ADVANCED GAS COOLED REACTORS

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Contents

Summary

There are several different classifications of nuclear reactors in operation and in design. The major differences in design generally include the reactor core layout, the fuel configuration, the moderator material, the coolant type and the type of control rods. With specific designs, each type of reactor also has particular operating characteristics.

An overview of the design and characteristics of the Advanced Gas Cooled Reactor (AGR) is given. This type of reactor is operational only in Great Britain. Currently, 14 AGR's are in operation at 6 different sites. Each station employs twin reactors. The evolution of the design and operating characteristics of the AGR in these stations is presented. Technical data is summarized and compared for each generation of the AGR design.

In brief, the AGR makes use of slightly enriched uranium fuel in a solid graphite moderator. The coolant is compressed carbon dioxide. The boilers are arranged around the reactor core within the prestressed concrete pressure vessel. Black and grey control rods are used for primary control. The thermal efficiency of the AGR is relatively high due to high coolant operating temperatures.

The AGR was a design improvement over the initial Magnox gas cooled reactor (GCR). No further development has taken place for the AGR design. The latest direction in the design of gas cooled reactors has been with the High Temperature Gas Cooled Reactor (HTGR). This new design makes use of even higher operating temperatures to further improve thermal efficiency.

1. Introduction

1.1. Magnox Reactors

The Magnox reactor was the forerunner of the Advanced Gas Cooled Reactor (AGR). Several were built and entered commercial service in the United Kingdom. Their subsequent performance and low fuel cost made them very economical electrical power producers in the United Kingdom. As they evolved into a more complex but more compact design they approached the design of the AGR and in the final version really only differed from the AGR in the type of fuel. Hence the Magnox and AGR can be considered to be essentially the same type of reactor.

The Magnox reactor was a gas cooled graphite moderated reactor with stacked graphite blocks making up the reactor core and using carbon dioxide under pressure as a coolant. The term “magnox” was derived from the fuel which was natural uranium metallic fuel clad in magnesium alloy (magnox). At the time when this reactor was developed in the United Kingdom, enriched uranium was not available but a combination of pure natural uranium fuel and a graphite moderator would give critical conditions and allow a continuous fission chain reaction provided the fuel cladding and coolant had low neutron absorption characteristics. The magnox cladding surrounding the fuel contained the fission products and, with fins on the outer surface, promoted good heat transfer to the coolant.

The general configuration of the magnox reactor was a large graphite block core with a square array of fuel channels into which the fuel elements were placed and through which the carbon dioxide coolant flowed. Provision was made for control rods to be inserted into the core for control and shutdown purposes. Carbon dioxide flow was upwards through the core and then downwards through adjacent boilers in which steam was generated. The steam circuit supplied conventional steam turbines.

1.2. Design Evolution

Design data	Station capacity MW	Reactor heat rating, MW	Main turbine-generators, MW	Thermal efficiency, %	Commissioning year
Berkeley	275	558	4 x 83	24	1962
Bradwell	300	531	6 x 52	28	1962
Hunterston A	320	569	6 x 60	28	1964
Hinkley Point A	500	971	6 x 93	26	1965
Trawsfynydd	500	860	4 x 145	29	1965
Dungeness A	550	840	4 x 143	33	1965
Sizewell A	579	948	2 x 325	31	1966
Oldbury	600	892	2 x 313	33	1967
Wylfa	1179	1876	4 x 334	32	1969

Data from "Modern Power Station Practice" by British Electricity International

Table 1: Development of magnox station capacity

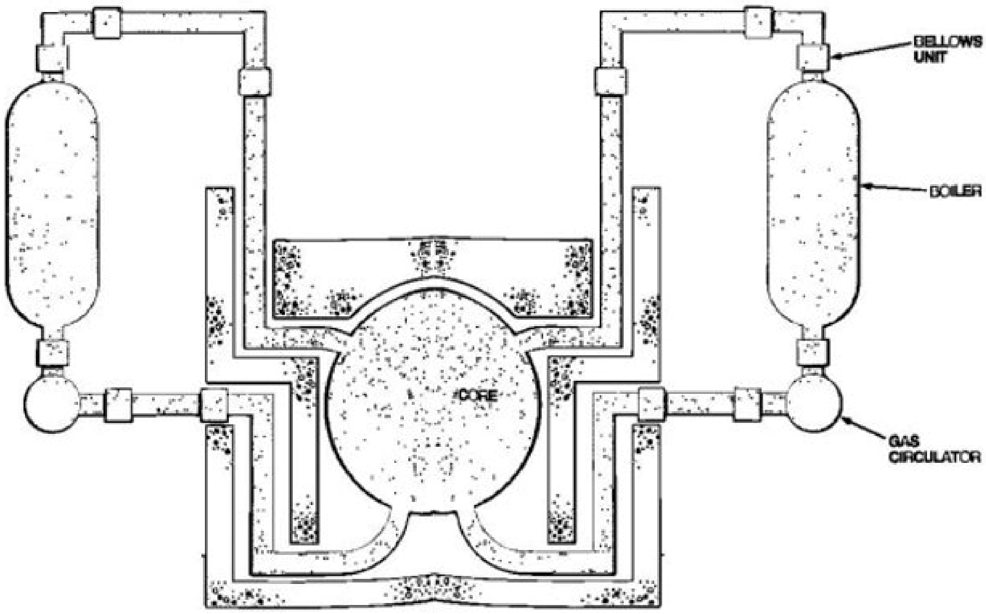

Figure 1: Magnox reactor steel pressure vessel and external boilers

A significant design constraint in the magnox reactors was the temperature at which the fuel could operate. Although pure uranium metal melts at 1130°C, it undergoes an α - β phase transition at 661°C. Associated with this transition is a volume change of about

1%. Any thermal cycling through this temperature thus leads to surface deformation and cavity formation. This limits the practical operating peak fuel temperature to not more than about 660°C. Furthermore the magnesium alloy, magnox, has a low melting temperature of about 650°C so the cladding is limited to a temperature of not more than this value. These limitations in turn limited the maximum reactor coolant outlet temperature to about 400°C which limited the maximum steam temperature. Design refinements over the years and the use of various alloying materials for both fuel and cladding allowed coolant and steam temperatures to rise slightly with the result that capacity and efficiency increased with more advanced designs as shown in Table 1.

Another significant parameter affecting the design and performance of magnox reactors was the pressure of the carbon dioxide coolant. An increased pressure of the gas results in increased density and an increase in the rate of heat removal from the reactor core. Most of the early magnox reactors had spherical steel pressure vessels surrounding the core and external coolant ducts leading to separate boilers as shown in Figure 1. This limited the pressure of the reactor coolant since the pressure vessel had to be large enough to accommodate the reactor core but its thickness not so great as to create manufacturing and erection difficulties. The first magnox reactors had carbon dioxide pressures of less than 1 MPa but this was gradually increased to nearly 2 MPa as the design evolved as shown in Table 2. To go beyond this value required an entirely new concept which was the development of the prestressed concrete pressure vessel.

Station	**MW (sent out) per reactor**	**Internal Diameter m**	**Gas pressure MPa**	**Shape**	**Steel thickness mm**
Berkeley	138	15.25	0.86	Cylinder	76
Bradwell	150	20.25	0.91	Sphere	76
Hunterston A	160	21.30	1.03	Sphere	73
Hinkley Point A	250	20.45	1.28	Sphere	76
Trawsfynydd	250	18.60	1.66	Sphere	89
Dungeness A	275	19.05	1.85	Sphere	102
Sizewell A	290	19.35	1.96	Sphere	105
Oldbury	300	23.45	2.42	Cylinder	Concrete
Wylfa	590	29.25	2.66	Cylinder	Concrete

Data from “Modern Power Station Practice” by British Electricity International

Table 2: Development of magnox reactor pressure vessels

The prestressed concrete pressure vessel as shown in Figure 2 was adopted for the last two magnox plants and for the next generation of advanced gas cooled reactors. With this design the steam generators are located adjacent to and around the periphery of the core of the reactor. The prestressed concrete pressure vessel surrounds both the reactor core and boilers and serves to contain the reactor coolant under pressure and to provide the necessary biological shielding for the rest of the plant. The concrete, being weak in tension, is maintained in compression by steel tendons located in helical fashion around the circumferential shell and in a semi-radial manner across the top and bottom slabs. Compression in the concrete is obtained by post-tensioning the steel tendons separately after construction. The stress in the tendons can be monitored and they can be re-tensioned if necessary. The pressure that such a vessel can withstand is determined by the mesh of steel tendons thus allowing higher internal gas pressures than with a simple steel shell. Carbon dioxide pressures for the last two magnox reactors are well above 2 MPa and for the next generation AGRs around 4 MPa.

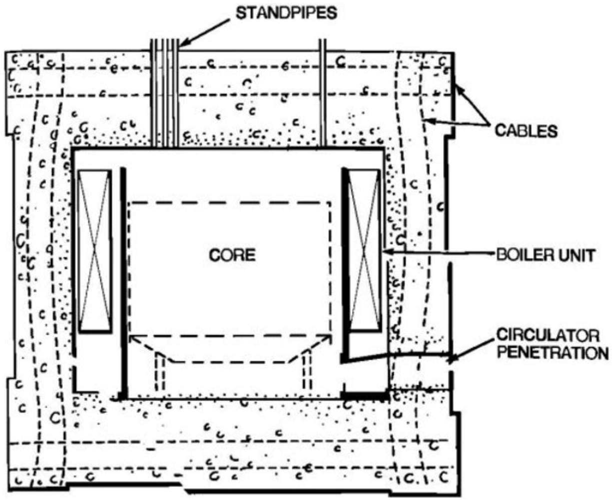

Figure 2: Magnox and AGR concrete pressure vessel with internal boilers

A further constraint imposed by limited fuel temperatures and hence relatively low gas outlet temperatures is that of steam generation. For good efficiency in the steam cycle, feedwater heating up to nearly saturated conditions is desirable. Most heat from the gas should be for evaporation and superheating. To match the gas conditions this requires a relatively low steam pressure which in turn is detrimental to cycle efficiency. However by adopting a dual pressure steam cycle, with an additional high pressure loop, the steam conditions can be made to better match the gas conditions and improve the thermodynamic efficiency. This naturally increases the complexity of the cycle. However with increased gas temperatures the single cycle could be used on the last magnox plant and on the subsequent AGRs.

1.3. Advanced Gas Cooled Reactors

The Advanced Gas Cooled Reactor (AGR) is an improvement over the earlier Magnox reactors built in Great Britain. The older Magnox gas cooled reactors are graphite-moderated and are cooled with pressurized carbon dioxide. The use of natural metallic uranium as fuel limited the heated coolant gas temperature to a maximum of about 400°C so that the fuel would not melt. At this temperature, the temperature and pressure of the steam produced is lower than that produced in a typical coal-fired boiler. The resulting thermal efficiency is only about 30%. This low efficiency together with a low core power density and core volume limited by the size of the pressure vessel gives a maximum electrical power output of about 300 MW. This was a limitation as "standard" 660 MW turbine-generators as used in coal and oil fired stations could not be used.

In developing the AGR, it was desired to operate at a much higher temperature in order to increase the thermal efficiency. Slightly enriched uranium dioxide (about 2.5% U-235) was then available, and in the oxide form, the fuel could withstand a much higher temperature. The coolant operating temperature was thus raised to about 650°C, and a higher pressure and power density could be employed. The resulting thermal efficiency reached about 40% and higher steam conditions allowed the standard 660 MW generating sets to be used.

The use of AGRs is at present limited to Great Britain. There are 14 AGRs in operation at seven different stations at six sites. Each station employs twin reactors. Table 3 summarizes all of the AGRs currently in operation. Not shown in the list is the first prototype AGR which was constructed at Windscale. It is now permanently out of operation. The * in the Table 3 denotes that the first generation design was somewhat modified in these two plants.

Plant	Gross Electrical Output (MW)	Generation of AGR	Start of Operation
Dungeness B	2 x 660	first	1983-85
Hinkley Point B	2 x 660	first	1976
Hunterson B	2 x 660	first	1976-77
Hartlepool	2 x 660	first*	1983-84
Heysham I	2 x 660	first*	1983-84
Heysham II	2 x 660	second	1988
Torness	2 x 660	second	1988

Data from “Description of the Advanced Gas Cooled Type of Reactor” by Erik Nonbol

Table 3: Summary of AGR stations in operation

2. General Configuration

2.1. General Reactor Arrangement

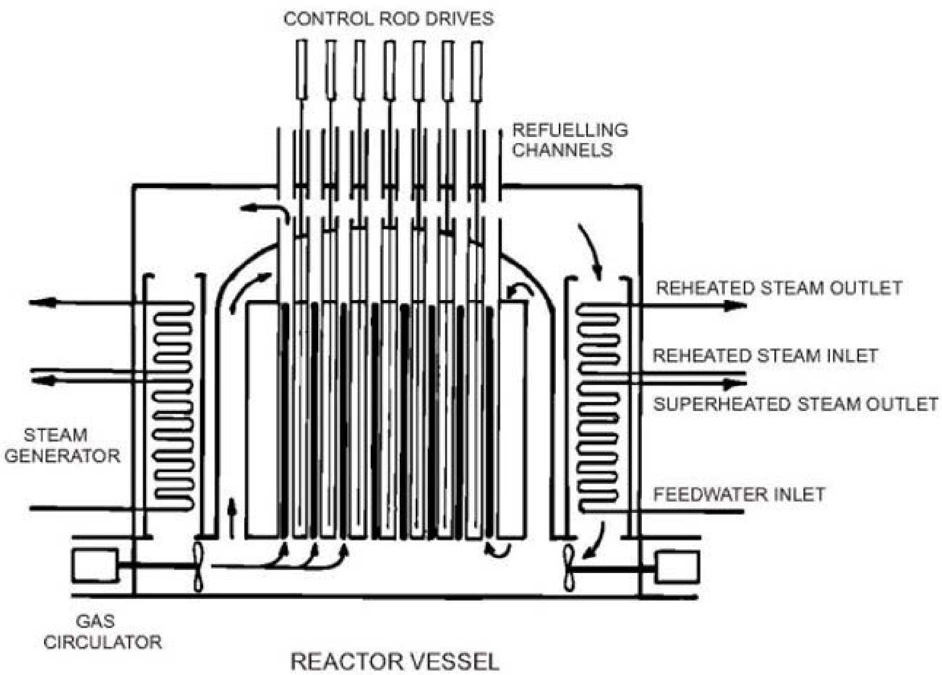

Figure 3: Diagrammatic cross-section of a typical AGR

The general layout of a typical AGR is shown in Figure 3. In each twin unit AGR power plant, two reactors serve two turbines in one turbine house with all auxiliary services combined in a single complex.

A common refueling machine is used for both units. For this type of reactor, refueling is performed while the reactor is on-line. The reactor core and boiler units are enclosed by a concrete pressure vessel. The CO_2 coolant is circulated through the graphite moderator where it absorbs heat.

This heat is then transferred to the boiler units arranged around the reactor core. Due to a relatively low core power density, the reactor core is quite large, leading to a large pressure vessel and a tall fueling machine to accommodate the long fuel elements. This leads to a very large structure for the reactor.

2.2. Reactor Core

A typical reactor moderator consists of a 16-sided stack of graphite bricks. Not only does it act as a moderator, but it also provides the channels necessary for fuel assemblies, control rods, and coolant flow.

Although the UO_2 fuel can withstand the higher coolant temperatures near 650°C, the graphite moderator will break down due to reactions with the CO_2. As will be explained in further detail in the coolant circuit section, a re-entrant flow pattern for the coolant was selected in order to minimize the degradation effects.

Generally, the maximum permissible weight loss of graphite is about 5% over a 30-year lifetime. Beyond this, the strength of the graphite begins to decrease significantly.

Shielding around the core is required to protect the surrounding steelwork and boilers from neutrons and gamma rays. An additional thickness of graphite and steel is provided around the core for this purpose.

The upper neutron shield consists of graphite and steel bricks while the lower shield is constructed of graphite bricks resting on steel plates. Steel rods located in two outer rings of graphite bricks provide the radial shielding.

This shielding is also important in that it reduces radiation levels during shutdown so that the boilers may be accessed.

The general layout of the reactor core is depicted in Figure 4. This figure shows a part cross-section of the reactor core at Torness station. The outer layer consists of graphite reflector elements.

For control purposes control rods are inserted into the core and, under emergency conditions, beads and nitrogen may be injected between the fuel channels as a means to absorb neutrons.

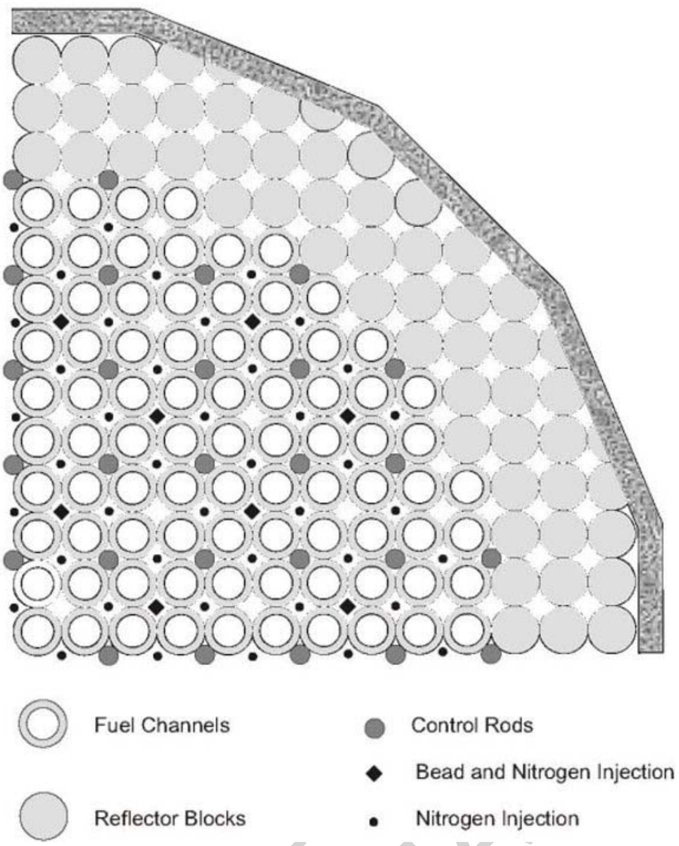

Figure 4: One quarter cross-section of reactor core

A summary of the design parameters for the reactor core of one unit of each of the generations of AGRs is given in Table 4. The initial design in the Dungeness station was significantly different from the designs that followed. The main difference was the lattice pitch. The fuel channels were much closer together, giving many more fuel channels in about the same size core. The new designs tended towards a larger fuel spacing which would give a longer slowing down distance for the neutrons.

	Dungeness B	**Hinkley Point B & Hunterson B**	**Hartlepool & Heysham I**	**Heysham II & Torness**
Moderator	Graphite	Graphite	Graphite	Graphite
Coolant Gas	CO_2	CO_2	CO_2	CO_2
Number of Fuel Channels	408	308	324	332
Lattice Pitch (square) (mm)	394	460	460	460
Active Core Diameter (m)	9.5	9.1	9.3	9.5
Active Core Height (m)	8.3	8.3	8.2	8.3

Data from “Description of the Advanced Gas Cooled Type of Reactor” by Erik Nonbol

Table 4: AGR reactor core parameters

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Biographical Sketch

Tim McKeen obtained a B.Sc. in chemical engineering from the University of New Brunswick in 2000, with some option course work taken in nuclear engineering. In 2003, he obtained a M.Sc. in chemical engineering from the University of Saskatchewan with his thesis on computational fluid dynamic simulation of fluidized beds. Between these two degrees and since 2003, he has worked in consulting engineering on the design and startup of various chemical, power and wastewater treatment processes. His experience includes projects for the power and energy industry such as the design of an Orimulsion fly ash handling and treatment facility and a study on recovery of energy from pulp and paper waste sludge using fluidized bed boilers. He currently is a process chemical engineer at ADI Limited.