HEAVY WATER LIGHT WATER REACTORS

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Contents

Summary

In the 1960s, a new type of reactor was developed to combine the advantages of the Pressurized Heavy Water Reactor (PHWR) and the Boiling Water Reactor (BWR) resulting in the Heavy Water Light Water Reactor (HWLWR).

Three HWLWRs have been developed in the world: one in the United Kingdom (Winfrith SGHWR), one in Canada (Gentilly-1 CANDU-BLW), and one in Japan in Tsuruga (Fugen ATR).

The HWLWRs are moderated with heavy water and cooled with light water. The design of the core allows for a direct cycle with the production of steam from the reactor itself. At the same time, the good moderating properties of the heavy water are used to

affect good neutron economy and to control the reactor power.

There were great expectations of savings for this new type of reactor (on-line refueling, less heavy water inventory, direct cycle) which were built first as prototypes to test the viability of each.

The Winfrith SGHWR, which started operation in 1967, was a positive experience showing good results in terms of efficiency, safety and reliability but the British government chose another nuclear development policy. Preference was given to a program that promoted the development of gas cooled reactors instead. The reactor however operated as a commercial entity for most of its planned life.
The Gentilly CANDU-BLW was not really a success because of thermal hydraulic instability. It was eventually shut down because of the high costs of the modifications needed for satisfactory operation.

The Fugen ATR was in operation from 1978 and was supported in Japan as part of the policy of using plutonium based fuels to meet national energy needs to the mid-21st century and beyond. However, in 1995 Japan's major power utilities came out against plans to build a demonstration commercial version of the Fugen ATR because of its high cost in comparison with standard light water reactors. It was the last reactor of this type in service.

1. Introduction

1.1. General

Heavy Water Light Water Reactors were developed in the 1960's. They were intended to combine the advantages of Pressurized Heavy Water Reactors (PHWR) like the Canadian Deuterium Uranium (CANDU) reactors and the Boiling Water Reactors (BWR).

Three HWLWRs were constructed and operated in the world:

- The Winfrith reactor in the United Kingdom known as the Steam Generating Heavy Water Reactor (SGHWR).
- The Gentilly-1 reactor in Quebec called the CANDU Boiling Light Water reactor (CANDU-BLW).
- The Japanese Fugen reactor in Tsuruga described as the Advanced Thermal Reactor (ATR).

They were considered as an advanced system because they offered great scope for savings. Economies were expected to show up in each of the major cost categories: capital, fuel, operations and maintenance. For Gentilly for example, a direct cycle, a single fueling machine and a lower heavy water inventory, compared with the CANDU-PHWR, all contributed to bringing down costs. It was expected that the use of boiling light water as a coolant would reduce heavy water upkeep costs.

1.2. Global Description

1.2.1. The Winfrith SGHWR Reactor

The Winfrith SGHWR reactor, shown in Figure 1, was situated in the United Kingdom 20 km east of Dorchester. It was a 100 MW(e) reactor owned by the United Kingdom Atomic Energy Authority (UKAEA) which was also the designer and the operator of the plant. Construction of this prototype took only five years. The reactor went critical in September 1967 and produced electricity in December 1967. It reached its design power in January 1968.

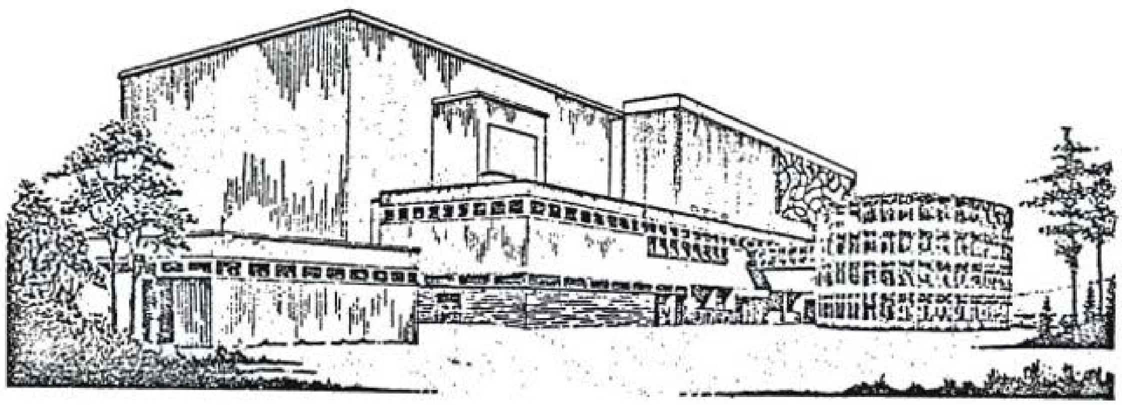

Figure 1. Perspective view of SGHWR plant

1.2.2. The Gentilly CANDU-BLW Reactor

The Gentilly CANDU-BLW reactor was a 250 MW(e) reactor located on the St. Lawrence River 15 km east of Trois-Rivieres. It was owned by the Atomic Energy of Canada Ltd. (AECL), which was responsible for its development. It was designed and built in cooperation with Hydro-Quebec, which was the operator and the customer for the electricity produced.

The Gentilly CANDU-BLW reactor was a natural further development from the CANDU-PHW pressure tube reactors by AECL. It took 4 years to build the entire power plant. First criticality was achieved in November 1970 and the first electricity flowed in April 1971. Full power was reached in May 1972.

1.2.3. The Fugen ATR Reactor

The Fugen ATR Reactor was the result of a Japan Atomic Energy Commission (JAEC) initiative. JAEC wanted to set up a power reactor development program in Japan and decided in May 1966 to establish a national policy for the development of heavy water moderated light water cooled reactors and fast breeder reactors.

The Fugen ATR Reactor with 165 MW(e) had a lower output than the Gentilly reactor but a higher output than the Winfrith reactor. It was built near Tsuruga in the province of Fukui in Japan. Its construction began in December 1970 and it reached criticality on March 1978. It was owned by the Power Reactor and Nuclear Fuel Development

Corporation (PNC), which was also the actual operator.

2. General Configuration

2.1. General Arrangement

Unlike most nuclear reactors the HWLWRs had no reactor pressure vessels. The Winfrith SGHWR, as shown in Figure 2, was typical of this type of reactor. The reactor core consisted of a calandria containing the heavy water moderator. Pressure tubes containing the light water coolant passed through the calandria and were connected to steam separating drums. The slightly enriched uranium dioxide fuel was immersed in the light water coolant within the pressure tubes in the core. Steam was generated in the pressure tubes and passed to the drum where it was separated from the coolant. Saturated steam was fed to the turbine and the condensate returned through a conventional feed heating train to the reactor.

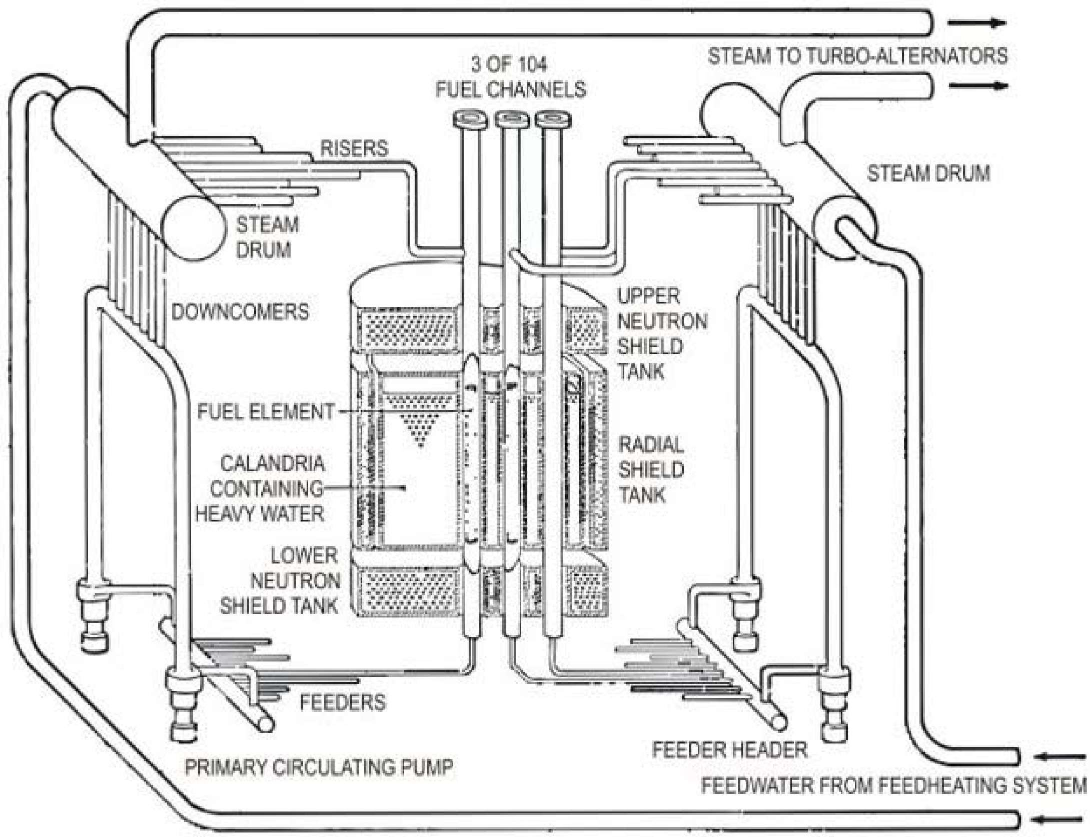

Figure 2. Reactor general arrangement

The Winfrith SGHWR was refueled from above by a single refueling machine while off load whereas the Gentilly CANDU-BLW reactor had a single refueling machine with an on-power refueling capability operating from below.

2.2. Moderator and Coolant

2.2.1. The Moderator

The role of a moderator is to reduce the energy of the neutrons emitted by the fission process. It should not adsorb neutrons excessively and it should have good slowing down properties. A good moderator slows down a neutron after a small number of collisions with its nuclei. The size of these nuclei should therefore be about the same as that of a neutron to ensure that the maximum amount of energy is transferred. Deuterium (heavy hydrogen) and hydrogen are excellent moderators because their nuclei consist of a proton and a neutron or just a proton, which is about the same size as a neutron. It is necessary to have a large number of moderator nuclei in a given volume (high density) as is the case where these nuclei are combined with oxygen to form heavy water and light water so that a neutron does not have to travel too long a distance before encountering a moderator nucleus.

Deuterium occurs in nature in a ratio of 1:7000 with ordinary hydrogen. By contrast, reactor applications employ heavy water D_2O with a 400:1 isotopic ratio due to the difficulty in obtaining and maintaining the ideal ratio. The separation process is also very expensive.

HWLWRs use heavy water as a moderator in order to slow down the neutrons emitted from the fission reaction. Other heavy water reactors such as the CANDU-PHWR are cooled by heavy water but what makes the HWLWRs peculiar is the fact that they are cooled by light water.

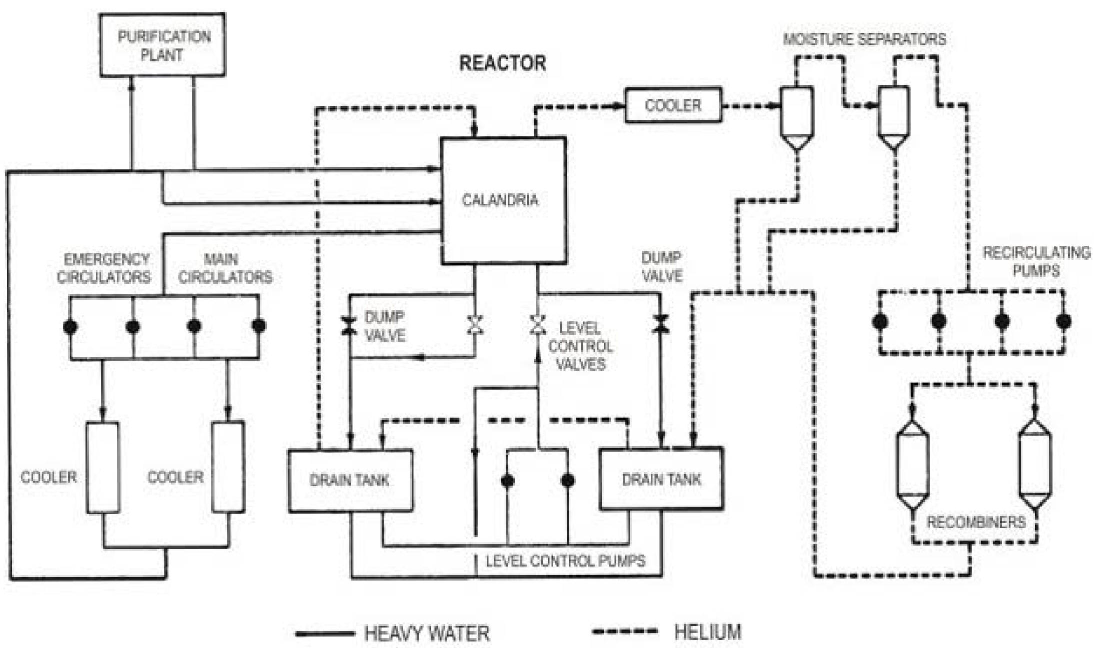

Figure 3. Heavy water moderator circuit

Figure 3 shows the heavy water circuit of the Winfrith SGHWR. This includes provision for control of the reactor by varying moderator level and draining of moderator in the event of an emergency shut down as well as purification and cooling of the moderator.

2.2.2. The Coolant

There are different types of coolants but water is very common as the coolant for most reactors. The liquid phase is always needed for adequate heat removal because steam, being less dense, has poor heat transfer properties compared with water. It also has a large latent heat capacity so absorbs a large amount of heat as it changes phase from liquid to vapor. The saturation pressure however rises rapidly as the temperature goes beyond about 300°C. This limits the maximum coolant temperature and hence limits the thermal efficiency in a water cooled nuclear plant. By allowing steam to be generated directly in the reactor core, high temperatures can be maintained without the need for very high pressures as, for example, in the PWR, where boiling in the reactor core is completely suppressed. All three HWLWRs were using H_2O as a coolant with steam production in the reactor core.

2.3. The Fuel

2.3.1. The Winfrith SGHWR Reactor

The fuel used in the Winfrith SGHWR was uranium dioxide (UO_2). Bi-annual fueling was chosen as this gave a greater irradiation level for a given initial enrichment than annual fueling. By using fuel with a dual feed enrichment, it was possible to obtain a good power distribution across the core without having to move fuel inwards at an intermediate irradiation. Fuel of enrichment 3.1% was fed into the outer zone and fuel of enrichment 2.0% into the inner zone.

2.3.2. The Gentilly CANDU-BLW Reactor

The fuel used in the Gentilly CANDU-BLW Reactor was uranium dioxide (UO_2). It was the most highly rated of any fuel in operating CANDU stations. Natural uranium with an enrichment of 0.7% was used. The fuel centre temperature could go up to 2100°C whereas the maximum cladding surface temperature was 290°C.

2.3.3 The Fugen ATR Reactor

The use of plutonium fuel in the Fugen-ATR demonstrated the feasibility of using a mixed oxide fuel (MOX). The reactor used plutonium topped natural uranium mixed oxide (PU-NU MOX) as a primary fuel. This was equivalent to a slightly enriched uranium fuel.

3. Core Arrangement

3.1. Reactor Vessel

3.1.1. The Winfrith SGHWR Reactor

The reactor consisted of an aluminum calandria approximately 3.658 m in height and 3.658 m in diameter. Figure 4 shows a plan view of the Winfrith SGHWR reactor core. Through this vessel passed 112 aluminum fuel channel tubes of 178 mm inside diameter on a square lattice pitch of 260 mm. A number of smaller diameter aluminum tubes passed between this in the interlattice positions. The calandria contained the heavy water moderator with a slight overpressure of helium.

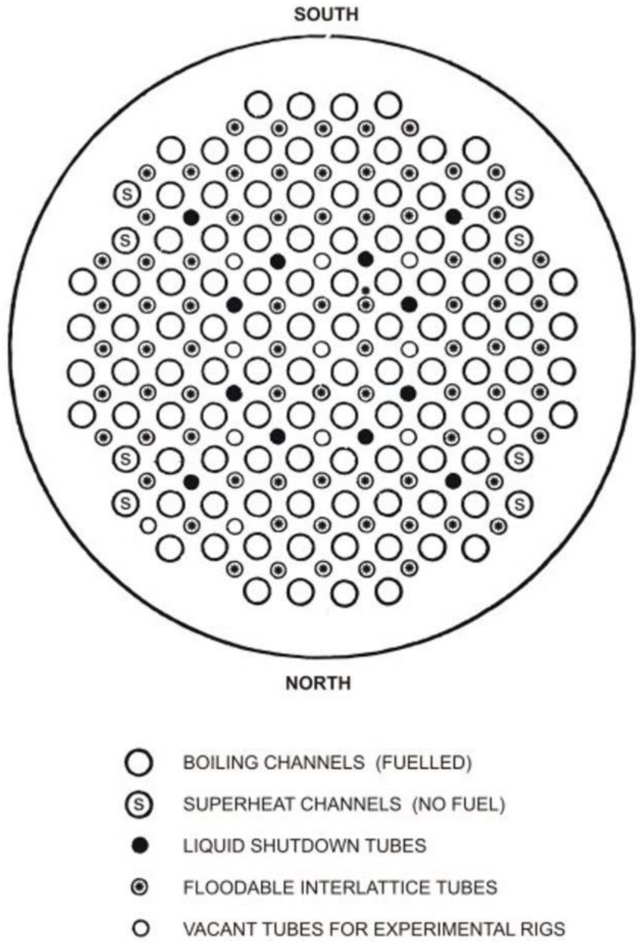

Figure 4. Reactor core plan view

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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.. He has recently been appointed as Chair of the Department of Chemical Engineering.