LIGHT WATER GRAPHITE REACTORS

R.A. Chaplin
Department of Chemical Engineering, University of New Brunswick, Canada

Keywords: Light Water Graphite Reactors, Reactor Core, Fuel Elements

Contents

Summary

The Light Water Graphite Reactor is like a combination of the Advanced Gas Cooled Reactor and the Steam Generating Heavy Water Reactors (Heavy Water Light Water Reactor). The moderator is graphite so the core is very similar to that of the Advanced Gas Cooled Reactor being made of graphite blocks with vertical holes for the fuel channels and control rods. The coolant is light water contained in pressure tubes which also carry the fuel elements as in the Steam Generating Heavy Water Reactor. Steam is generated directly in the reactor core and separated from the water externally in steam drums. This direct steam cycle has the advantage of circuit simplicity.

The Light Water Graphite Reactor was designed as a large power producing reactor to be built at central generating stations having typically four reactors each. They were intended to provide base load power for the grid system. At the time of initial construction steam turbines of the required capacity were not yet available so it was common to have one reactor supplying steam to two turbine-generators.

Certain factors favored the choice of this type of reactor. Since the main element of the reactor core was an independent fuel channel there was no definite upper limit to capacity as additional channels could be added to the basic design. The components being modular could be manufactured at existing facilities. Refueling on line was possible with independent fuel channels leading to high load factors. Subsequent operation indicated that design reserves were more than adequate and that, with minimal changes, power could be increased by a factor of 1.5 in subsequent designs of the same physical size.

This type of reactor as designed by the Soviet Union proved to be robust and reliable in operation. However certain safety aspects considered to be essential for nuclear reactors in western countries were not incorporated into the design. It is however not clear whether such additional safety features would have prevented the infamous accident to one of these reactors at Chernobyl as, at the time of the accident, various safety systems had been bypassed and operation was beyond the specified limits for stable operation.

1. Introduction

The RBMK series of nuclear reactors are classified as Light Water Graphite Reactors (LGR) having a light water coolant passing through fuel channels in a graphite moderator. The design was developed by the Soviet Union at a time when there was minimal technology transfer to or from western bloc countries. The design of the RBMK therefore evolved separately. Although many principles are very similar to other reactors such as the Advanced Gas Cooled Reactor (AGR) and the Steam Generating Heavy Water Reactor (SGHWR) certain design standards, particularly with regard to safety, were not as rigorous as those in western countries. Nevertheless the RBMK reactors were built as robust and reliable units for the generation of base load electrical power. The design was modular in concept so could be easily adapted for larger units. Also many components were adapted from the regular power industry so could be manufactured using standardized technology and conventional techniques. They served the Soviet Union well and have since continued operation in both Russia and the Ukraine.

2. General Configuration

Light water graphite moderated reactors use graphite blocks as the moderator. The RBMK - 1000 type reactors, 1000 meaning 1000 MW of electrical output, contain approximately 1700 tons of graphite blocks. The graphite core is arranged cylindrically as a 7 m tall and 11.8 m diameter stack. Graphite is an excellent moderator. This is due to the fact that it has a very large neutron scattering cross section while a very low neutron adsorption cross section. Graphite however has a very long neutron slowing down distance and thus these reactors are very large in size as with other forms of graphite moderated reactors. Figure 1 shows an extremely simplified version of the reactor core. This diagram however is useful in that it allows the pressure tubes, control rods, coolant pumps and steam separator relative to the graphite core to be visualized. Through the graphite core, pressure tubes carry saturated water and small amounts of steam which have been generated. In the RBMK-1000 series reactor there are 847 of these pressure tubes. The water boils in the reactor core and removes heat by direct contact with the fuel assemblies which are also located in the pressure tubes. Control of the reactor core is done through various control rods. The control rods are strategically arranged in the core. In the RBMK reactor there are 179 control rods. Control rods are not cooled by the primary circuit coolant but have their own separate coolant circuit.

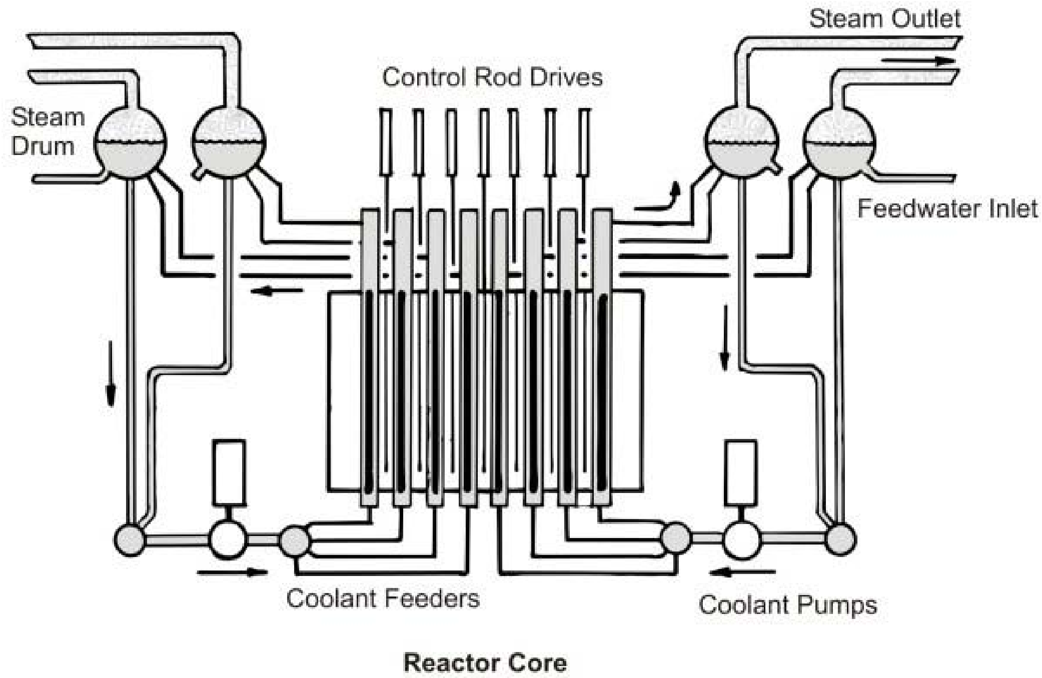

Figure 1: General arrangement of reactor

3. Core Arrangement

3.1. Core Structure

Being a graphite moderated reactor the core is made up of prismatic graphite blocks. For the RBMK- 1000 reactor the active core is approximately 12 m in diameter and 7 m in height. This is surrounded by a reflector to give a total core size of about 14 m in diameter and 8 m in height. The moderator consists of 2488 vertical columns made up of graphite blocks 250 mm by 250 mm. Some 1661 columns in the active core region have vertical holes to form the fuel channels in a square array with a pitch of 250 mm as shown in Figure 2. The pressure tubes forming the fuel channels are made of zirconium alloy with an internal diameter of 88 mm and a wall thickness of 4 mm. Each fuel channel carries two fuel sub-assemblies each of length 3.5 m and having 18 fuel rods and a supporting tube. A further 223 columns in the active core have vertical holes to provided for control and instrumentation devices. These are set in a square array at 45° to the fuel channel array and with a pitch of 707 mm. They are lined with zirconium alloy tubes also with an internal diameter of 88 mm but with a wall thickness of 3 mm. A separate water circuit is used to cool the devices with water flowing down the channels. Of these 223 channels, 211 carry control rods and 12 vertical power profile sensors and are uniformly distributed across the active core. For radial power monitoring, self powered detectors are in the central tubes of 130 fuel assemblies. In addition, there are 20 vertical holes 4 mm in diameter along joints in the graphite blocks to take thermocouples at different heights for monitoring the temperature of the graphite.

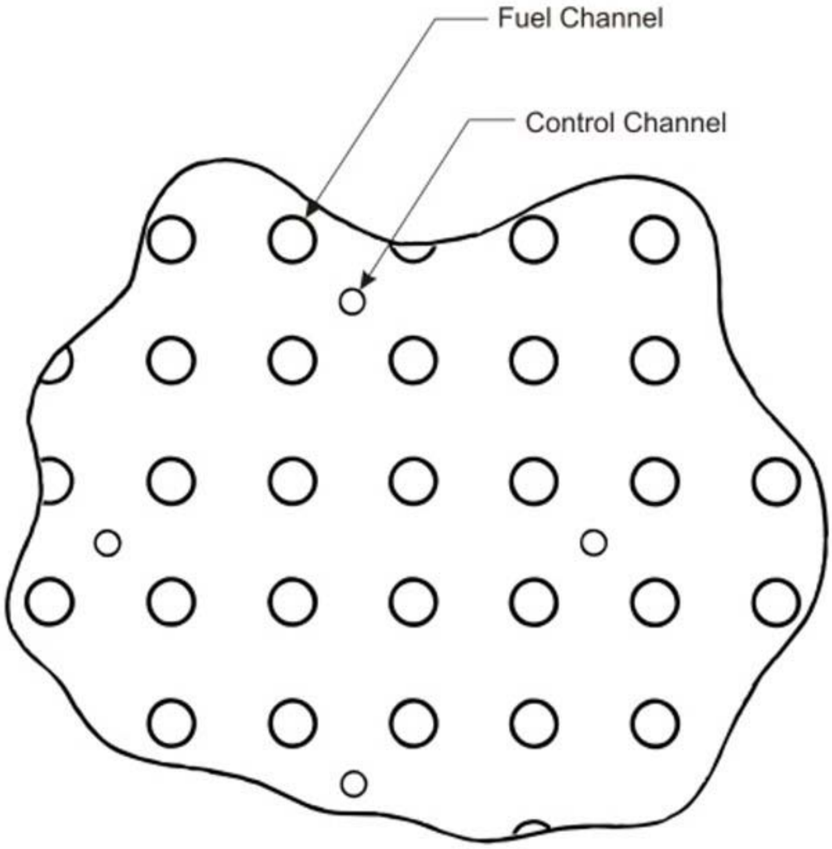

Figure 2: Reactor core part cross section

The control rods are made up of six elements with articulated joints. Additional non-absorbing elements at the bottom prevent displaced water from filling the region vacated by the rods as they are withdrawn to avoid counteracting the reactivity changes effected by the rods.

3.2. Fuel

The fuel used in the LGR is high purity uranium dioxide UO_2. It should be noted that the 2 does not literally mean that every uranium atom has two oxygen atoms attached to it. This number corresponds to an average value which normally lies somewhere between 1.9 and 2.1. The uranium is primarily U-238 but contains from 1.4 % to 2.4 % U-235 which is the fissionable isotope. This concentration of the U-235 isotope represents slightly enriched uranium dioxide. The high purity uranium dioxide is fabricated into pellets. The pellets are dished at each end and have holes drilled axially through them in order to accommodate the build up fission products. Figure 3 shows a vertical cross section of the fuel pellet.

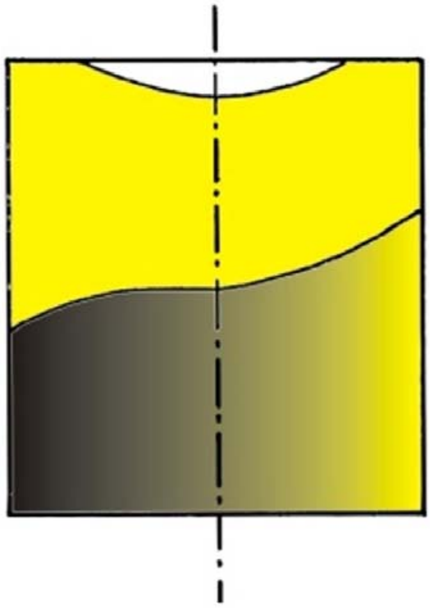

Figure 3: Fuel pellet

The pellets are encapsulated in a zirconium alloy sheath which is commonly referred to as the cladding. The cladding is filled with a pressurized inert gas, typically helium, and sealed with an end plug. The reason for the gas is to partially offset the external pressure during operation within the pressure tubes. The fuel rods are made into bundles with 18 fuel rods arranged in two concentric circles around a central supporting bar. These are then incorporated into an assembly consisting of two bundles and a suspension bracket. Figure 4 shows a single fuel rod, also known as an element, while Figure 5 shows a fuel bundle and the arrangement of the supporting grid.

Some of the design parameters of the fuel bundles making up the assemblies are found in Table 1.

Parameter	Value
Material	UO_2
Enrichment, initial core	1.8/2.4 %
Enrichment, reload	2.4 avg %
Form	pellet
Number of rods per assembly	18 x 2
Rod height	347 mm
Rod outside diameter	13.63 mm
Pellet height	15.0 mm
Pellet outside diameter	11.5 mm

Table 1: Design parameters for fuel assemblies

Figure 4: Fuel rod

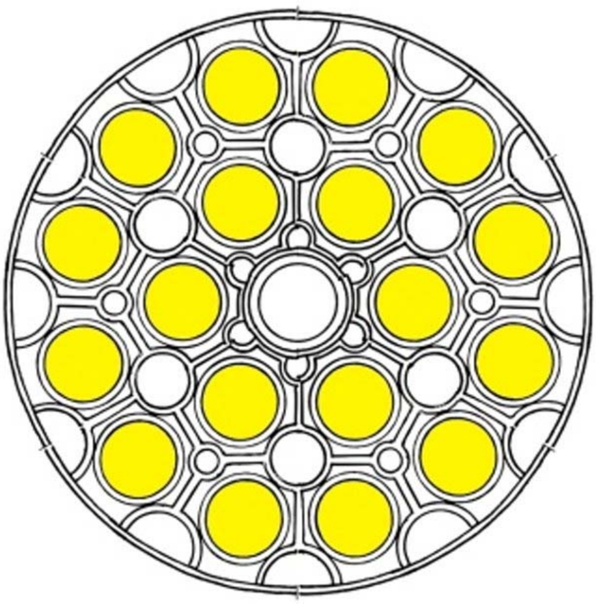

Figure 5: Fuel bundle showing supporting grid

3.3. Coolant

Light water or H_2O passes through the reactor core and absorbs heat. A feature of this reactor (and other BWRs) is that most heat is absorbed through the change in phase from liquid to gas. This allows for the elimination of a secondary steam generating circuit and associated steam generators but still requires some provision for the separation of the steam. Figure 6 shows a very simplified version of the coolant circuit and steam system.

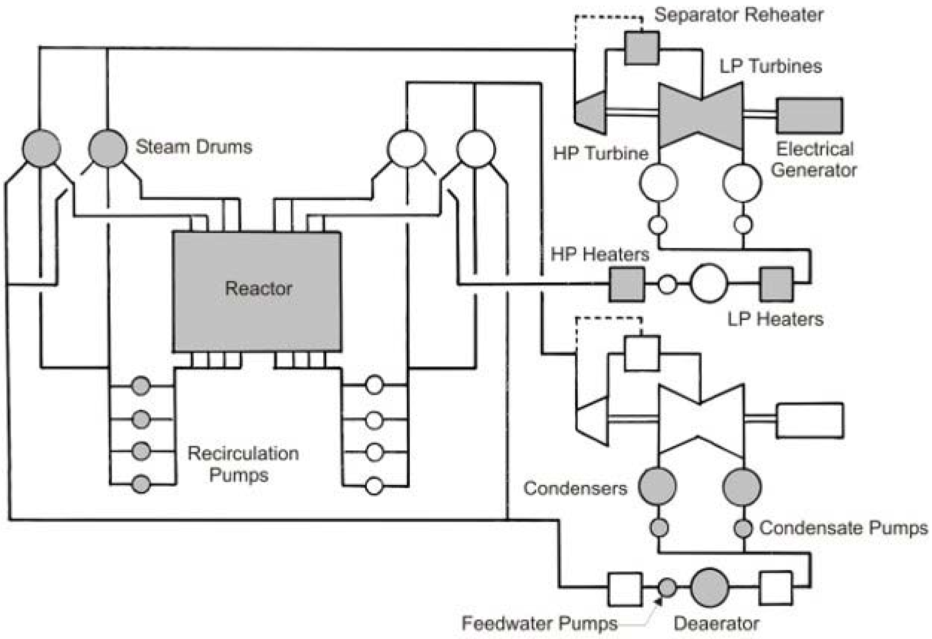

Figure 6: Reactor coolant and steam supply circuit

Steam is generated in the core of the reactor at 6.5 MPa. In the core steam is of very low quality and it must be separated from the water. This is done in four steam drums (two per loop) with each drum being supplied with feedwater from the feedwater heating system. After separation nearly pure steam leaves each steam drum while the water is recirculated back to the reactor core. There are two main recirculation pumps for each steam drum which serve this purpose. The steam passes through the turbine and is subsequently condensed. The feedwater is pumped from each of the four main condensers to the steam drums by condensate and feedwater pumps. Table 2 contains some technical information on the reactor coolant.

As can be seen from Figure 6 there are two main loops. Each loop has one steam turbine driving a 500 MW electrical generator (of the K-500-65 type). The HP turbine is supplied by steam from the reactor at 6.5 MPa and 0.1% to 0.2% wetness. The two LP turbines are in turn supplied with steam from the HP turbine. Design parameters for the reactor coolant are given in Table 2.

Parameter	**Value**

Material	H_2O
Mass in primary circuit	650 Mg
Pressure	6.87 MPa
Inlet temperature	270°C
Outlet temperature	284°C
Number of primary pumps	8
Total mass flow	10.42 Mg/s
Number of Loops	2

Table 2: Design parameters for reactor coolant

The main advantage of a simpler circuit not requiring steam generators is somewhat offset by other factors. One disadvantage of the LGR is that steam is generated in the reactor core. Since the water itself acts as a moderator the formation of steam results in discontinuities in the reactor core neutron adsorption properties as load on the generators changes. This results in some instability under certain circumstances between the hydraulics and neutronics of the reactor.

The reason for this is that as the load changes the density of the steam-water mixture does as well. This in turn changes the degree of neutron absorption and the reactivity of the reactor and hence the rate of steam generation and the electrical output.

In the RBMK this void coefficient is positive due to less neutron absorption so an increase in steam generation promotes an increase in power and further steam generation.

-
-
-

Bibliography

Knief, A.R., Nuclear Engineering, 2nd edition, Taylor & Francis, Mechanicsburg Pennsylvania, 1992. [This text covers different reactor types as well as fuels and fuel processing]

Lamarsh, J., R., Introduction to Nuclear Engineering, 2nd ed., Addison-Wesley Publishing Company, 1983. [This is a general book on nuclear and reactor physics and includes aspects of different reactor types].

Rahn, F.J. et. al., "A Guide to Nuclear Power Technology", Wiley-Interscience Publication, John Wiley & Sons, Toronto, 1984. [This text gives very good coverage of all aspects of nuclear power]

Valey, J., "World Nuclear Industry Handbook", Nuclear Engineering International, England, 1994. [This is a general reference on nuclear energy and reactors]

Biographical Sketch

Robin Chaplin obtained a B.Sc. and an M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.