BOILING WATER REACTORS

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Keywords: Boiling Water Reactors, Reactor Core, Fuel Elements, Control Rods

Contents

Summary

Boiling Water Reactors were developed in the United States as well as in Europe. They followed the development of Pressurized Water Reactors, the motivation being a simplification of the system with steam generated directly by the fuel elements within the

reactor core.

In the boiling water reactor, steam produced in the reactor is passed directly to the turbine. After expansion and condensation, the water is returned to the reactor via a series of feedwater heaters which preheat the feedwater before it is returned to the reactor. Since a high rate of heat removal from the fuel elements in the reactor is essential, a high core flow of coolant is maintained with only a relatively small amount of steam being generated. This steam is separated while the major portion is recirculated through the core as water.

The fuel elements consist of many fuel rods extending the full height of the core and arranged in a square array. Each fuel element is surrounded by a shroud to ensure that a consistent flow of coolant is maintained even when boiling occurs. Boiling in the reactor core produces voids which in turn affect the degree of moderation of neutrons. Appropriate design allows for this to have a partial self regulating effect on reactor operation. Neutron absorbing control rods are still required for overall control of the reactor. Since steam separators are required above the reactor core, the control rods are driven in from below. Also, because of the shrouding around the fuel elements, the control rods are inserted between sets of four fuel elements and are cruciform in shape. Since light water is used as a moderator, slightly enriched fuel is required.

As with the pressurized water reactor, the reactor must be shut down about once a year for refueling.

1. Introduction

1.1. General Information

The Boiling Water Reactor, commonly known by its acronym BWR, was developed a little later than the Pressurized Water Reactor (PWR) and shared many common features. In the BWR however steam is generated directly in the core of the reactor. The steam conditions of the BWR are similar to those of the PWR but, since boiling is not suppressed, the pressure in the reactor vessel is much lower. On the other hand, because boiling does occur, the power density cannot be as high in the BWR as in the PWR leading to a larger size reactor core for the same power output. The reactor vessel must also provide for separation of the steam and recirculation of the water. Hence the reactor vessel for the BWR is much larger than that of the PWR.

There were initially two types of BWR, the dual and single cycle. The dual cycle plant has steam generated at two pressures. Approximately half of the steam is generated in the core at the higher pressure and the other half generated externally at the lower pressure. The steam is generated at the lower pressure either by flashing some high pressure water from the core or by heat exchange from the high pressure water. The high pressure steam flows through the initial stages of the turbine before joining the lower pressure steam. The combined flow then passes through the final stages. The single cycle is the more common in BWR plants with steam being generated only in the reactor core.

There are about 90 BWRs in service, giving a total capacity of nearly 80 000 MWe. Of these, about 40% are in service in the USA. This reactor type was originally designed in the USA by General Electric (GE). Since then GE plants have been built in Germany, Italy, India, Netherlands, Japan, Spain, Sweden and Switzerland through various licensing agreements. Hitachi and Toshiba in Japan have, together with GE, developed an advanced large BWR. Kraftwerk Union (KWU) in Germany and ASEA-Atom in Sweden have embarked on their own innovative designs.

1.2. General Arrangement

Like the PWR the BWR is surrounded by a robust containment to protect the reactor from external influences and to contain radioactive products in the event of a major system rupture. However with the reactor core and steam generator all within a single vessel it is possible to divide the interior of the containment into two parts with the reactor cavity venting via a drywell to a toroidal suppression pool as shown in Figure 1. Any steam release due to a loss of coolant accident (LOCA) is thus directed into the suppression pool and condensed. By contrast, in the case of a LOCA in the PWR, the steam is released into the whole containment, as shown in Figure 2, and condensed by water sprays within the upper containment. The more recent BWR designs, as shown in Figure 3, combine the two philosophies and have any steam release directed via the drywell and through vents into an annular suppression pool, where most steam should be condensed, before entering the main containment. This has water sprays in the upper containment as a backup in the event of a major steam release.

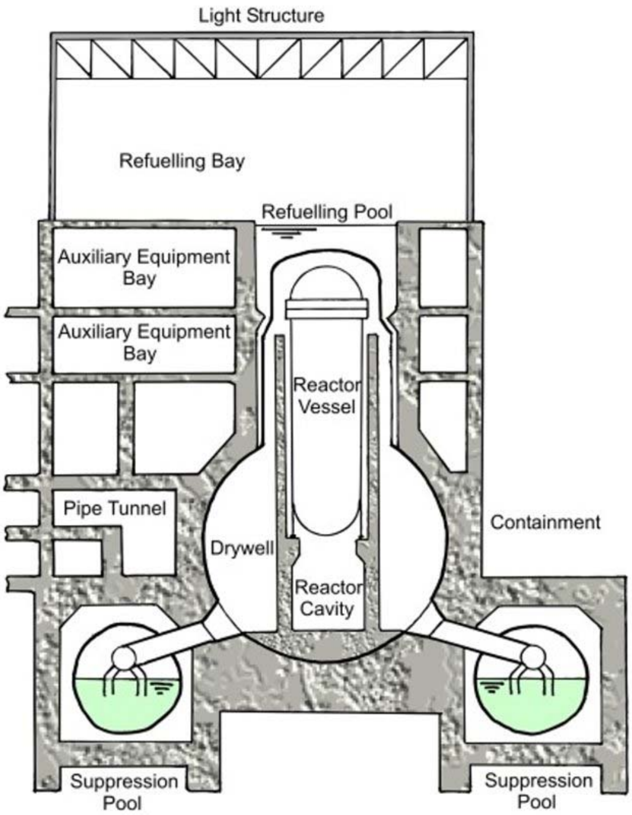

Figure 1: Early BWR containment structure

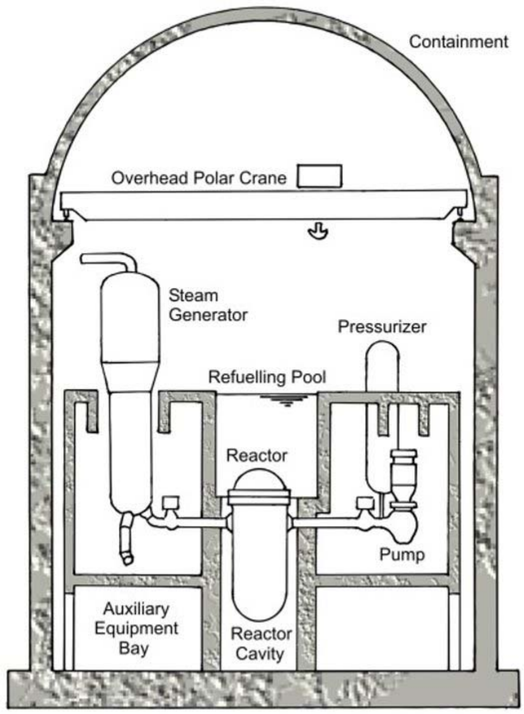

Figure 2: PWR containment structure

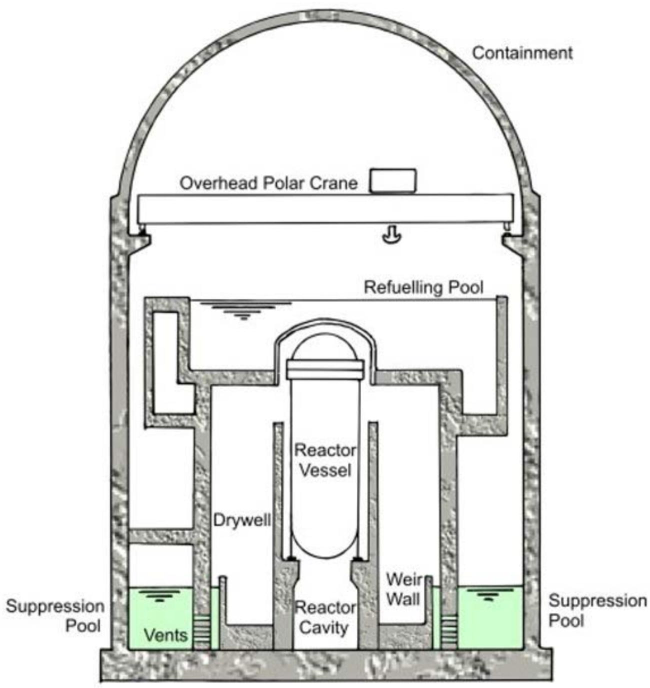

Figure 3: Later BWR containment structure

It should be noted that the water inventory is very large, as is desirable to enhance reactor safety following a LOCA, and in the event of a pipe rupture a large amount of steam would be produced by flashing of the water as the pressure in the system decayed. This steam would expand some 60 times as the pressure dropped from reactor pressure to atmospheric pressure making it necessary to condense as much as possible.

The BWR is designed to withstand a LOCA, including a double-ended, circumferential rupture of a reactor coolant external recirculating line resulting in a loss of reactor coolant at the maximum rate. This is accomplished by several secondary cooling systems which provide redundant cooling to prevent fuel damage and excessive heat buildup in the reactor core. In addition, the reactor building is designed to be a controlled leakage structure which will control the release of filtered reactor building atmosphere under the design basis accident conditions. A gas treatment system is on standby to filter and release reactor building air to the main stack during plant containment conditions to minimize the release of airborne radioactive particles.

2. General Configuration

2.1. Reactor Arrangement

The BWR, as the name implies, boils water and generates steam within the reactor core. As with the PWR the coolant and moderator is light water. Since the neutron moderating distance is short in a light water moderator, the individual fuel rods are close together separated by only a relatively small amount of moderator which also serves as the coolant. The core is thus fairly compact but nevertheless larger than that of the PWR since, on boiling, the coolant increases in volume and requires an adequate flow area. Furthermore, since some parts of the fuel rods may be exposed to vapor, heat transfer coefficients are more conservative than those of the PWR leading to a larger fuel rod surface area and also a larger core.

A typical cross-section of a BWR is shown in Figure 4. Overall the reactor vessel is considerably larger than that of the PWR as it has to house the larger reactor core as well as control rods below and steam separators and dryers above the core. The core consists of a large number of fuel elements resting on the core plate. Control rods are driven in from below the core because of the need to locate the steam separators and dryers above the core. The coolant flows upwards in the core and is driven by a series of jet pumps located in the annulus between the core and the reactor vessel. About 30 % of the total circulating flow is boosted in pressure outside the reactor vessel and returned to be used as the driving flow for the jet pumps.

Steam is generated in the core and passes upwards into the steam separators where the swirling action of the vertical cyclones separates the steam from the water which is returned to be recirculated through the reactor core. Only about 14 % of the circulating water is converted to steam which after separation from the water passes upwards to the steam driers.

These are of chevron or mesh construction to trap the remaining moisture in the steam so that it can be passed to the steam turbine in a very nearly dry condition. The steam outlet nozzles are on the side of reactor vessel to allow the reactor vessel head to be removed more easily for refueling. The steam dryers and steam separators do however have to be removed to gain access to the reactor core.

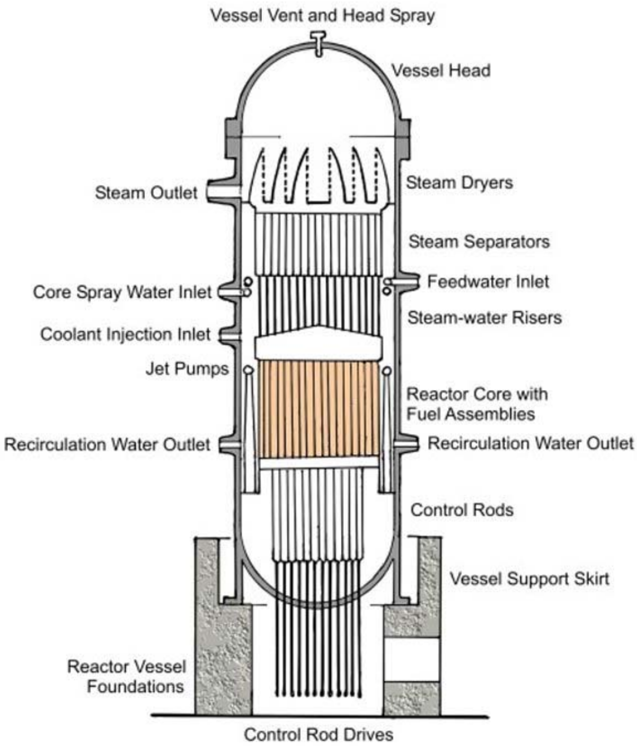

Figure 4: BWR vessel cross-section

From the reactor vessel steam passes through the main steam lines to the high pressure turbines which drive the generator. Generally the steam goes from a high pressure turbine via the moisture separators and reheaters to one or more low pressure turbines. A 1000 MWe plant would typically have one high pressure and three low pressure turbines.

Since boiling occurs in the core, pressure in the core is maintained at saturation, that is, about 7 MPa. Although the pressure vessel is larger than a PWR, the pressure is lower so the wall thickness is approximately the same as that of a PWR. Operating temperature of the reactor is approximately 285°C (545°F) and 6.9 MPa (1000 lbf in^{-2}). Table 1 shows parameters for typical BWRs as power levels and efficiencies were improved with design evolution.

Parameter	**Brown's Ferry (1974)**	**Hartsville (1986)**	**Later BWR**
Heat Output	3293 MW	3600 MW	3830 MW
Electrical Output	1098 MW	1233 MW	1330 MW
Overall Efficiency	32.9%	33.8%	34.2%

Power Density	51 kW/L	54 kW/L	56 kW/L

Table 1: Comparison of BWRs

2.2. Recirculation Pumps and Jet Pumps

Boiling in the reactor core produces a buoyant effect that promotes natural circulation up through the core and down through the annulus surrounding the core. This is enhanced by the chimney effect of the additional height created by the steam separators and their inlet risers. Natural circulation however is insufficient on its own to provide the desired flow rate through the core so jet pumps are provided to ensure the necessary forced circulation. These are located in the annulus between the core and the reactor vessel in such a manner as to allow natural circulation when they are not operating. When operating, a portion of the reactor coolant is withdrawn from the reactor vessel, pumped by recirculating pumps and returned to the jet pump nozzles inside the reactor vessel. This higher pressure water, on discharge through the nozzles, develops a high velocity and draws in the remaining reactor coolant which mixes with it in the diffusers. A typical BWR, as shown in Figure 5, may have two recirculation loops supplying a total of 10 to 12 jet pump assemblies each having a pair of jet pumps. The jet pump diffusers are located in the annulus in such a way that the inlets are near the top of the core. Thus, in the event of a pipe break in an external recirculation loop, coolant can only be lost from the annulus and not from the reactor core. This is one safety feature of the reactor to guard against loss of coolant in the core.

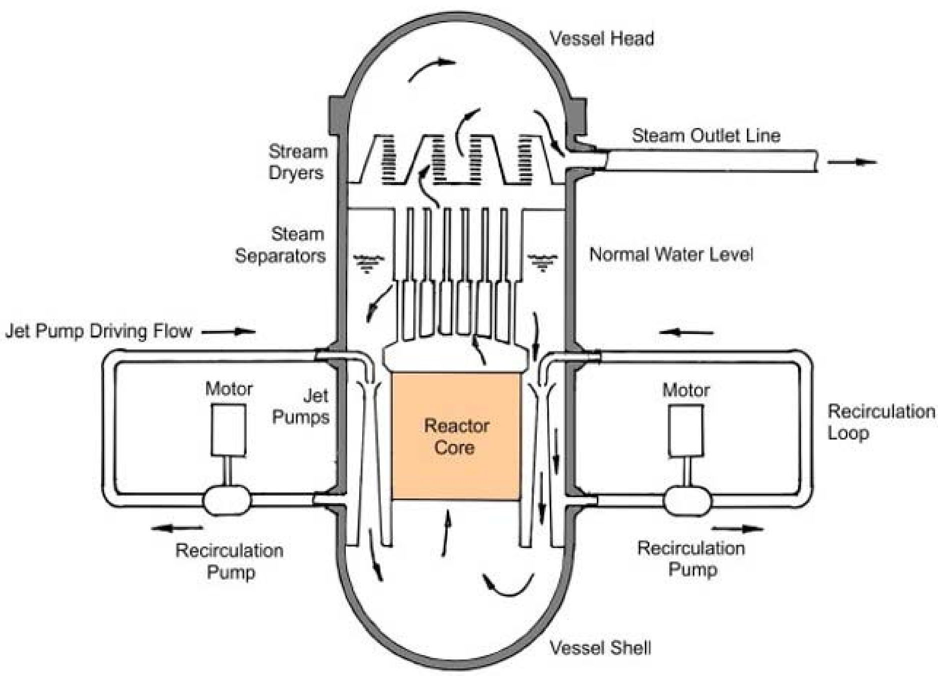

Figure 5: BWR coolant circulation and steam separation

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and 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.