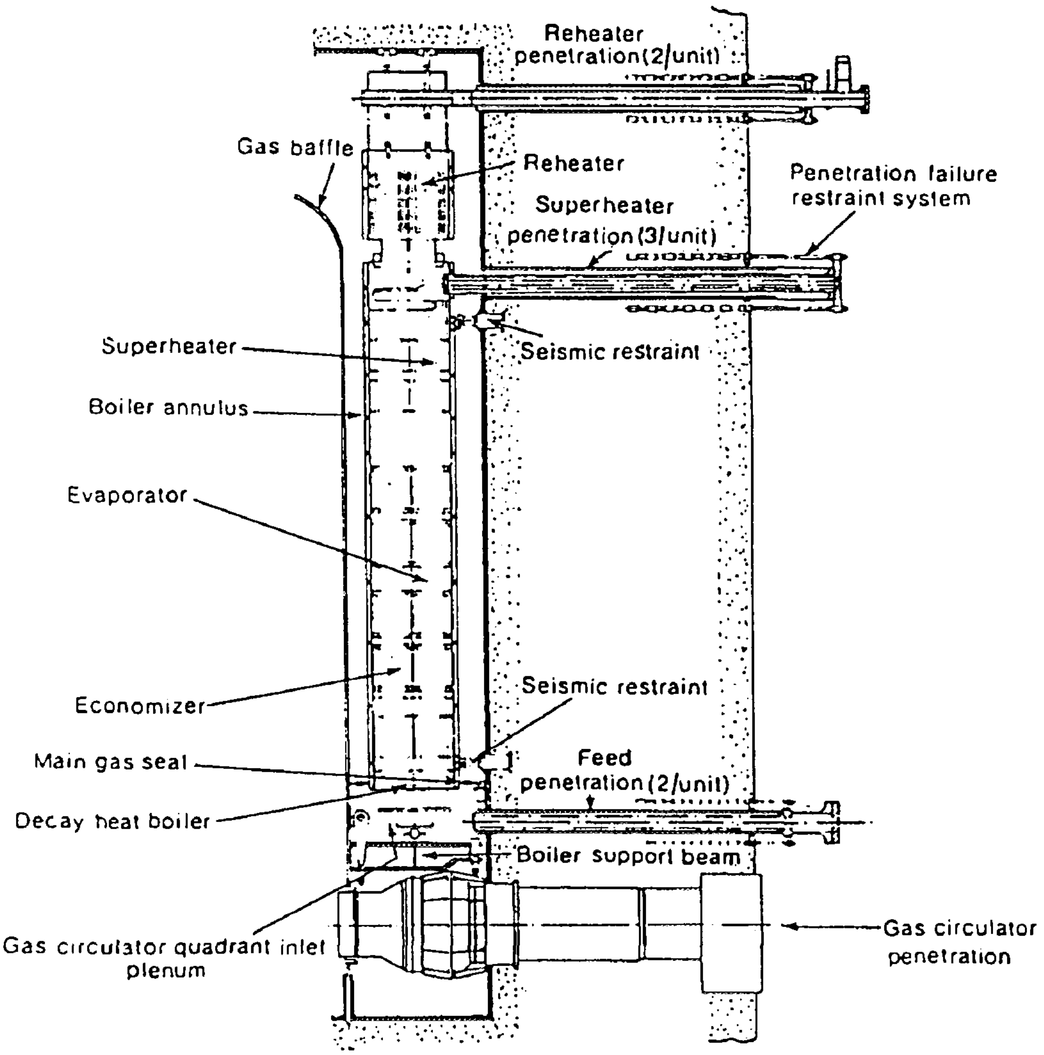


Figure 5.15. AGR boiler unit.

After expansion through the high-pressure turbine the steam is returned to the boiler reheat section at the top of the boiler unit, from which it flows to the intermediate-pressure turbine inlet.

Any boiler quadrant may be taken out of operation while the reactor is on-load without hot gas flows through it. Reverse flow of cool gas through the shutdown boiler will be limited by closure of the inlet guide vanes of the stopped circulators.

The gas coolant flows on the shell side of the boilers, while the water flows and boils inside the boiler tubes. The materials for the boiler tubes are specially selected to avoid undue corrosion or erosion by the coolant gas and water/steam. A 1 % chromium steel is used for the feedwater tube penetrations, low-temperature economiser and decay heat boiler tubing to avoid water-side erosion. The middle section of the boiler is fabricated in 9 % chromium material to resist gas-side corrosion and to be resistant to stress corrosion. The top section of the main boiler and reheater are made of austenitic stainless steel to obtain the necessary resistance to gas-side corrosion.

The chemical composition of the coolant is controlled by a bypass loop which receives about 1 % of the total circulator mass flow of about 4000 kg/s. The loop includes cyclone filters to remove particulate matter, a catalytic recombination unit in which the hydrogen and carbon monoxide produced in the radiolysis of the methane are oxidized to water and carbon dioxide, respectively, and dryers to remove moisture produced in the reactor and recombination unit. An iodine absorption unit can be inserted in case of fission products are present in the coolant as a result of a fuel element failure.

The decay heat boilers are located directly beneath the main boiler economiser sections. One inlet feedwater penetration and one outlet steam/water penetration in the reactor vessel are provided for each boiler quadrant. The material used is ferritic, so that operation with lower quality water can be tolerated.

The decay heat boilers are brought into service for reactor start-up duty, and the system is initiated automatically after a reactor trip as a part of the reactor shut down sequence.

5.6 Residual heat removal systems

To ensure adequate cooling of the reactor and associated plant under shutdown and faulty conditions, two boiler-feed systems are provided - the decay heat boiler-feed system and the emergency boiler-feed system, of which the latter is described in section 5.7.

The two systems are not quit independent of each other, since the emergency boiler-feed system is a backup for the normal decay heat boiler-feed system. The diversity of the two systems are shown in Figure 5.16.

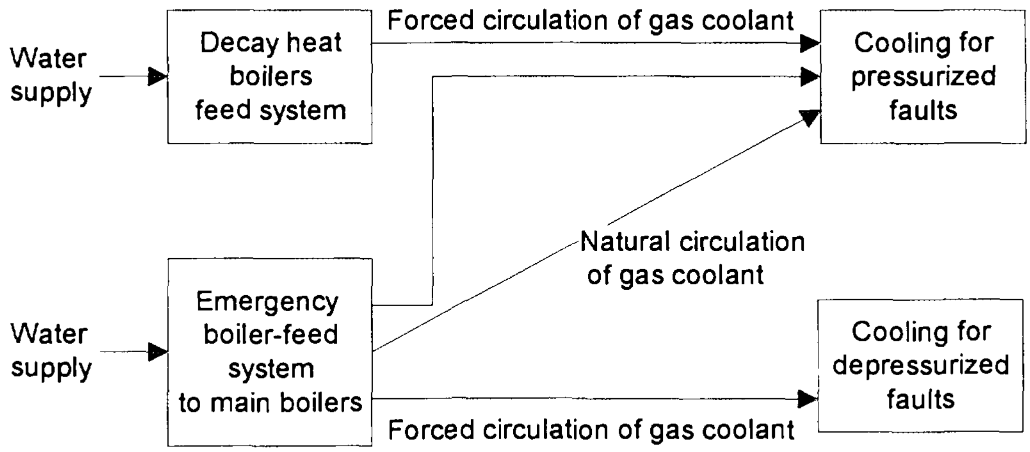


Figure 5.16. Diverse boiler-feed systems.

The decay heat boiler-feed system provides feedwater to the decay heat boilers and is used in conjunction with the gas circulators to remove reactor decay heat under normal shut down and for pressurized trips. The system is arranged so that all four decay heat boilers are being fed by four pumps, each sized so that any two will provide the required minimum flow to each boiler unit.

Initially, decay heat boiler-feedwater is supplied from a feed tank by the feed pumps and the resulting steam from the boiler is passed through a flash vessel and steam dump condenser to return as condensate to the feed system, Figure 5.17. The dump-condenser is vented to the atmosphere and, in the early stages of decay heat boiler operation, steam will be released until the reactor decay heat load has been reduced to a level, where cooling of the condenser by the decay heat boiler air-cooling system matches the load and allows the feed system to become recirculatory.

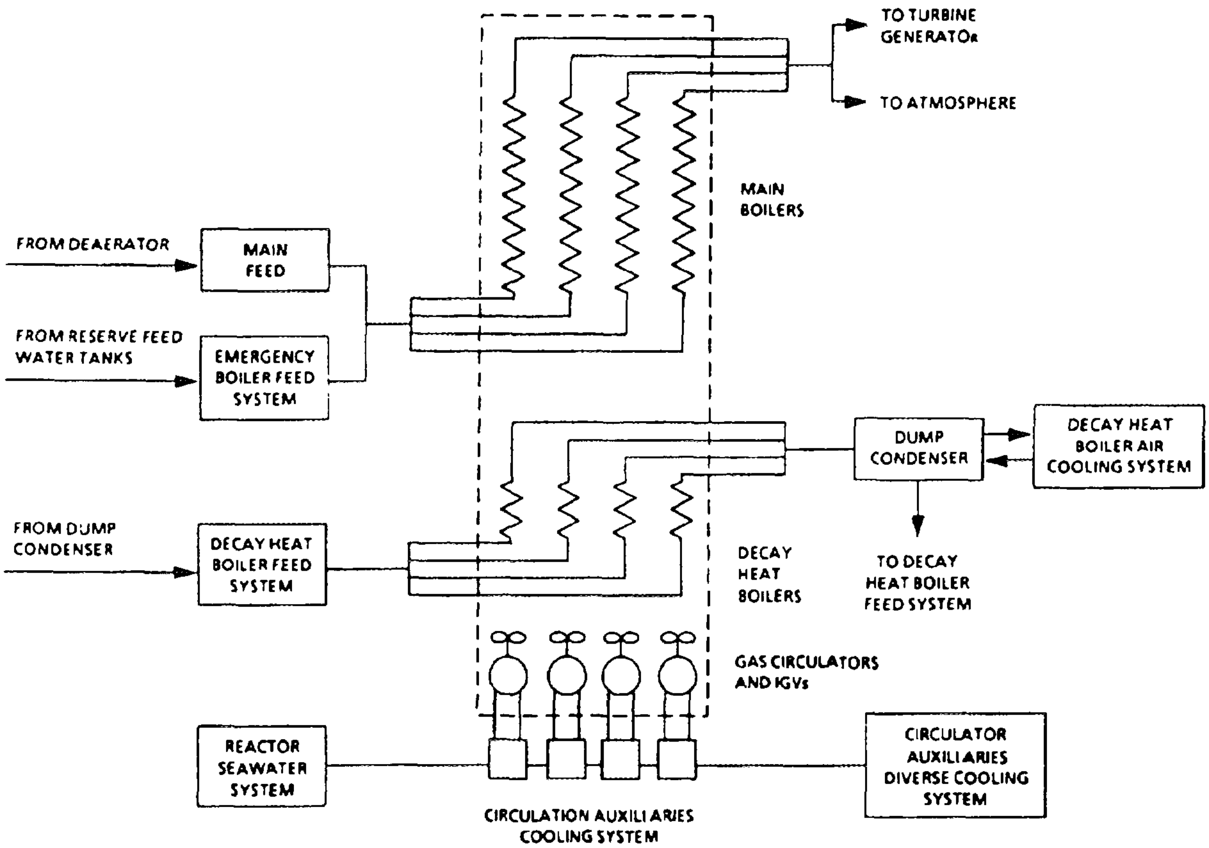


Figure 5.17. Decay heat and emergency boiler feed system.

The decay heat boiler air-cooling system provides a heat sink for the boiler's feed system following a reactor trip. The cooling system consists of a cooling loop with two forced-draught dry cooling towers connected in series and four pumps that circulate water from the outlet of the boiler's dump-condenser tubes to the towers and then back to the condenser tube inlet. Each cooling tower is powered by two separate trains sized so, that any two trains will satisfy the heat removal requirements of the system and maintain the boiler feedwater below a specified temperature.

The normal removal of the decay heat following a reactor trip is via the gas circulators with the main and decay heat boilers and associated feed systems providing diverse means of heat removal from the reactor, each entirely capable in the event of failure of the alternate system.

Although all four boiler quadrants normally operate post-trip with feedwater to both set of boilers, a single quadrant in which both gas circulators operate and where either the main or decay heat boiler is fed with feedwater, will provide safe cooling.

In the unlikely event of all gas circulators failing to operate, natural circulation is an effective means of heat removal provided feedwater is supplied to the main boilers and the core is still pressurized. However, in that case at least two quadrants must receive main boiler feed.

5.7 Emergency core cooling systems

The emergency boiler-feed system is used to supply boiler feedwater to the main boilers under post-trip faulty conditions, and provides a way of removing decay heat with the reactor either pressurized or depressurized.

The system takes water directly from the stations reserve feed water tanks for delivery to the main boilers, Figure 5.17. Normally, the system acts as a redundant and different backup system for post-trip feed to the main boilers. It is activated at any reactor trip.

For pressurized trip conditions (shut down with the system pressure maintained), there are two modes of operation:

1. Emergency feed flow into one or more main boiler in conjunction with the operation of the associated main circulator producing forced flow of the coolant gas.

2. With loss of all eight circulators, natural circulation of the coolant gas provides adequate reactor cooling as long as at least two main boilers are fed through the emergency feed system. The decay heat boiler system is unavailable without forced circulation.

Thus, when a reactor trip is initiated, the coolant gas flow is reduced to about 15 % of normal operating level by tripping all eight gas circulators from their normal power supply at 50 Hz and driving them at 7.5 Hz through individual frequency converters. Secondary coolant flow to the boilers is adjusted by isolating the main feed system and supplying the main boiler units through 10 % feed lines from electrically driven main feed pumps.

The decay heat boilers act as a backup for the main boiler system immediately after the trip. Later the coolant is fully provided by the decay boilers as long as the reactor is pressurized and the gas circulators running.

For depressurized trip conditions, adequate cooling is provided by emergency feed to the main boilers coupled with gas circulator operation producing forced flow of the coolant gas. As gas pressure decreases, natural circulation becomes ineffective and reliance is placed on the gas circulator operating. To compensate for the falling density of the coolant gas the circulator speed is automatically increased as pressure falls until full speed (50 Hz) is reached at about 3 bar. Only two boiler units are necessary to sustain adequate cooling during a depressurization trip, and even one is sufficient provided carbon dioxide is injected into the pressure vessel for about 20 hour to keep the pressure above 2 bar.

For both the emergency boiler-feed operation and the decay boiler-feed operation no operator actions are required during the first 30 minutes following a trip.

The following positive features of the AGR plant reduce the frequency for activating the emergency core cooling systems.

- The arrangement of reactor, boilers and gas circulators entirely within a pre-stressed concrete vessel, ensuring a high integrity boundary for the primary coolant.
- In the event of a total gas circulator failure at full coolant pressure, natural convection is sufficient to remove decay heat.
- The greatest possible leak cross-sections, a break in the CO_2 bypass pipe, are relatively small, 360 cm^2. Thus the time for depressurization is 10-20 minutes.
- In the event of loss of coolant gas, the decay heat can be removed by means of the emergency cooling system, even at atmospheric pressure, provided air ingress is prevented until:
    - The graphite has cooled sufficiently (below 250 °C) to preclude graphite air oxidation or
    - the breach is closed.
- The power density of the reactor is relatively low and the large heat capacity of the graphite helps to limit overheating during faults with low coolant flow.
- Use of a single phase coolant allows better understanding of conditions throughout the reactor, especially in fault situations.
- There is no risk of explosive evaporation of the coolant, or exothermic fuel-clad coolant interaction.
- Reactivity changes during on-load refuelling are low; potential reactivity faults do not have serious consequences.
- On-load refuelling enables early removal of failed fuel if this should be necessary.

5.8 Containment systems

5.8.1 Overall system information

In AGR designs there are basically three barriers preventing the release of radioactivity into the atmosphere during steady state and transient operation. These are:

1. The fuel matrix
2. The fuel clad
3. The primary circuit (pressure vessel / containment)

In LWR design four barriers exist:

1. The fuel matrix
2. The fuel clad
3. The primary circuit (pressure vessel)
4. Containment

Thus, there seems to be a barrier less in AGR compared with LWR reactors. In AGR's the pressure vessel and containment is one unit, but the vessel contains the total primary circuit.

The main reason for this difference is the single phase CO_2 coolant used in AGR compared with the H_2O coolant in LWR. CO_2 cannot undergo suddenly phase change as a result of an unexpected rise in temperature or pressure, i. c. it cannot flash as water. It means that there can be no sudden discontinuity of cooling under fault conditions, and changes in flows, temperatures and pressures progress rather slow.

Also, it is almost impossible to lose the coolant in an AGR. The pressure may fall in case of a major leakage to the atmosphere, but the core will not become uncovered or being exposed to the problem of missing cooling due to incompletely filled circuit.

Finally, if an AGR is exposed to a depressurization accident of the CO_2 coolant, the large heat sink represented by the graphite moderator together with natural circulation of the coolant provide alternative cooling before impermissible fuel temperatures are reached.

5.8.2 Containment structure

The pre-stressed and post-tensioned concrete pressure vessel/containment with 5-7 m thick walls contain around 3600 steel tendons threaded through steel tubes that are embedded in the concrete during construction. The tendons are anchored in stressing galleries at the top and bottom of the vessel. The galleries provide access to the tendons where insertion and stressing of the tendons can take place, Figure 5.18.

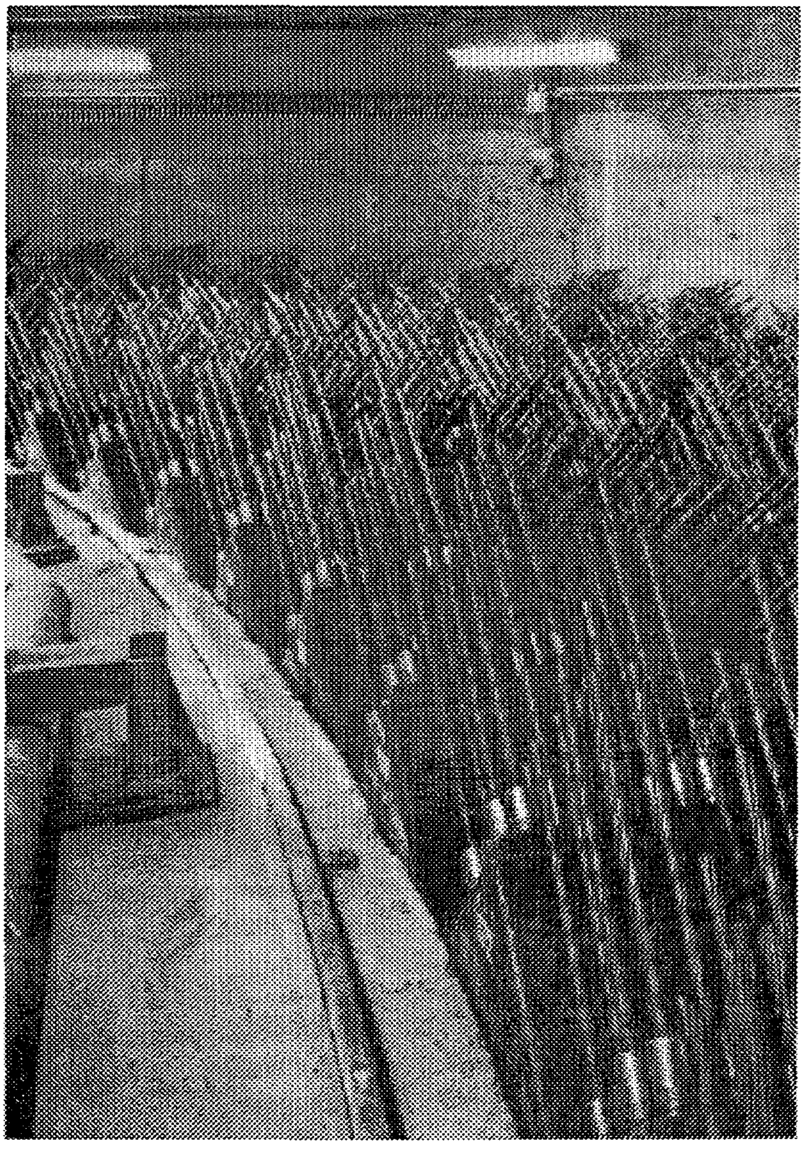


Figure 5.18. The stressing gallery for the tendons at the top of the vessel.

Routine checking of the tendons is carried out during the life of the reactor. All the tendon strand anchorage loads can be checked individually and tendons re-tensioned or replaced if needed.

The pressure vessel is designed to 45 bar with 40 bar being the normal operating pressure. Pressure relief-valves are provided. They are designed to keep the pressure below 49.5 bar during over-pressurization transients, and release the pressure before the vessel starts to fail. This happens at 112.5 bar (2.5 x design pressure).

The failure of a pre-stressed concrete pressure vessel would under normal working pressure conditions require gross failure or relaxation of the tendons. Tests have shown, that the failure mode of this type of pressure vessel is gradual. Sudden, severe failure of the vessel prestress is therefore not considered.

Further more the tendon anchorage loads are monitored continuously. The same applies for examination of the tendon strands for corrosion. Finally, the insulation and cooling system described in section 5.8.4 assure, that the temperature of the tendons is kept within design limits.

5.8.3 Containment penetrations

The top part of the vessel is penetrated by the fuel channels and the control and service channels. Outside the main core zone, there are two large penetrations to provide access for personnel and a number of smaller penetrations for neutron flux measuring equipment and for in-service inspection.

In addition to the eight large horizontal penetrations through the vessel walls which house the gas circulators, horizontal penetrations are provided for inlet and outlet coolant tubes to the boilers and for access to the vessel for inspection purposes. The bottom part of the vessel is provided with penetrations to give access for the secondary shutdown and hold-down system, Figure 5.19. The penetrations have either restrictor plates, to minimize the discharge of coolant gas in the event of failure or some form of closure retention system.

5.8.4 Containment liner

The concrete pressure vessel is on the inside provided with a water-cooled steel liner to form a leak-tight membrane to prevent the escape of CO_2 through the concrete, thus minimizing the release of radioactivity from the plant. It is also part of the cooling and insulation systems that protect the concrete from excessive temperatures. In addition it protects the concrete from erosive action of the hot circulating gas and transfers loads from reactor components to the concrete vessel.

The liner is generally in a state of bi-axial compression due to the prestressing of the concrete, and is anchored to the concrete by numerous ties to prevent buckling. The liner is also keyed to the concrete by vertical and radial panel stiffeners and by the network of cooling pipes.

Thermal insulation is provided on the inside of the liner to limit heat losses from the reactor gas circuit. This insulation together with the closed-loop cooling system which circulates water through the network of pipes between the liner and concrete, is able to maintain acceptable temperature conditions in the vessel concrete (below 70 °C) and the liner. The cooling loop is divided into two independent circuit, each of which may operate alone. Each of the circuits will maintain the walls of the pressure vessel below design temperature for at least two days with the reactor at full power. The cooling system is provided with a heat exchanger which is connected to the sea-water cooling system.

5.8.5 Pressure reducing systems

The pressure vessel is provided with a safety relief-valve system designed to protect the reactor pressure vessel and coolant gas circuit against excess pressures. These could be generated in the gas circuit due to faulty conditions within the reactor system, e. g. by a boiler tube break.

The relief-valve capacity is designed to keep the pressure below 49.5 bar (1.1 x design pressure) under any normal operating or credible fault condition. The system is doubled and connected to the coolant circuit through the gas circulators. The discharges are filtered by sintered stainless-steel filters before it is released to the atmosphere at 70 m above ground level.

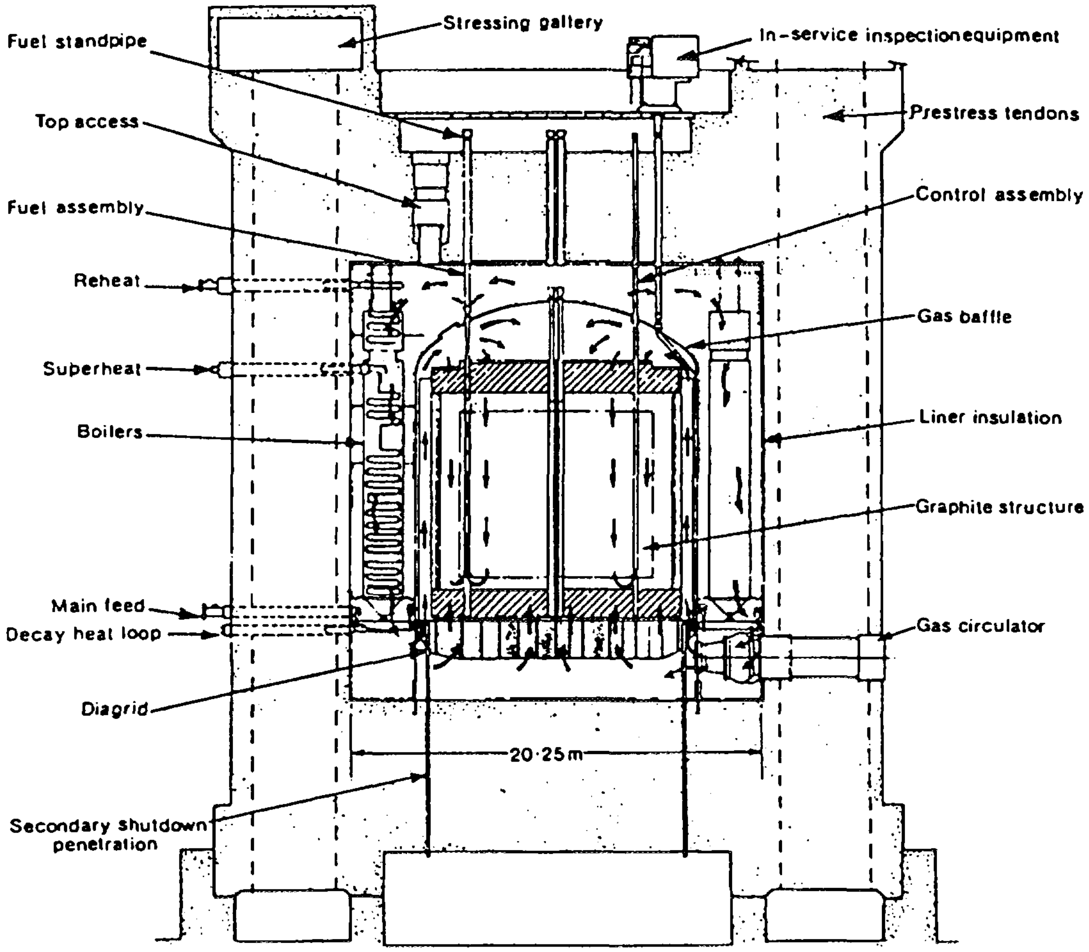


Figure 5.19. Pressure vessel with penetrations.

5.9 Steam and power conversion systems

The main data for the turbine plant are shown in Table 5.7. The turbine comprises one single-flow eight staged high-pressure (HP) turbine, one double-flow seven stage intermediate-pressure (IP) turbine and two double-flow five stage low-pressure (LP) turbines, from which the steam flows to a transverse underlying condenser.

Table 5.7. Design data for turbine plant.

High pressure turbine:		
Number of flows	1	
Inlet pressure	167	bar
Inlet temperature	538	°C
Exhaust temperature	344	°C
Intermediate pressure turbine:		
Number of flows	2	
Inlet pressure	41	bar
Inlet temperature	538	°C
Low pressure turbine:		
Number of flows	4	
Number of feedwater heaters	4	
Feedwater pump driven by steam		
Generator:		
Stator cooled by water		
Rotor cooled by hydrogen		
Voltage	23500	V

5.9.1 Turbine-generator

The HP, IP and two LP rotors are solidly coupled to form a single shaft supported by spherically-housed bearings. The turbine governing system is electronic, and fire-resistant fluid at high pressure is used for emergency stop and governing valve operation.

The condensers are of the single pass type and are arranged in two independent and identical tube banks. Each bank contains approximately 5000 titanium tubes and is separately connected to the sea water cooling culverts via isolating valves and expansion pieces. At full load, the cooling water flows at a rate of 2000 m^3 per minute. Four stages of low-pressure feedwater heating together with a de-aerator give a final feedwater temperature of 156 °C. The low-pressure feedwater heaters are of the surface type with the 3 stages located within the condenser neck sections.

The feedwater flow from the condensers to the boilers is ensured by use of a 100 % duty steam turbine driven feed pump. For starting and standby operation two 50 % duty electric feed pumps are used.

The generator supplies power at 23.5 kV and has a water-cooled stator and hydrogen-cooled rotor.

5.9.2 Main steam supply system

Steam at a pressure of 167 bar and temperature of 538 °C flow from the boiler superheater section through penetrations in the reactor pressure vessel wall and via a system of control valves and pipework to the high-pressure turbine inlet. After passing through this turbine, the steam flows to the reheat section of the boiler.

The reheated steam flow at a pressure of 41 bar and a temperature of 538 °C back to and passes through the intermediate-pressure and low-pressure turbines and on to the condenser. Any losses in the steam cycle are made up with water from the make-up water treatment system. The condensed water then passes through the condensate polishing system for filtration and treatment before it is heated through the feedwater heaters and returned to the boiler economiser section.

Throttles valves are provided to regulate the amount of steam flowing to the turbines and thus the electric generator output. Combined isolation and emergency stop valves are provided to isolate the turbine from the steam supply when required, and to act as protective devices to shut off the steam quickly in emergency situations, when faults have been detected on the turbine-generator system. In particular, these valves prevent turbine run-away if the generator load is lost. Since the steam is non-radioactive, it can be dumped to the atmosphere, if the turbine is isolated.

5.10 Fuel and component handling and storage systems

The route of the fuel from loading of new fuel to unloading of irradiated fuel is shown in Figure 5.21. The route consists of the following major parts:

- The refuelling machine is loaded with a new 23 m long fuel assembly (Figure 5.20), which is exchanged in the core with a hot irradiated fuel assembly.

- The refuelling machine transfers the hot irradiated fuel assembly, at pressure from the reactor to a decay (or buffer) store with 64 assembly positions. Here the fission products are allowed to decay while the assembly cools. The storage continues until the decay heat has fallen to a level appropriate for fuel assembly dismantling at atmospheric pressure in air, i. e. is about 30 days.

- Transport from the decay store to an irradiated fuel dismantling cell, where the fuel assembly is dismantled. The fuel elements are transferred to the storage pond, and the non-fuel components are transferred to a waste vault. The plug unit is reused.

- Finally, after about 80 days in the storage pond the fuel is stored in skips for later loading into transport flasks for despatch to off-site reprocessing or to on-site in dry fuel storage.

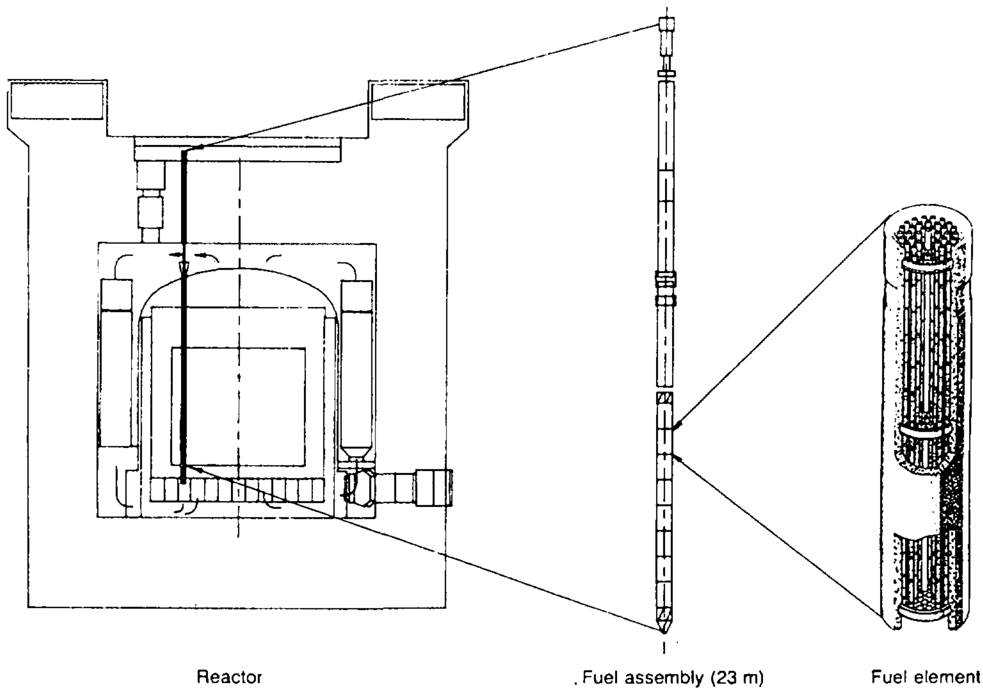


Figure 5.20. Location and size of fuel assembly/fuel element.

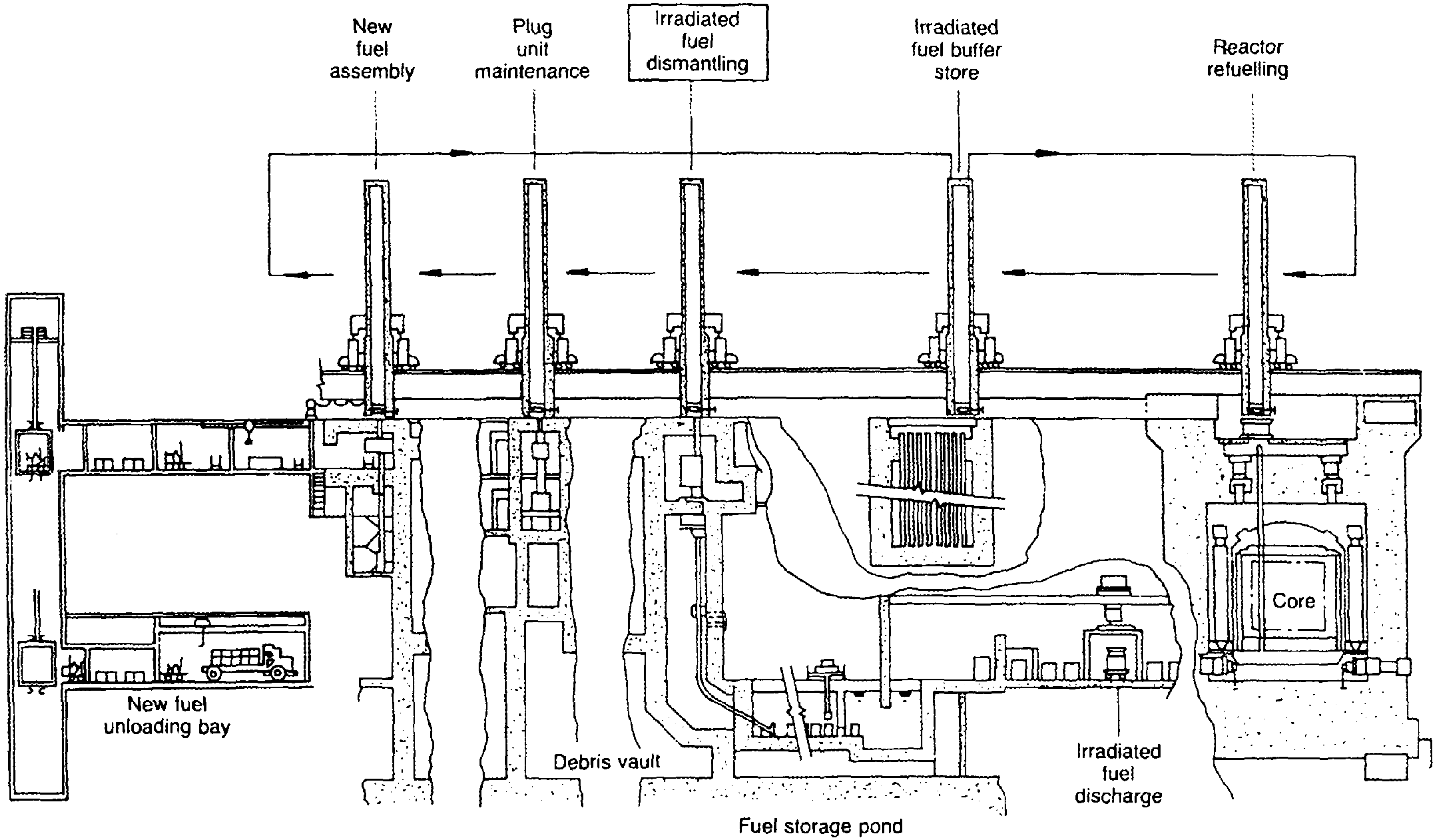


Figure 5.21. Fuel route from loading of new fuel to unloading of irradiated fuel.

5.11 Radioactive waste systems

During power operation the major part of radioactive wastes is produced in the irradiated fuel and contained in the fuel matrix. However, certain other wastes produced at nuclear power stations in gaseous, liquid or solid form may be radioactive to some degree. The radioactivity is due to neutron irradiation of materials in the reactor.

The management of medium and low-level wastes are an important part of nuclear power station design and operation. The general approach is in the case of low-level liquid and gaseous wastes to filter, dilute and disperse to the environment. Solid wastes, such as redundant plant items, filter dusts and sludges, ion-exchange resins, and discharged protective clothing are stored in special buildings.

The irradiated fuel is transferred to a cooling pond at the site before it is transported to Windscale for further storage and eventual reprocessing. The resulting high-level waste is stored at Windscale pending ultimate disposal.

5.11.1 Liquid waste system

The principal sources of radioactive liquid effluents are:

- Water from the reactor coolant driers
- Soluble and insoluble activity from the irradiated-fuel cooling pond
- Soluble activity from the sludge and resin tanks
- Washing water from plant and fuel flask decontamination and drainage from reactor areas

Tritium is produced in the graphite core and reflector from the reaction,

$$ {}^{6}_{3}Li + n \rightarrow {}^{3}_{1}H + \alpha $$

where the *Li-atoms* are present in the graphite as impurities. The tritium atoms exchange with hydrogen in the methane present in the coolant and is finally removed in the coolant driers as tritiated water.

5.11.2 Gaseous waste system

The main source of radioactive releases to the atmosphere is the radioactivity associated with the reactor carbon dioxide coolant. The coolant is released to the atmosphere when the reactor or refuelling machine is depressurized (blowdown). Additionally, as in any large pressurized vessel, leakage occurs through glands and seals. Other sources of radioactive releases include ventilation air from contaminated areas and the air used to purge the reactor pressure vessel during periods when man-access is required within it.

The major contributors to the radioactive discharge to the atmosphere are:

^{41}Ar, ^{14}C, ^{16}N, ^{3}H and ^{35}S.

Treatment of effluents during reactor blowdown

Full reactor blowdown
A full reactor blowdown is carried out when it is necessary to depressurize the reactor totally for the purpose of access and maintenance inside the pressure vessel. This occurs approximately once every two years for every reactor during planned shutdowns for maintenance. Blowdown can be carried out over a period of 12 or 24 hours.

There is one filtration system serving each reactor. It has a dual role of reactor coolant bypass filter, filtering continuously up to 0.6 % of reactor flow during normal operation, and blowdown filter. The filters have sintered stainless-steel elements with high efficiency for small particles.

After passing through the blowdown filter, the CO_2 is routed to one of two identical charcoal beds and finally to the blowdown stack or chimney. One charcoal bed is reserved for emergency use and the other for routine discharges.

The blowdown discharge pipework passes up the inside of one of the stacks for contaminated ventilation air. The stacks pass up the inside of the reactor building and terminate at a height of 70 m above ground level, which is approximately 3 m above the height of the reactor building roof. The stacks also provide the main route for the safety-release-valve discharge from the pressure vessel and from the irradiated fuel facilities.

Minor blowdown
Minor blowdowns, consisting of partial reactor blowdowns, are carried out for pressure adjustment, auxiliary circuit depressurization or coolant chemistry adjustment. The coolant gas is passed through the same route as for full blowdown.

Emergency blowdown
Incidents leading to unacceptable amount of fission products in the coolant may create a need for depressurization of the reactor. In this case the coolant gas is passed through the charcoal bed reserved for emergency blowdowns. This bed has a removal efficiency of at least 99.5 % for methyl iodide. A monitoring instrument gives a continuous indication of the activity discharged. An alarm is given when a preset amount of ^{131}I has been released.

5.11.3 Solid waste system

Solid waste other than low-activity waste is accumulated and stored on-site in a manner that will permit its retrieval at some future date. Low-activity waste is sent for burial at a site in Cumbria.

Several safety measures are introduced for on-site storage, e. g. fire alarms, automatic water sprinklers, provision for filtration of air before discharged and for the sampling and monitoring of discharges. Also any water leakage is collected and pumped to the active drainage system.

Filter sludge and ion-exchange resins are stored in steel-lined concrete tanks; the rooms in which they are located provides secondary containment.

5.12 Control and instrumentation systems

The AGR has a safe dynamic behaviour. Although the moderator temperature of reactivity becomes positive once the initial fuel charge has undergone sufficient irradiation to build up some plutonium - the resulting value of η, the average number of neutrons emitted per thermal neutron absorbed in the fuel, increases with the hardening of the neutron spectrum caused by the higher graphite temperature - the fuel temperature coefficient of reactivity is always negative. Since the thermal capacity of the moderator is vastly greater than that of the fuel, the negative reactivity contribution from the fuel acts more rapidly than the positive effect of the moderator; hence, adequate stability is ensured. This means that the power coefficient of reactivity is always negative.

An important operation principle which influences the design, is that, in the event of a fault operator actions to improve or ensure safety is not required within at least 30 minutes after the fault. This has led to the provision of automatically initiated and controlled systems. This also means that the operators do not have to identify and control fault conditions rapidly with the risk of faulty actions.

5.12.1 Protection system

Fault detection is provided by measuring a number of physical parameters and plant conditions which are carefully selected as prime indicators of fault conditions. These parameters include:

- Fuel channel gas outlet temperatures
- Circular gas outlet temperatures
- Neutron flux level
- Neutron flux period
- Gas circulator supply voltages
- Gas circulator speeds
- Gas circulator inlet vane positions

For each parameter at least four separate measurements are made and if two out of these four measurements, two-out-of-four system, exceeds specified limits, the reactor is shut down. All the parameters are combined in a Main Guardline System, MGL, based on magnetic logic and designed to be fail safe.

A separate Diverse Guardline System, DGL, is also available. This system is based on relays and uses certain of the trip parameters from the MGL system to independently initiate reactor shutdown.

Trip signals from either the main or the diverse guardlines interrupt the power supply to the contacts of a set of four groups of relays. Each group controls an electrical supply to the electromagnetic clutches of about twenty control rods of the primary shutdown system. Interruption of the clutch power supply to any group causes the rods to fall by gravity into the core.

5.12.2 Regulating system

The operation of the AGR reactor involves a number of operating regimes. These include:

- Reactor start-up
- Operation at power and variation of load
- Adjustment of channel gas flows and refuelling

Reactor start-up

The operator controls the approach to criticality and the operation at low power. During this period, he is prevented by interlocks from carrying out actions that are potentially hazardous. Control rods, except for safety rods, must not be raised until the main reactor protection system is operative, and subsequently their withdrawal rate is subject to limitations on the rate of reactivity increase. Other interlocks ensure that the automatic post-trip equipment is operational before a significant power level is reached.

Operation at power and variation of load

The station automatic control loops ensure that during steady-state and transient conditions the turbine-generator loading is matched to the reactor output without contravention of any imposed plant constraints. The role of the operator is to monitor the state of reactor to ensure that it is maintained within the limits of the operating rules. Any control loop can be overridden by manual operation, but interlocks are provided to assist in preventing erroneous operator actions and malfunctions of the control system.

Adjustment of channel gas flows and refuelling

When the reactor is at power, fuel burnup over the core is non-uniform. In order to maintain the coolant gas temperature within the design limits, individual channel control valves (gags) have to be operated as a routine manual operation. Upon receipt of any signal indicating an excessive channel gas outlet temperature (more than 675 °C) alarms are given and further gag closure inhibited.

Station auto-control system

The principal auto-control system is based on the following three control loops:

- Reactor power control through individual regulation of the 45 grey control rods to maintain reactor gas outlet temperature constant
- Reactor gas mass flow control through setting gas circulator control valves in accordance with the grid load demand.
- Boiler feedwater flow through adjusting regulating valves to keep the boiler outlet temperature constant

The principal operation of the auto-control system is arranged in such a way that, a demand for an increase in reactor power, due to an increase in grid load, results in an increase in the gas circulator inlet valves opening and thus an increase in the mass flow of the coolant gas. This action reduces the outlet gas temperature and forces the control rods to rise to keep the outlet temperature constant.

This load following regulation can be made at a rate of change of 10 % of full power per minute within the operation regime 20 to 100 % of full power. Furthermore, step changes up to about 20 % can be met without jeopardising the control system.

Two methods of load control are applied to the AGR plants:

1. • "Boiler/reactor follows turbine"

and

2. • "Turbine follows boiler/reactor"

The oldest AGR plants apply method one, while the other apply method two. Method one follows load variations faster, but it has given rise to disturbances in the boiler/reactor system.

Thus, method two is provided for AGR plants operating as base load plants and method one for plants operating as load following plants.

5.13 Electrical power systems

The electrical power system is shown in Figure 5.22. Under normal conditions the electrical system for each reactor operates as four separate 11 kV systems. Two unit boards are supplied via the generator transformer and after shut down via the 400 kV grid when the generator switch opens to isolate the turbogenerator. Two station boards are supplied via the station transformer from a separate 132 kV supply.

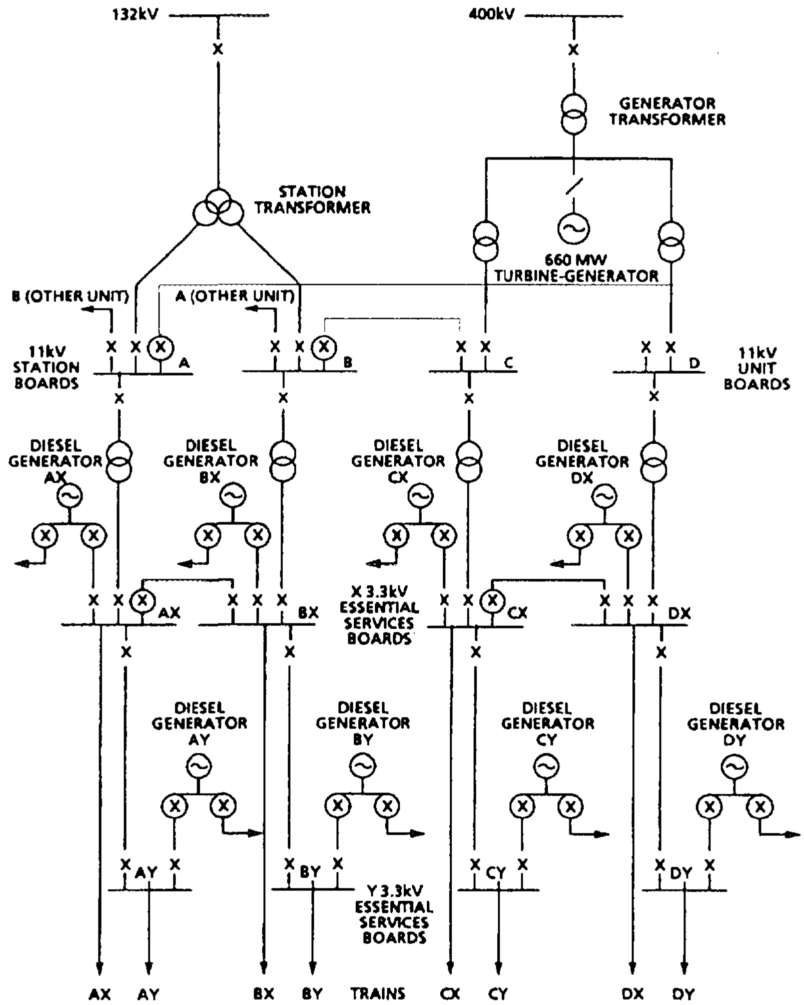


Figure 5.22. Electrical system

Each of the four separate 11 kV systems supply its own quadrant in the reactor (in Figure 5.22 named A, B, C, and D) through four associated 3.3 kV boards. These boards are divided into X and Y trains, AX, BX, CX, DX, and AY, BY, CY, DY which are operated independently if the grid supply is lost.

Loss of grid supply following a reactor trip results in reliance on the stations eight diesel generators, four per reactor. In this case electrical power is provided by four X and four Y diesel generators with the electrical and mechanical cooling systems divided into eight separate trains. The diesel generators are station based. Thus, each diesel generator serves two equivalent trains, one on each reactor. E. g. diesel generator AX serves train AX on unit 1 and train AX on unit 2.

Although the same major component are used for all eight diesel generators, careful consideration has been given to the possibility of common-cause failure. This has resulted in the provision of diversity within certain systems.

The gas circulators and decay heat boilers systems are supplied from the X electrical systems with the emergency feed system supplied by the Y system to satisfy the requirement for diversity.

Furthermore, both the X and Y trains are equipped with battery power supply, which is sufficient to cover the starting time of the diesel generators. Even, if the diesels fail to start, the battery capacity is sufficient to supply power to the X and Y trains for at least 30 minutes.

6 Fire protection, Wigner Energy and Graphite oxidation

Protection against fire hazards is a requirement of the safety guidelines, and their possibility and consequences are specifically taken into account in the design approach. Defences adopted in the protection against fires are:

- Use of non-combustible materials
- Separation and provision of sufficient space between diverse systems or redundant parts of one system such that the consequences of a possible fire are limited
- Segregation, e.g. provision of rated fire barriers between groups of components to limit possible fire consequences

The phenomena of energy storage in irradiated graphite (Wigner Energy) is well known and represents a safety problem in reactors operating with graphite temperatures below 300 °C. In general, the amount of stored energy increases with integrated dose and decreases with irradiation temperature. The effect is caused by fast neutrons, which displace atoms from their normal lattice positions. If the graphite temperature is subsequently raised above the irradiation temperature, some of the displaced graphite atoms will return to their original positions whereby the stored energy is released. If the energy release per unit temperature rise exceeds the specific heat of the graphite, a spontaneous release of energy can occur

However, in AGR's operating with graphite temperatures around 400 °C no large quantity of stored energy is expected to accumulate, Figure 6.1.

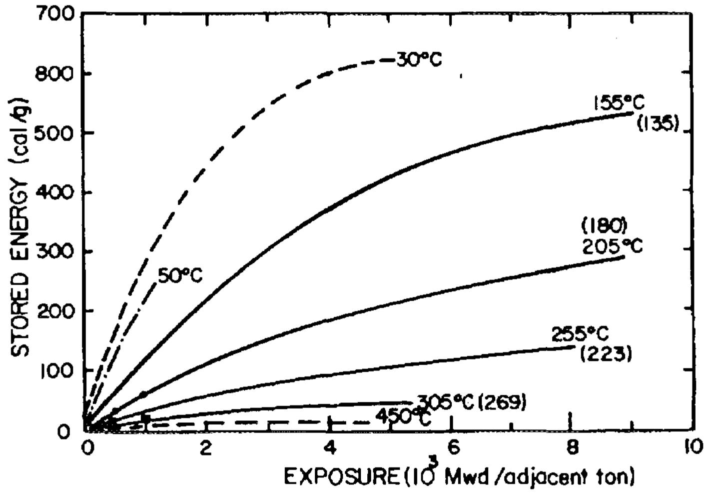


Figure 6.1. Accumulation of stored energy in graphite, (Ref. 6).

One of the main concerns is to avoid ingress of air into the graphite channels to avoid significant graphite air oxidation. This is special important in case of a coolant gas leakage in connection with a depressurization of the primary system. Significant air ingress is prevented by CO_2 injection until the leakage has been stopped or the graphite has cooled sufficiently to avoid air oxidation (below 250 °C). Except for the graphite fuel sleeves the core graphite temperatures are normally below temperatures, where significant air oxidation can lead to graphite burning . Thus a fire in the graphite moderator is very unlikely.

Compared to the Chernobyl reactor type (RBMK) the only common feature is the use of graphite as a moderator. The RBMK uses boiling water as coolant and has a positive void coefficient of reactivity during most of its operating conditions. Leakage of water/steam from the fuel channels of an RBMK reactor into the hot graphite causes strong reactions with pressure build up and large risk for reactivity excursion without a fast acting control rod system to intervene.

The AGR does not involve a positive reactivity coefficient, but very low probability for a heat-up accident with possible graphite burning. Overall, there is no credible mechanism that could lead to a rapid energy release like that experienced in the Chernobyl-4 reactor.

7 Plant performance during normal operation

Most of the AGR's in the UK have not performed very satisfactory during the period from the early sixties to the nineties. This is due to a number of reasons some of which are:

- Very long construction times
- Problems with the long fuel stringer design
- Multiple steam generator tube failure
- Loss of weight of the graphite moderator

Construction of the first of the AGR plants started at Dungeness B in 1966, but already in 1969 the on-site constructed gas baffle had to be replaced due to distortion and the construction consortium collapsed. Problems with vibrations in the boilers and with the pressure vessel insulation liners came later and were followed by instability of the fuel stringer. It took 19 years to commission the first of the two units at Dungeness, and the construction time of many of the other AGR's in UK was also very long, Table 7.1 (*Ref. 7*). Only Heysham I and Torness were finished almost within the scheduled time.

Table 7.1. AGR Construction times and year for start of operation.

Plant	Construction years Planned	Construction years Actual	Start of operation
Dungeness B	5	19	1983-85
Heysham I	6	14	1983-84
Hartlepool	6	16	1984
Hinkley Point B	5	9	1976
Hunterston B	5	9	1976
Heysham II	6	8	1988
Torness	6	8	1988

The planned construction costs were exceeded too, in the case of Dungeness B by a factor of 5.

The fuel stringer problems

In the original design the fuel stringer, carrying 7 fuel elements, was to be loaded into and discharged from the core with the reactor at full power. However, violent oscillatory behaviour of the fuel stringer has been observed, both during loading the fuel channel and during unloading. The mechanism of the oscillations is not fully understood, but it is connected to the pressure differential between the channel being loaded and the adjacent channels which causes significant cross flow of coolant gas.

An intolerable fault condition arises if an irradiated stringer is discharged and the tie bar fails, so that the fuel elements crashes to the bottom of the channel. The resulting disintegration of the elements will effectively prevent the coolant gas from entering the channel and the fuel may reach the melting point within 6-8 minutes. Although the reactor is tripped immediately, it is not possible to force coolant through the fuel stringer debris, during the 6-7 minutes the gas circulators are coasting down, before they are again supplied with electrical power.

In the early seventies a fuel stringer broke up during a test at Windscale AGR prototype reactor, and since then the nuclear authorities in UK has refused to permit AGR's to refuel while on-load. However, some stations have later received permission to refuel at 30 % load.

Multiple steam generator tube failure
A boiler tube failure result in a rapid ingress of steam and water into the primary circuit due to the pressure difference between the steam side, 160 bar, and the gas side, 42 bar. In response the automatic safety relief-valves of the reactor gas circuit opens to the atmosphere to relieve the vessel pressure. Boiler depressurization and isolation is activated, but before the isolation becomes effective, 6 to 8 tonnes of water can enter the reactor from a single damage boiler tube.

If a significant number of tube fail simultaneously the automatic relief-valves would not be able to keep the primary pressure below the design pressure. Since a major reason for tube failure in steam generators is stress corrosion due to bad water chemistry combined with the large temperature gradients occurring during the different boiling regimes, great care is taken to keep the feedwater quality within narrow limits.

During the AGR's development programme several changes were made relating to the boiler design. These changes caused many prolonged shutdowns of the plants.

Loss of weight of the graphite moderator
Core weight loss is caused by progressive oxidation of the graphite moderator by carbon dioxide coolant. The process can be inhibited by adding carbon monoxide and methane to the coolant (Section 5.3.1), but too much of these inhibitors leads to carbon being deposited on the boilers and fuel pins. The carbon buildup limits the heat transfer capabilities so that the operating temperatures of the core have to be lowered to reduce deposition or avoid exceeding the safety limits. Furthermore, if the weight loss of the graphite structure exceeds about 10 %, the stability of the graphite bricks can be threaten by crack formation.

So, the AGR operators are faced with a balancing act:

- Lower temperatures to allow higher methane levels, giving longer core life but resulting in lower output levels, versus
- higher temperatures and lower methane levels, giving shorter core life but higher output.

All AGR's except Dungeness B have output restriction due to carbon deposition. Dungeness B has as yet no power limitations because of its lower historic availability.

The original safety case for the lifetime of an AGR core assumed that there was no cracks in the graphite - an assumption considered to be very conservative. The condition of the graphite and its geometry is checked very thoroughly. This enables the operators to build up a data bank of how the graphite is behaving during operation. Thus, the operators hope by gaining this experience to be able to replace the conservative design assumption on cracks by a more probabilistic approach to the problem.

The operators of the AGR plants hope that, within the next two ore three years they will be able to come up with a "modified safety case" to support life extension at Hinkley Point B, Hunterston B, Heysham II, and Torness from 30 to 35 years.

The commercial implications of this extension would be substantial, since the operators could depreciate assets over a longer period, lowering the unit costs and increasing the time available to build up the decommissioning fund.

The lifetimes of the two sister stations Heysham I and Hartlepool are restricted to 25 years due to design differences, causing the oxidation to progress more rapidly.

To quote *Ref. 7* the essence of the AGR situation can be outlined as:

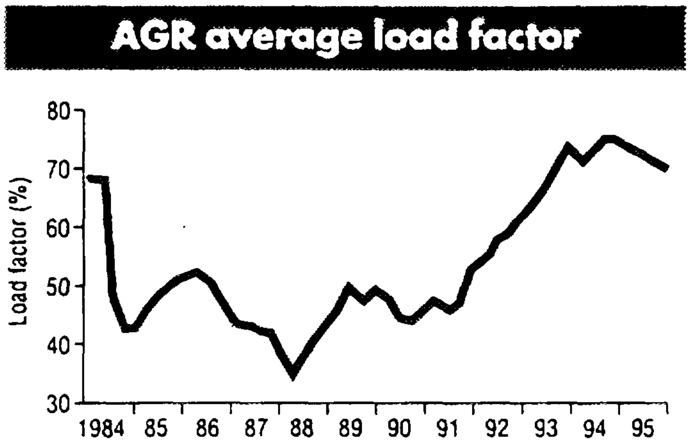
> *" If the AGR design had been successful then, no doubt, the considerable advantaged offered by the higher steamside temperatures, on-load refuelling, in-core fuel shuffling, and reactor availability would have produced a reactor system competitive with if not superior to the light water reactors adopted by other nations. "*

8 Planning and organisation

In 1990 the electricity industry in UK was privatised except for the nuclear part of it. At the same time two public companies were founded, Nuclear Electric and Scottish Nuclear, to operate the seven AGR stations and the PWR Sizewell B. The holding company of the two public operators was called British Energy. At the same time the six first-generation Magnox stations still operating were take over by a public company with a possible later transfer to British Nuclear Fuels Ltd. The two oldest Magnox stations at Calder Hall and Chapelcross are operated by BNFL.

The privatisation of the nuclear part of the electricity supply was also considered in 1990, but the poor performance of the AGR stations prevented this.

However, during the last 5 years the AGR plants have performed rather well (Figure 8.1 where the load factor is defined as the ratio between the actual produced energy and the energy production if the plant had operated at design capacity for the same period),



▲ *Source: Nuclear Engineering International.*

Figure 8.1. AGR average load factors.

and the efficiency of the nuclear industry has dramatically improved (*Ref. 8*). Back end fuel costs are under control with fixed price contracts with British Nuclear Fuels Ltd. Sizewell B is running with a high load factor and the Magnox stations have been transferred to a public company called Magnox Electric. The operating costs for British Energy have been reduced from 3.27 p/kWh in 1992 to 2.37 p/kWh in 1996.

With all this in mind the UK government will try by mid-summer 1996 to sell its share in the holding company British Energy, operating the 7 AGR stations and Sizewell B. British Energy is responsible for about 20 % of the electricity production in the UK.

The HSE, Health and Safety Executive, has assessed the implication of the privatisation on safety and concluded that there is no reason to make any major changes in the safety regime to deal with the new industrial structure.

The privatisation will not in itself require any changes to existing nuclear legislation. However, any important management changes will require new licensing procedures and the new company will have improve some of the safety issues. It will also have to request new authorisations for the discharge of radioactive waste at Thorp.

The load factors for the two units at Torness AGR station are shown in Figure 8.2. After a start-up period of about two years the load factors seem to have stabilised around 70 to 80 %.

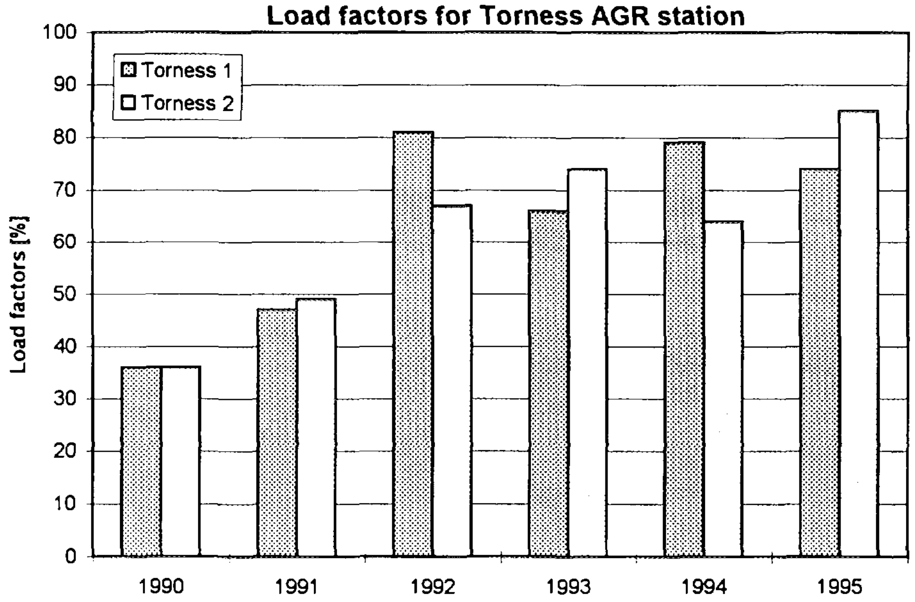


Figure 8.2. Load factors for Torness AGR station.

9 References

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Ref. 9 *Directory of Nuclear Power Plants in the World 1994.* Japan Nuclear Energy Information Centre, Tokyo. ISSN-0912-7003.

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10 Appendices

Appendix A : Dungeness B AGR station

Dungeness B in Kent 20 km south-west of Dover (Figure 10.1) was the first commercial size AGR to be ordered. The construction work began in 1966, but the electricity production started as late as 1983 after numerous technical problems had been solved and the original contractors had collapsed. The power station includes two Magnox units called Dungeness A each of which has a power level of 285 MWe.

The two AGR units at Dungeness belong to the first generation of AGR's. The sister stations Hinkley Point B and Hunterston was ordered one year later.

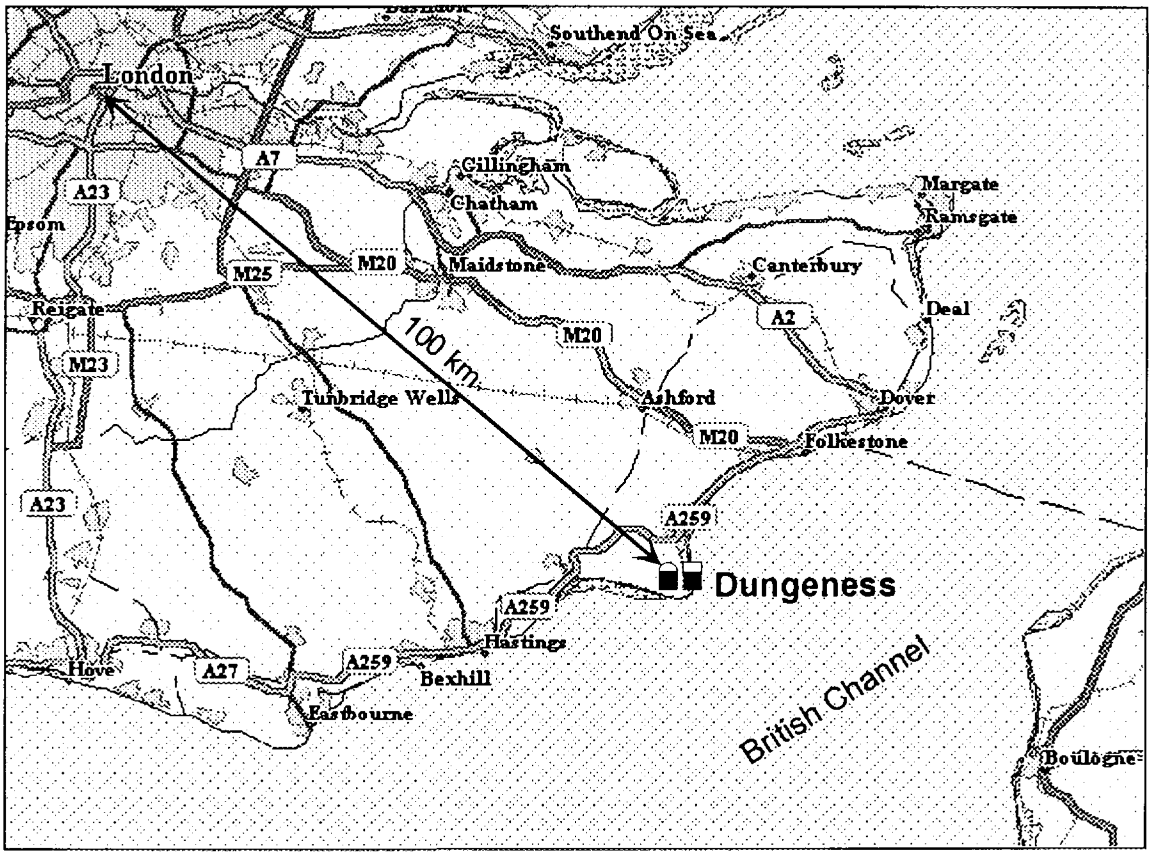

Figure 10.1. Location of Dungeness Nuclear Power Station.

Table 10.1 shows a summary of design data for the Dungeness AGR plant. Since it was the first commercial AGR to be build some design parameters are different from later designs. The most important differences are listed below:

- Number of fuel channels
- Gas coolant pressure
- No secondary shutdown system
- Number of gas circulators
- Number of steam generators

Table 10.4 at the end of the report shows a comparison of the main data for all AGR's in UK.

Table 10.1. Summary of design data for Dungeness AGR nuclear power station

Station design		
Reactor type	AGR	Advanced Gas Cooled
Electrical output (gross)	2 x 660	MWe
Thermal output (gross)	2 x 1496	MW
Efficiency	41.6	%
Reactor		
Moderator	Graphite	
Coolant gas	CO_2	
Number of fuel channels	408	
Number of control rod channels	57	
Secondary shutdown system	none	
Lattice pitch (square)	394	mm
Active core diameter	9.5	m
Active core height	8.3	m
Mean gas pressure	32	bar
Mean inlet gas temperature	320	°C
Mean outlet gas temperature	675	°C
Total gas flow	3378	kg/s
Fuel elements		
Material	UO_2	
Type	36 pin cluster	in graphite sleeve
Pellet diameter	14.5	mm
Inner graphite sleeve diameter	178	mm
Cladding material	Stainless steel	
Cladding thickness	0.4	mm
Element length	1036	mm
Number of elements per channel	8	
Enrichment	2.2 - 2.7	%
Power density	2.4	kW/litre
Mass of uranium per reactor	152	tonnes
Mean fuel rating	9.5	MWt/tU
Mean fuel discharge	18,000	MWd/tU
Pressure vessel		
Material	Pre-stressed	concrete
Inner liner	Stainless steel	
Internal diameter	20.0	m
Internal height	17.7	m
Side wall thickness	3.8	m
Top slap thickness	6.3	m
Bottom slap thickness	5.9	m
Design pressure	33.6	bar

Table 10.1 continued

Gas circulators		
Type	Centrifugal	
Regulation	Variable speed	
Number circulators	4	
Total power consumption	45	MWe
Boilers		
Number of boilers	4	
Number of units per boiler	1	
Feedwater temperature	163	°C
Gas inlet temperature to reheater	661	°C
Gas outlet temperature	279	°C
Superheater outlet pressure	172	bar
Superheater outlet temperature	571	°C
Steam generation	468	kg/s
Reheater inlet pressure	44	bar
Reheater inlet temperature	376	°C
Reheater outlet pressure	41	bar
Reheater outlet temperature	571	°C
Turbine plant		
High pressure turbine:		
Number of flows	1	
Inlet pressure	163	bar
Inlet temperature	566	°C
Outlet pressure	44	bar
Outlet temperature	376	°C
Intermediate pressure turbine:		
Number of flows	2	
Inlet pressure	41	bar
Inlet temperature	566	°C
Low pressure turbine:		
Number of flows	6	
Number of feedwater heaters	4	
Feedwater pump driven by steam		
Generator:		
Speed	3000	rev./min
Stator coolant	Water	
Rotor coolant	Hydrogen	
Voltage	23500	V

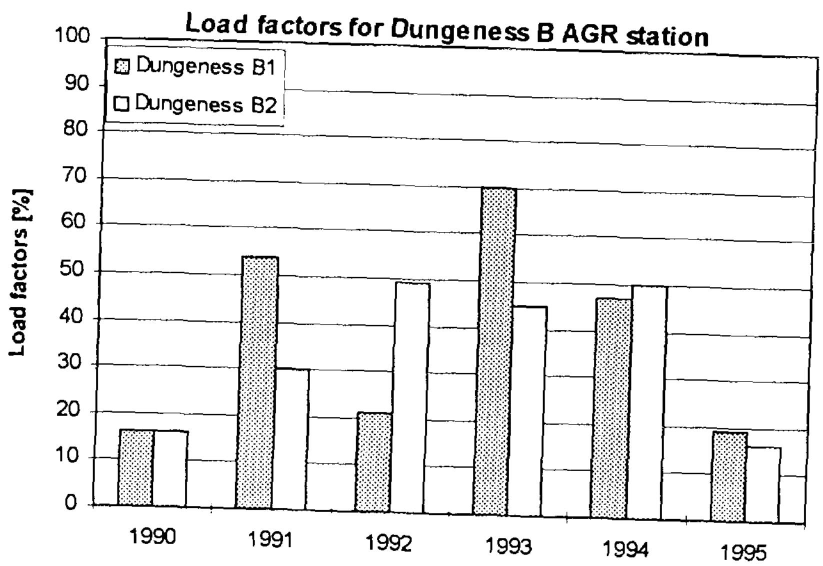

Figure 10.2. Load factors for Dungeness B AGR station.

Appendix B : Hinkley Point B AGR station

The Hinkley Point B advanced gas cooled nuclear power station is located at the Bristol Channel, 50 km south-west of the town of Bristol (Figure 10.3). The station began operation in 1976 after a construction period of about 9 years. At the same site is located Hinkley Point A, a Magnox station with two units, each of 270 MWe.

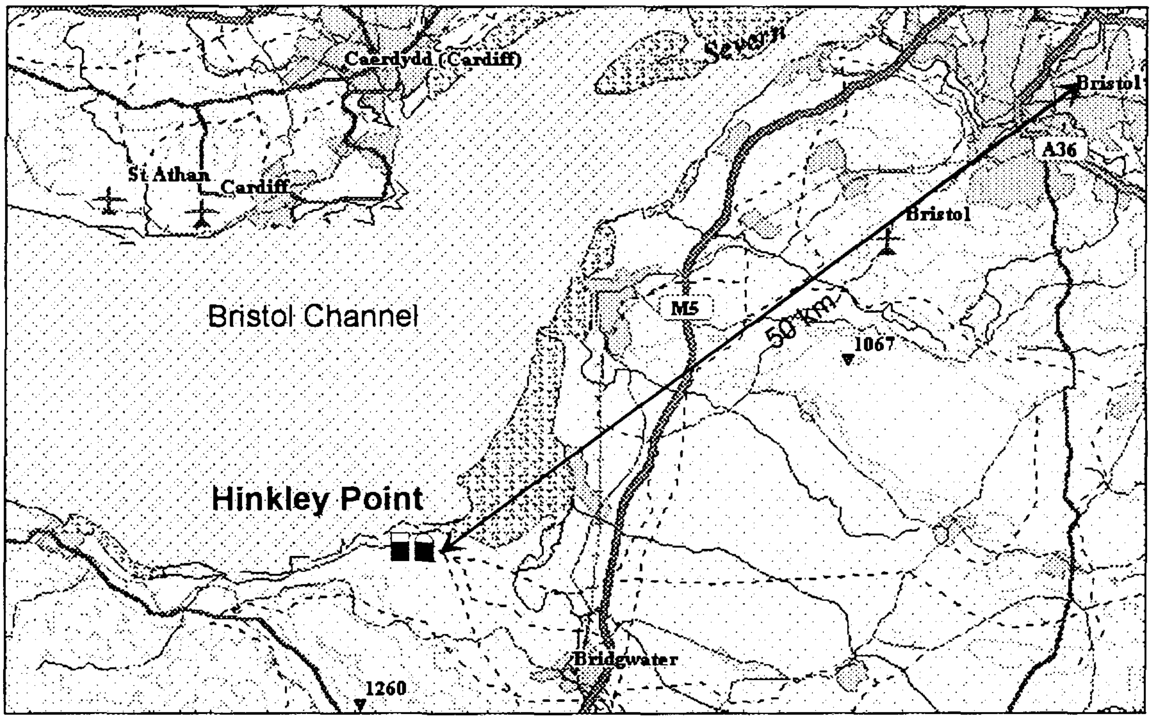

Figure 10.3. Location of Hinkley Point Nuclear Power Plant.

Hinkley Point B belongs like Dungeness B to the first generation of AGR stations. However, some design changes have been introduced. Among the most important are:

- Secondary shutdown system, which consists of nitrogen injection in special core channels
- Higher gas coolant pressure with increased number of gas circulators
- Reduced number of fuel channels

Both Hinkley Point B and the sister station Hunterston B revealed during their early operation in the late seventies a number of operational problems. However, this experience became valuable for the development of the later AGR's. In 1968 it was discovered that a serious corrosion of mild steel in the Magnox gas environment could take place when the CO_2 temperature exceeded 350 °C. This led in 1972 to speculations of possible corrosion in 9 % chrome material used in boiler tubes under AGR conditions and caused many component modifications to be made to the boilers.

Table 10.2. Summary of design data for Hinkley Point AGR nuclear power station

Station design		
Reactor type	AGR	Advanced Gas Cooled
Electrical output (gross)	2 x 660	MWe
Thermal output (gross)	2 x 1500	MW
Efficiency	41.1	%
Reactor		
Moderator	Graphite	
Coolant gas	CO_2	
Number of fuel channels	308	
Number of control rod channels	81	
Secondary shutdown system	nitrogen	
Lattice pitch (square)	460	mm
Active core diameter	9.1	m
Active core height	8.3	m
Mean gas pressure	41	bar
Mean inlet gas temperature	292	°C
Mean outlet gas temperature	645	°C
Total gas flow	3680	kg/s
Fuel elements		
Material	UO_2	
Type	36 pin cluster	in graphite sleeve
Pellet diameter	14.5	mm
Central hole diameter	5.1	mm
Inner graphite sleeve diameter	190	mm
Cladding material	Stainless steel	
Cladding thickness	0.38	mm
Element length	1036	mm
Number of elements per channel	8	
Enrichment	2.2 - 2.7	%
Average power density	2.8	kW/litre
Mass of uranium per reactor	129	tonnes
Mean fuel rating	13.2	MWt/tU
Mean fuel discharge	18,000	MWd/tU
Pressure vessel		
Material	Pre-stressed	concrete
Inner liner	Stainless steel	
Internal diameter	19.0	m
Internal height	17.7	m
Side wall thickness	5.0	m
Top slap thickness	5.5	m
Bottom slap thickness	7.8	m
Design pressure	43.3	bar

Table 10.2 continued

Gas circulators		
Type	Centrifugal	
Regulation	Constant speed	variable inlet vanes
Number circulators	8	
Total power consumption	45	MW
Boilers		
Number of boilers	4	
Number of units per boiler	3	
Feedwater temperature	168	°C
Gas inlet temperature to reheater	634	°C
Gas outlet temperature	288	°C
Superheater outlet pressure	160	bar
Superheater outlet temperature	538	°C
Steam generation	---	kg/s
Reheater inlet pressure	42	bar
Reheater inlet temperature	376	°C
Reheater outlet pressure	39	bar
Reheater outlet temperature	538	°C
Turbine plant		
High pressure turbine:		
Number of flows	1	
Inlet pressure	160	bar
Inlet temperature	538	°C
Outlet pressure	42	bar
Outlet temperature	376	°C
Intermediate pressure turbine:		
Number of flows	2	
Inlet pressure	39	bar
Inlet temperature	538	°C
Low pressure turbine:		
Number of flows	6	
Number of feedwater heaters	5	
Feedwater pump driven by steam		
Generator:		
Speed	3000	rev./min
Stator coolant	Water	
Rotor coolant	Hydrogen	
Voltage	23500	V

At the beginning, the two plants were commissioned for only 82 % of design power to reduce the operating temperature of the coolant gas and ensure the integrity of the boiler tubes. However, with the accumulation of oxidation data, it was proved that the corrosion rate was not excessive. Thus the temperature reduction was no longer necessary, and the power restriction was lifted.

The fuel assembly stringer design also caused corrosion problems. Excessive wear was seen in the fuel channel gas regulation valves (gags). The solution of these problems caused a delay of one year.

These and other events delayed the start-up, and limited the initial load factors of Hinkley Point B and Hunterston B. But like most other systems, load factors have increased as the years of operation have accumulated.

The load factors for the five last years are shown in Figure 10.4. The years 1993 to 1995 show a good performance for both units.

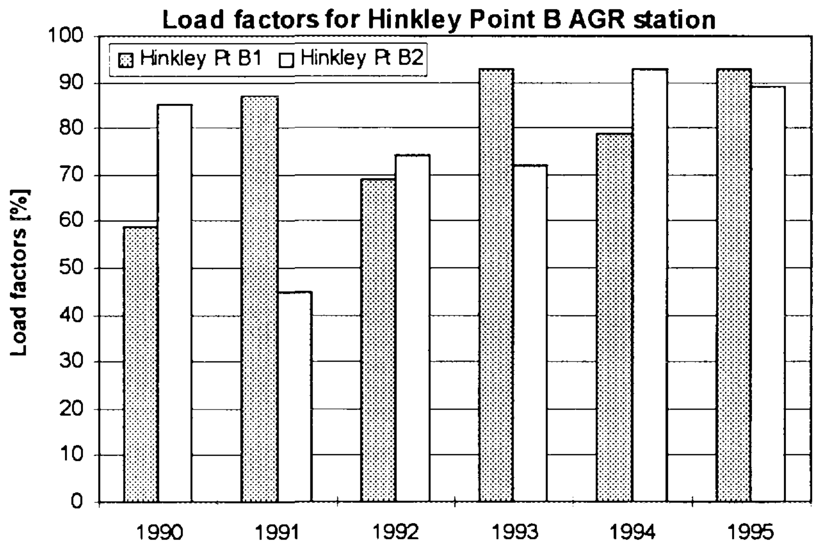

Figure 10.4. Load factors for Hinkley Point B AGR station.

Appendix C : Hunterston B AGR station

Hunterston B Nuclear Power Station is located in Scotland in Strathclyde Region on the Firth of Clyde 60 km south-west of Glasgow (Figure 10.5). The station has two AGR units and stands alongside the Magnox station Hunterston A, which has been under decommissioning since 1989.

Hunterston belongs to the first generation of AGR's and the construction began in 1967 with the first electricity generated in 1976.

In 1977 unit 2 of Hunterston B had an incident, where sea water entered the reactor vessel, causing a shutdown of the unit until 1980. Again in 1982 the unit was shutdown for about 3 months in order to carry out extended inspection and overhaul to confirm that there was no excess of salt in the reactor.

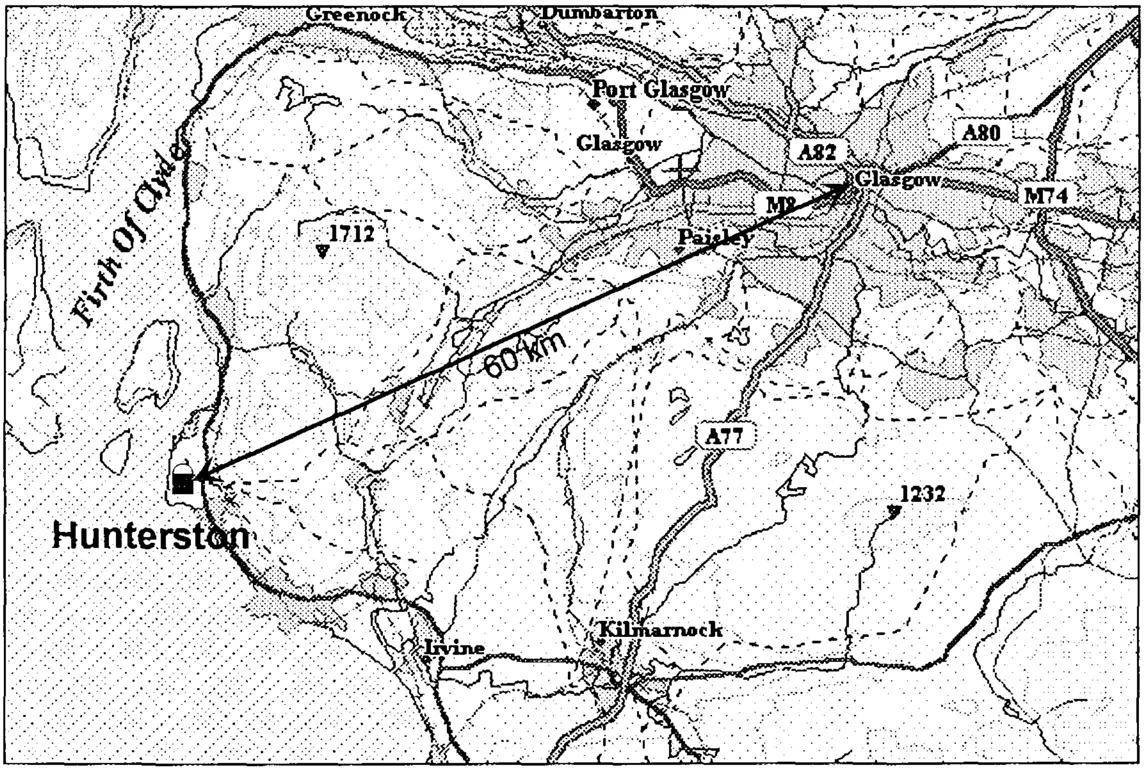

Figure 10.5. Location of Hunterston Nuclear Power Plant.

Hunterston B is a sister station to the Hinkley Point B AGR station. Thus the summary of design data are giving in Table 10.2 page 72.

The load factors for the five last years are shown in Figure 10.6. During the last two years, 1994 and 1995, the plant has performed rather well.

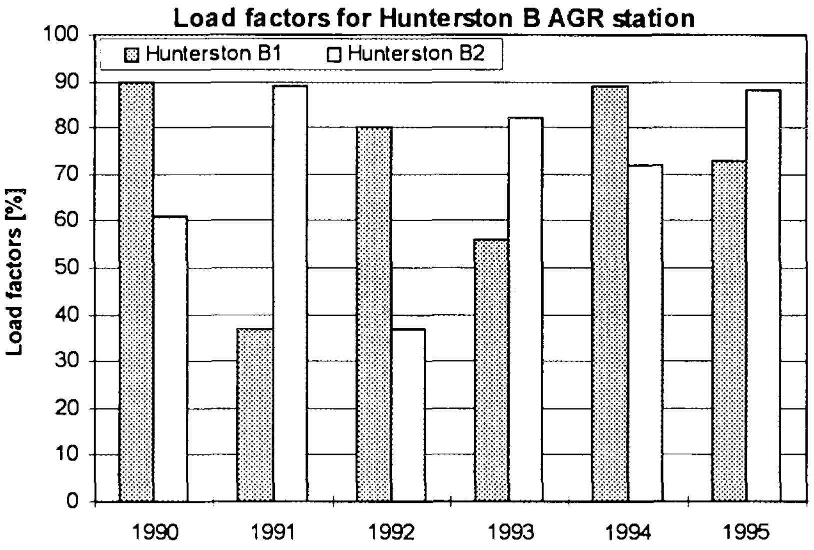

Figure 10.6. Load factors for Hunterston B AGR station.

Appendix D : Hartlepool AGR station

Hartlepool advanced gas cooled nuclear power station is located 60 km south-west of Newcastle and only 15 km north of Middlesbrough. (Figure 10.7). The station began operation in 1984 after a construction period of about 16 years.

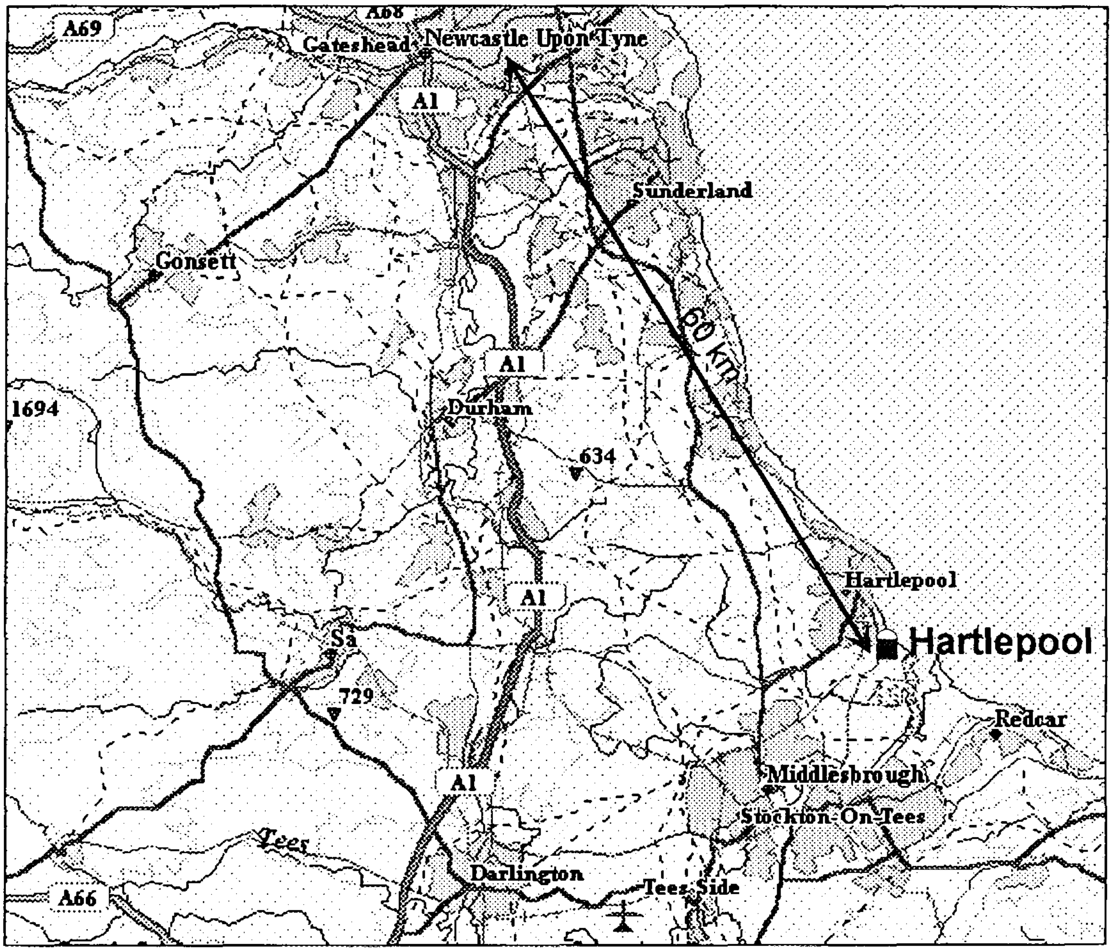

Figure 10.7. Location of Hartlepool Nuclear Power Station.

The station belongs to the so-called modified first generation type of AGR's. Its design, is characterized by the location of the boilers in special cavities in the pressure vessel. Thus it is named a multi-cavity pressure vessel design.

Figure 10.8 shows a schematic comparison of the design of the pressure vessel for Dungeness B, Hunterston B and Hartlepool. It is seen that a slight evolution of the design took place from Dungeness B to Hinkley Point B, whereas a quite different approach was introduced at Hartlepool.

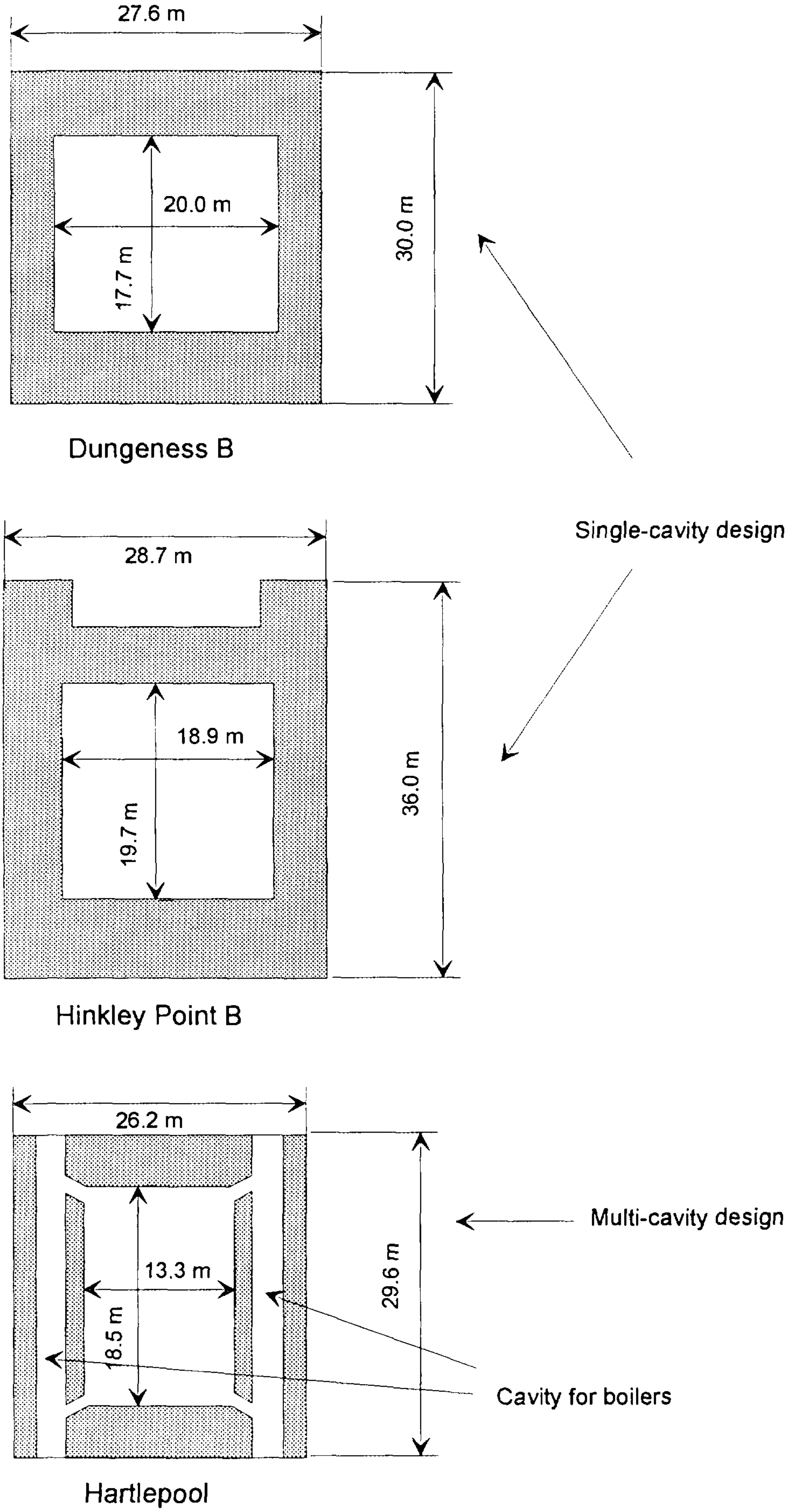

Figure 10.8. Dimensions of single- and multi-cavity pressure vessels.

Figure 10.9 shows a layout of the multi-cavity design for the Hartlepool AGR station, where the eight boilers are located in separate cavities in the concrete walls. The gas circulators are mounted vertically below the boilers and all feedwater, superheat steam and reheat connections are brought out through the top of the cavity. The concept of this boiler layout is called pod-boilers

The main reason for choosing this design is that the boiler units can be pre-fabricated in the workshop, ready for insertion into the vessel. Thus site work is reduced, and the concrete vessel can be completed in parallel with the fabrication of the boilers. Furthermore, the boilers can always be removed if major repair or replacement becomes necessary. In this design no major tube penetrations exist in the side of the concrete pressure vessel.

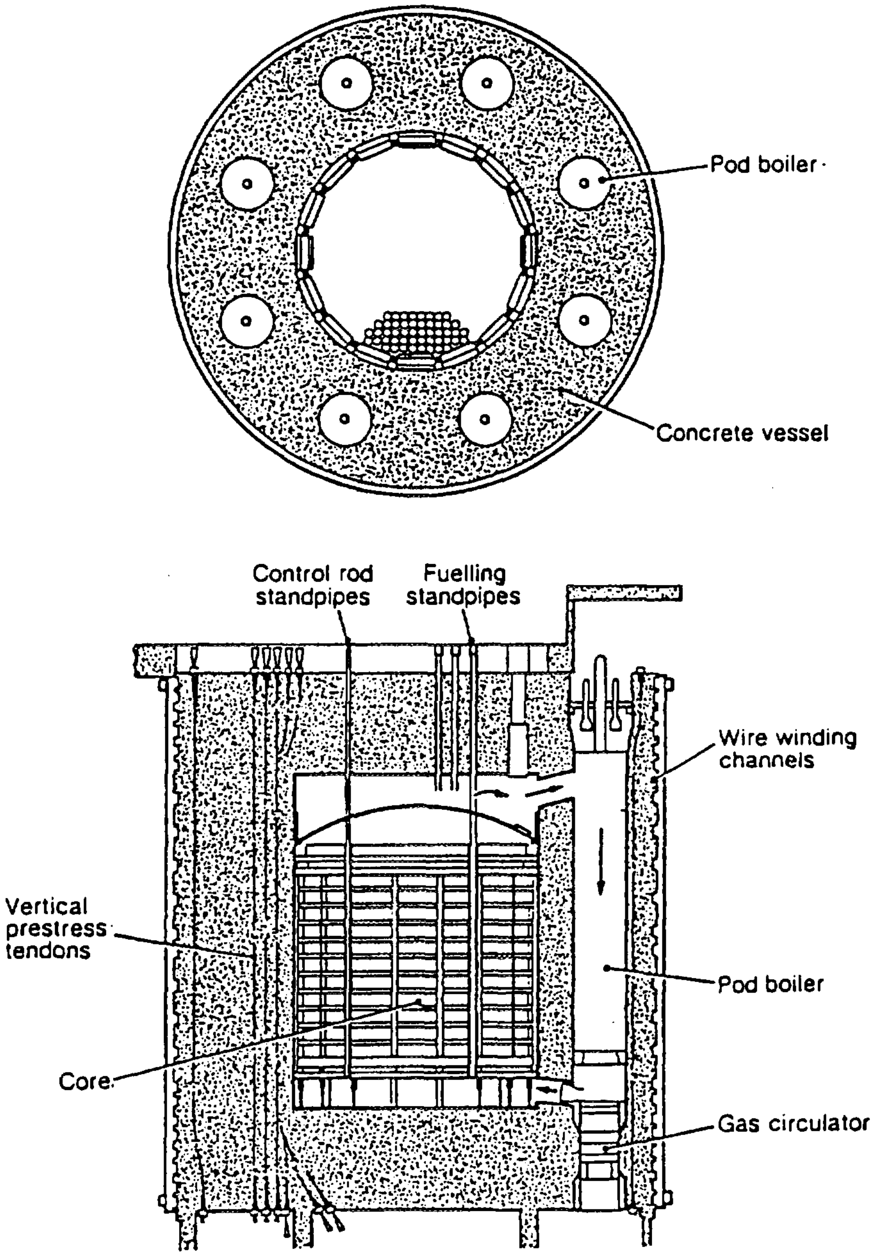

Figure 10.9. Pressure vessel layout for Hartlepool AGR.

However, the multi-cavity design was abandoned again in the second generation AGR's. This was mostly due to problems with sealing of the top heads of the pod-boiler pressure vessel plug. Thus, the integrity of the containment was challenged. Also the economic benefits of the design turned out to be less than expected. Finally new enhanced safety requirements were difficult to include in the design.

Figure 10.10 shows the load factors for Hartlepool AGR station and Table 10.3 the main design data.

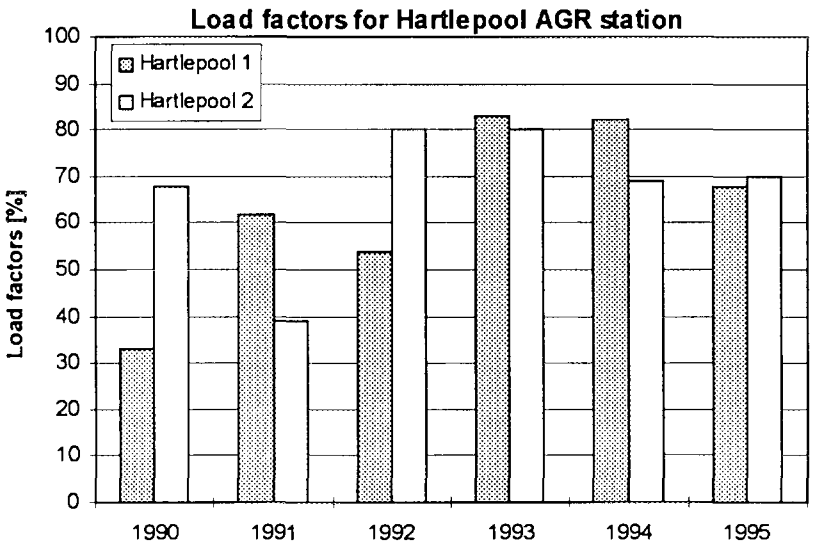

Figure 10.10. Load factors for Hartlepool AGR station.

Table 10.3. Summary of design data for Hartlepool AGR nuclear power station

Station design		
Reactor type	AGR	Advanced Gas Cooled
Electrical output (gross)	2 x 660	MWe
Thermal output (gross)	2 x 1500	MW
Efficiency	41.1	%
Reactor		
Moderator	Graphite	
Coolant gas	CO_2	
Number of fuel channels	324	
Diameter of fuel channel	270	mm
Number of control channels	81	
Diameter of control channels	114	mm
Secondary shutdown system	nitrogen	
Lattice pitch (square)	460	mm
Active core diameter	9.3	m
Active core height	8.2	m
Mean gas pressure	41	bar
Mean inlet gas temperature	286	°C
Mean outlet gas temperature	648	°C
Total gas flow	3623	kg/s
Fuel elements		
Material	UO_2	
Type	36 pin cluster	in graphite sleeve
Pellet diameter	14.5	mm
Central hole diameter	5.1	mm
Inner graphite sleeve diameter	190	mm
Cladding material	Stainless steel	
Cladding thickness	0.37	mm
Element length	1036	mm
Number of elements per channel	8	
Enrichment	2.2 - 2.7	%
Average power density	2.8	kW/litre
Mass of uranium per reactor	129	tonnes
Mean fuel rating	12.5	MWt/tU
Mean fuel discharge	18,000	MWd/tU
Pressure vessel		
Material	Pre-stressed	concrete
Inner liner	Stainless steel	
Internal diameter	13.1	m
Internal height	18.3	m
External diameter	25.9	m
External height	29.3	m

Table 10.3 continued

Design pressure	45.3	bar
Gas circulators		
Type	Centrifugal	
Regulation	Constant speed	variable inlet vanes
Speed	2970	rev/min
Number circulators	8	
Total power consumption	34	MW
Boilers		
Number of boilers	4	
Number of units per boiler	2	
Feedwater temperature	156	°C
Gas inlet temperature to reheater	634	°C
Gas outlet temperature	278	°C
Superheater outlet pressure	175	bar
Superheater outlet temperature	543	°C
Steam generation	---	kg/s
Reheater inlet pressure	42	bar
Reheater inlet temperature	342	°C
Reheater outlet pressure	40	bar
Reheater outlet temperature	539	°C
Turbine plant		
High pressure turbine:		
Number of flows	1	
Inlet pressure	163	bar
Inlet temperature	538	°C
Outlet pressure	42	bar
Outlet temperature	342	°C
Intermediate pressure turbine:		
Number of flows	2	
Inlet pressure	39	bar
Inlet temperature	538	°C
Low pressure turbine:		
Number of flows	6	
Number of feedwater heaters	4	
Feedwater pump driven by steam		
Generator:		
Speed	3000	rev./min
Stator coolant	Water	
Rotor coolant	Hydrogen	
Voltage	23500	V

Appendix E : Heysham AGR station

Heysham AGR nuclear power plant, located in Lancashire 30 km north-west of Preston (Figure 10.11), consists of both first generation of AGR's, Heysham I and second generation Heysham II.

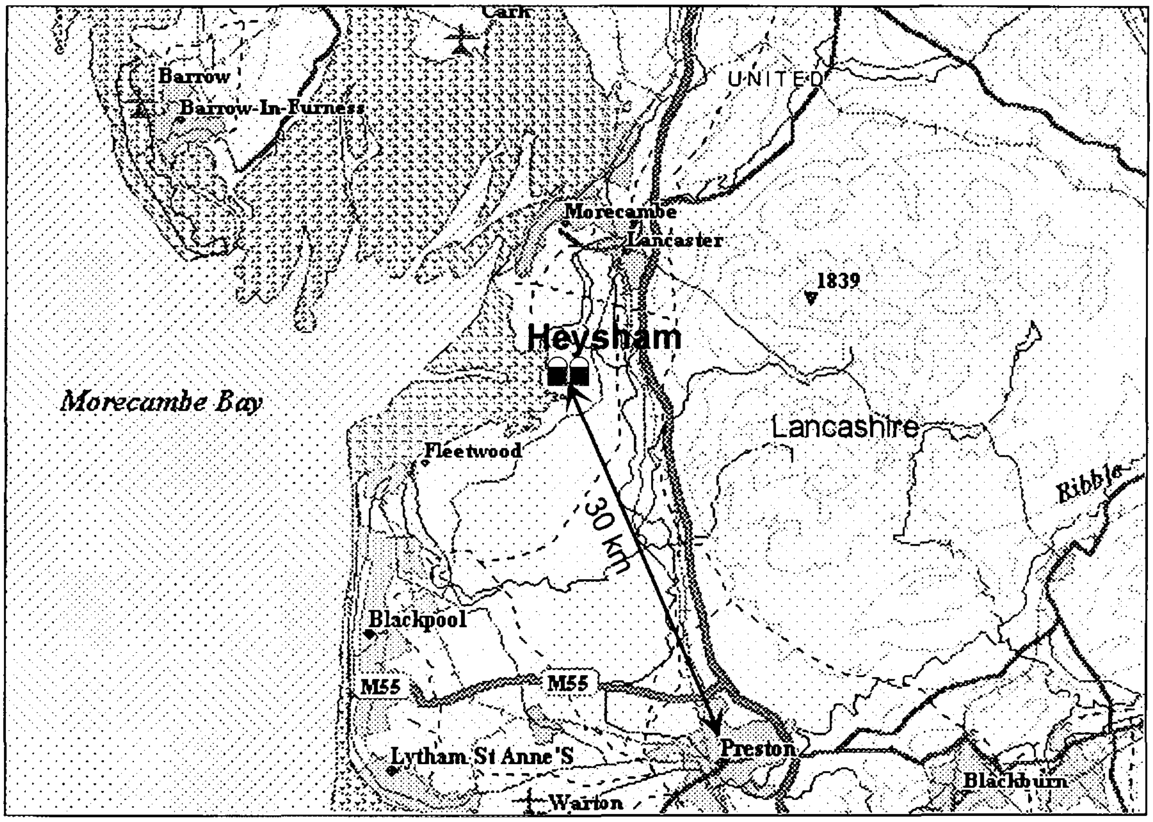

Figure 10.11. Location of Heysham AGR station.

Heysham II is sister station to Torness and the design parameters are those of Torness. The construction of Heysham II began in 1980 and it was connected to the grid in 1988. The load factors for both units of Heysham I respectively Heysham II are shown are shown in Figure 10.12 and Figure 10.13.

Heysham I belongs to the so-called modified first generation of AGR's with multi-cavity pressure vessel design. Hartlepool AGR is sister station to Heysham I. Therefore a more detailed description of the design is found in *Appendix D : Hartlepool AGR station* page 77.

The construction of Heysham I began in 1969 with the first electricity production in 1983. Figure 10.14 shows a comparison of the layout between Heysham I and Heysham II. Heysham I is characterized as having an integral reactor-generator complex, which acts as a single main power station building. This was a utility requirement at that time.

Finally Table 10.4 shows a comparison of the main data for all seven stations of AGR's.

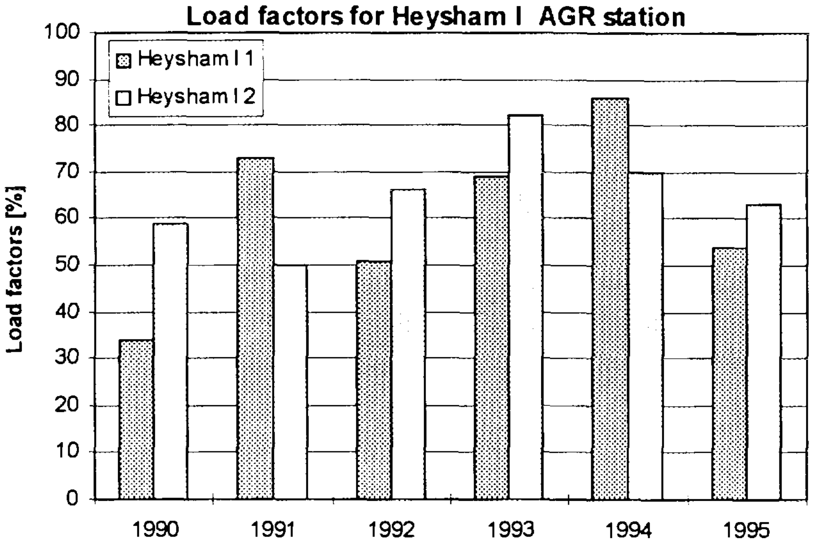

Figure 10.12. Load factors for Heysham I AGR station.

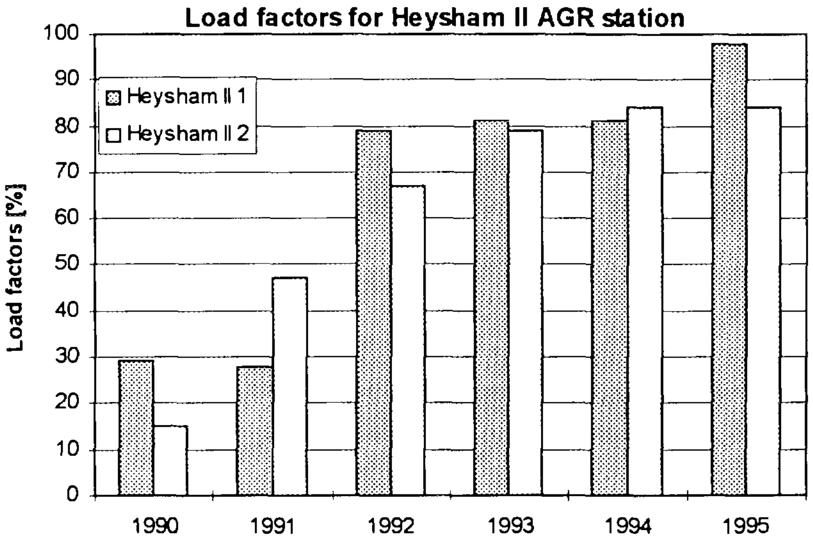

Figure 10.13. Load factors for Heysham II AGR station.

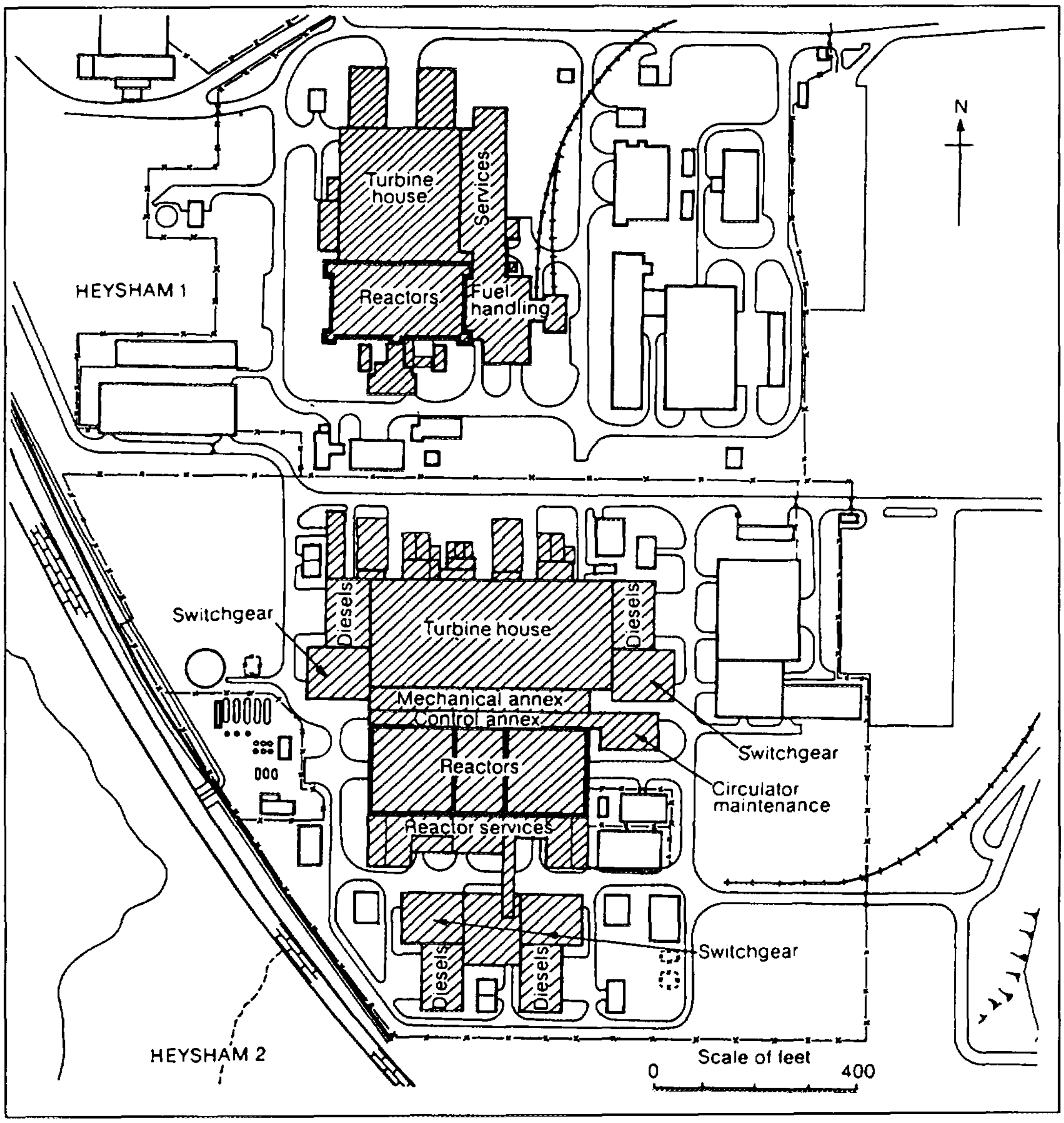

Figure 10.14. Comparison of layout of Heysham I and Heysham II AGR stations.

Table 10.4. Comparison of main data for all 7 sites of AGR's in UK.

Type of AGR	First generation			Modified first generation		Second generation	
Station	Dungeness B	Hinkley Point B	Hunterston B	Hartlepool	Heysham I	Heysham II	Torness
Reactor							
Power (MWe)	2 x 660	2 x 660	2 x 660	2 x 660	2 x 660	2 x 660	2 x 660
Start of construction	1966	1967	1967	1968	1969	1980	1980
Year of first operation	1983	1976	1976	1984	1983	1988	1988
Num. of fuel channels	408	308	308	324	324	332	332
Lattice pitch (mm)	394	460	460	460	460	460	460
Core diameter (m)	9.5	9.1	9.1	9.3	9.3	9.5	9.5
Core height (m)	8.3	8.3	8.3	8.2	8.2	8.3	8.3
Num. of control channels	57	81	81	81	81	89	89
Mean gas pressure (bar)	32	41	41	41	41	41	41
Mean inlet gas temp. (°C)	320	292	292	286	286	339	339
Mean outlet gas temp. (°C)	675	645	645	648	648	639	639
Total gas flow (kg/s)	3378	3680	3680	3623	3623	4067	4067
Fuel elements							
Type	36 pins	36 pins	36 pins	36 pins	36 pins	36 pins	36 pins
Pellet diameter (mm)	14.5	14.5	14.5	14.5	14.5	14.5	14.5
Num. of elements per chan.	8	8	8	8	8	8	8
Power density (kW/litre)	2.4	2.8	2.8	2.8	2.8	3.0	3.0
Mass of uranium (tonnes)	152	129	129	129	129	123	123
Pressure vessel							
Material	concrete	concrete	concrete	concrete	concrete	concrete	concrete
Internal height (m)	17.7	17.7	17.7	18.5	18.5	21.9	21.9
Internal diameter (m)	20.0	19.0	19.0	13.3	13.3	20.3	20.3
Side wall thickness (m)	3.8	5.0	5.0	Figure 10.8	-	5.0	5.0
Top slap thickness (m)	6.3	5.5	5.5	Figure 10.8	-	5.4	5.4
Bottom slap thickness (m)	5.9	7.8	7.8	Figure 10.8	-	7.5	7.5
Design pressure (bar)	33.6	43.3	43.3	45.3	45.3	45.7	45.7
Gas circulators							
Number of circulators	4	8	8	8	8	8	8
Power consumption (MWe)	45	45	45	34	34	42	42
Boilers							
Number of boilers	4	4	4	4	4	4	4
Number of units per boiler	1	3	3	2	2	3	3
Feedwater temp. (°C)	163	168	168	156	156	158	158
Gas inlet temp. (°C)	661	634	634	634	634	619	619
Gas outlet temp. (°C)	279	288	288	278	278	293	293
Superheater outlet pres. (bar)	172	160	160	175	175	173	173
Superheater outlet temp. (°C)	571	538	538	543	543	541	541
Turbine plant							
High pressure turbine							
Number of flows	1	1	1	1	1	1	1
Inlet pressure (bar)	163	160	160	163	163	167	167
Inlet temperature (°C)	566	538	538	538	538	538	538
Intermediate pressure turbine							
Number of flows	2	2	2	2	2	2	2
Inlet pressure (bar)	41	39	39	39	39	41	41
Inlet temperature (°C)	566	538	538	538	538	538	538
Low pressure turbine							
Number of flows	6	6	6	6	6	6	6

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