PRESSURIZED HEAVY WATER REACTORS

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

Keywords: Pressurized Heavy Water Reactors, CANDU Reactors, Reactor Core, Fuel Elements

Contents

Summary

Pressurized Heavy Water Reactors commonly known as CANDU Reactors were developed in Canada due to the availability of heavy water and natural uranium. The lack of enrichment facilities necessitated the use of natural uranium. This fuel, in combination with heavy water as moderator and coolant, permitted a viable reactor system to be developed.

The CANDU reactor is unique in being set with its axis horizontal and having horizontal fuel channels. The heavy water moderator is contained in an unpressurized calandria through which pass high pressure tubes containing the fuel and coolant. The heavy water coolant is circulated by primary circulating or heat transport pumps to steam generators at each end of the reactor. Flow through adjacent pressure tubes is in opposite directions. Heat is transferred from the heavy water coolant to the light water working fluid in the steam generators. The steam generators and steam circuit are very much like those of the pressurized water reactor (PWR). The fuel is in the form of relatively small bundles of fuel rods which are inserted into the pressure tubes. Refueling can be done while the reactor is on power by pushing new fuel bundles in at one end of a fuel channel while spent fuel bundles are removed at the other end. This allows the CANDU reactors to achieve high capacity factors compared with those reactors which have to be shut down periodically for refueling. Furthermore the relative simplicity of the fuel bundles and the use of natural uranium leads to low fuel costs for CANDU reactors. With no heavy reactor pressure vessel and the possibility of modular construction the erection time of a CANDU reactor can be shorter than that of some other reactor systems. Having been developed to use natural uranium in conveniently small fuel bundles, the CANDU reactor has the ability of utilizing low enriched or blended fuel from other sources. This makes it attractive as part of a fuel reprocessing and recycling scheme involving different nuclear plants and facilities.

1. Introduction

The CANDU reactor was developed in Canada following the Second World War when a supply of heavy water was available in the country along with ample resources of natural uranium. No uranium enrichment facilities were available in Canada. However the combination of natural uranium and heavy water in a suitable lattice of uranium dioxide rods immersed in a heavy water moderator allowed a self-sustaining fission chain reaction to be established and maintained. Hence the acronym CANDU, which stands for CANadian Deuterium Uranium, where deuterium is the heavy hydrogen isotope in heavy water and uranium refers to natural uranium, was adopted.

The CANDU reactor has evolved progressively and has been marketed in several other countries. Three standardized versions, CANDU-300, CANDU-600 and CANDU-900, in different capacities were developed. These are now known as CANDU 3, CANDU 6 and CANDU 9 respectively. The original numbers indicate roughly the electrical output in megawatts but later developments have enabled much greater outputs to be achieved by the respective models. Table 1 shows the range in outputs available from these three types.

	CANDU 3	**CANDU 6**	**CANDU 9**
Moderator	D_2O	D_2O	D_2O
Coolant	D_2O	D_2O	D_2O
Number of Fuel Channels	232	380	600
Fuel	UO_2	UO_2	UO_2
Number of Elements in Bundle	37	37	37
Number of Bundles per Channel	12	12	12
Number of Steam Generators	2	4	8
Number of Heat Transport Pumps	2	4	4
Reactor Outlet Pressure	10.0 MPa	10.3 MPa	10.3 MPa
Reactor Outlet Temperature	310°C	312°C	312°C
Reactor Coolant Flow Rate	5.3 Mg/s	7.6 Mg/s	13.5 Mg/s
Steam Temperature	260°C	260°C	265°C
Steam Pressure	4.7 MPa	4.7 MPa	5.1 MPa
Steam Flow Rate	0.70 Mg/s	1.05 Mg/s	1.61 Mg/s
Total Fission Heat	1441 MW	2156 MW	3394 MW
Net Heat to Steam Cycle	1390 MW	2060 MW	3347 MW
Gross Generator Output	470 MW	676 MW	1121 MW
Net Electrical Output	450 MW	626 MW	1031 MW

Table 1. Comparison of CANDU reactor types.

The CANDU series of reactors all utilize a novel and distinct approach to the design of the reactor. The reactor is a horizontal stainless steel cylinder or calandria with hundreds of pressure tubes passing through it in a horizontal manner. This is very different from most conventional reactor designs such as the PWR and BWR which have vertical cylindrical pressurized reactor vessels.

Fuel bundles are located in the pressure tubes and coolant passing over them removes heat and generates steam in a separate steam generator. This latter part of the system is similar to that of a PWR.

The calandria contains the moderator which acts to slow down the neutrons produced from fission so that they become thermalized and can then react with more fuel to form a self-sustaining chain reaction. Heavy water (D_2O) was chosen as a moderator in the Canadian design because the facilities for heavy water production in Canada were already present. Also, as a moderator, heavy water is superior to light water (H_2O) because heavy water has an extremely low neutron capture cross-section and hence a very low neutron absorption rate. One characteristic with heavy water as a moderator is that in heavy water the neutron slowing down distance is much longer than it is for light water. As a result of this increased slowing down distance, the pressure tubes containing the fuel bundles in which the fission takes place must be spaced some distance apart with moderator in between, unlike light water cooled reactor types where the coolant between the fuel rods provides sufficient moderation. In all CANDU reactors the moderator in the calandria is maintained at atmospheric pressure and a temperature of about 70°C.

2. General Configuration

2.1. Plant Arrangement

The general arrangement of the plant is shown in Figure 1. The active part of the reactor is cylindrical in shape and set horizontally. The moderator is contained in the calandria having a length of about 6.0 m and a diameter of about 7.6 m for the CANDU 6. Because of the low internal pressure of the calandria the thickness of its shell and its tubes have only to be sufficient to be structurally sound and to support the weight of the moderator. Only the pressure tubes located within the calandria tubes are pressurized. These pressure tubes containing the fuel and through which the coolant flows are arranged horizontally in an axial direction. The coolant is fed to and from the pressure tubes by feeder tubes which in turn are connected to headers situated above the reactor. The headers in turn are connected to steam generators in which heat from the coolant is used to generate steam. Circulating pumps usually known as heat transport pumps drive the coolant around the primary circuit. A pressurizer maintains pressure in the primary system so as to suppress large scale boiling and maintain operating temperatures.

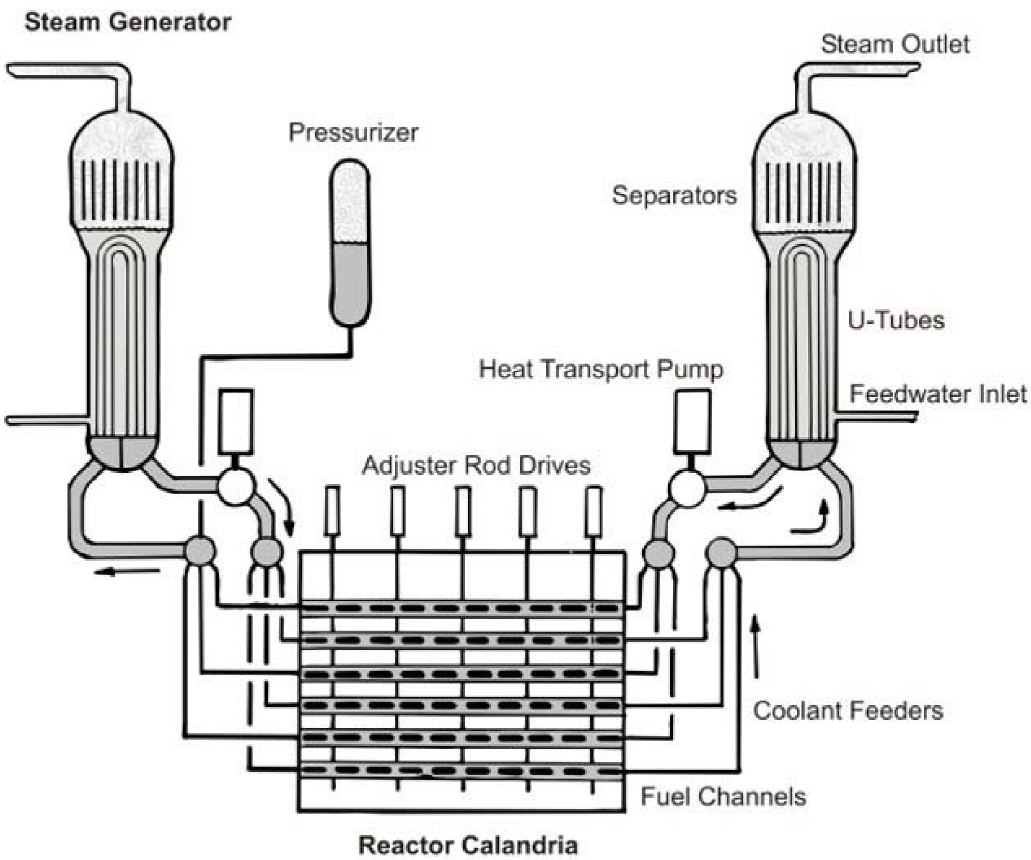


Figure 1. Diagrammatic cross section of typical CANDU (PHWR)

2.2. Coolant Circuit

The fundamental function of the primary coolant circuit is to circulate the heavy water coolant and transport heat from the fuel elements to the steam system. The entire circuit consists of pumps, headers, feeder pipes, pressure tubes and steam generators as shown in Figure 2. Also, in the circuit there is a single pressurizer. The coolant used in CANDU reactors is heavy water to minimize neutron absorption. Instead of employing a pressure vessel, the CANDU design utilizes a system of pressure tubes that traverse the length of the reactor calandria. There are 232, 380 and 600 of these pressure tubes in the CANDU 3, CANDU 6 and CANDU 9 respectively. The calandria is not pressurized but the pressure tubes are kept at a pressure of about 10 MPa. In these horizontal tubes the coolant flows are opposite in adjacent tubes except in the CANDU 3 where the flows are unidirectional. Thus the coolant passes from the steam generators at one end of the reactor through half the tubes to the steam generators at the other end of the reactor and back again through the other adjacent tubes.

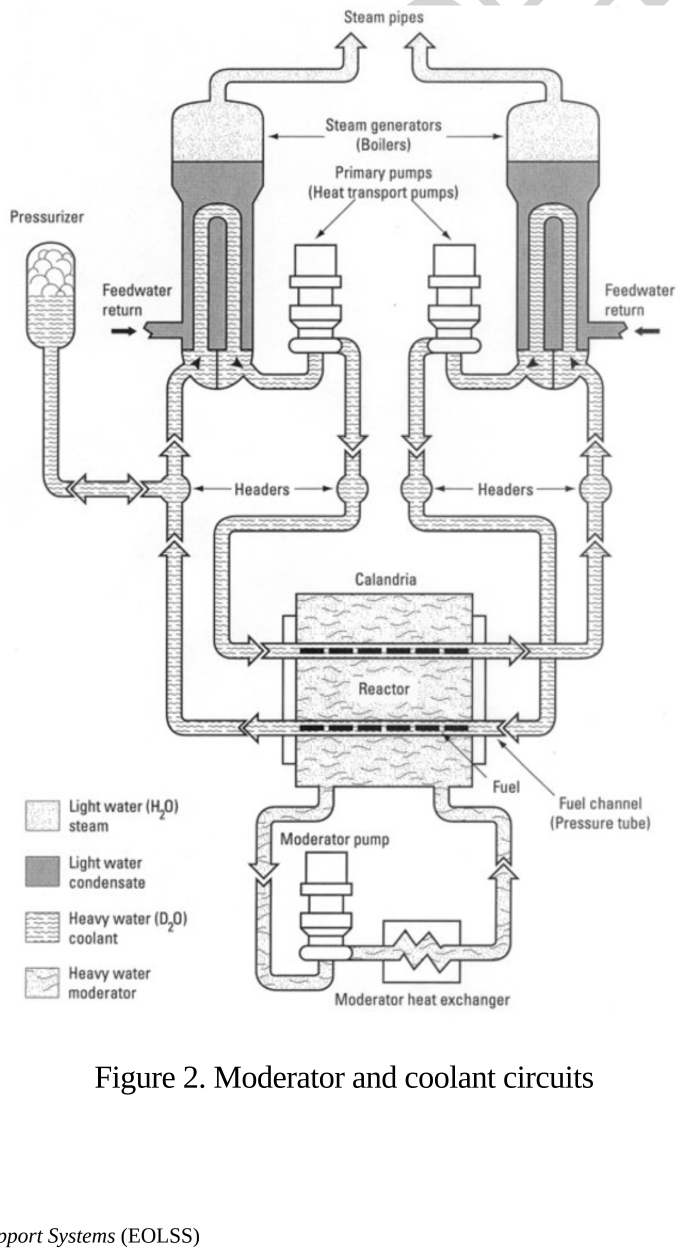
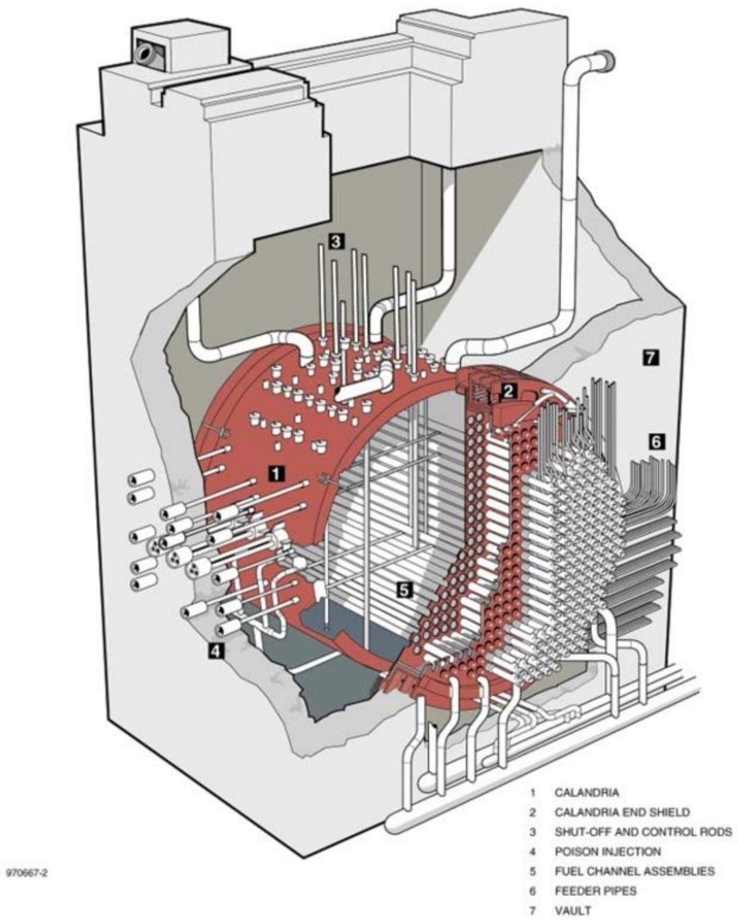


Figure 2. Moderator and coolant circuits

3. Core Arrangement

3.1. Fuel Channels

Fuel channels are arranged in a square array across the reactor as shown in Figure 3 while Figure 4 shows a close up view of the feeder pipes connected to the pressure tubes at one end of the reactor. The calandria, which contains the moderator at essentially atmospheric pressure has axial tubes to accommodate the pressurized fuel channels or pressure tubes which in turn contain the fuel bundles and the primary system coolant. A small annular gas filled space between the calandria tubes and the pressure tubes minimizes heat transfer and hence heat loss from the primary coolant circuit. Inside each pressure tubes are twelve fuel bundles or fuel elements arranged to abut one another. In most CANDU reactors the individual fuel bundles have 37 fuel rods each containing a stack of uranium dioxide fuel pellets. The separate bundles are more easily handled in this horizontal configuration than long single fuel elements as used in most reactors with vertical fuel channels. New fuel bundles can be pushed into one end of a fuel channel by a refueling machine while spent fuel bundles are discharged into a similar machine at the other end. This allows the reactor to be refueled while on load.



CANDU 6 Reactor Assembly

Figure 3. Reactor vault assembly

Figure 4. Feeder tube assembly on reactor face

-
-
-

Bibliography

Atomic Energy of Canada Limited *Technical Summary CANDU Nuclear Generating Station*, AECL, Mississauga Ontario, Canada [Provides a technical description of all reactor components as well as technical data for 600 MW and 950 MW CANDU nuclear generating stations.]

Cameron, I.R. (1982) *Nuclear Fission Reactors*, Plenum Press, New York. [Provides general review of nuclear reactor theory and different reactor types. Includes chapter on heavy water moderated reactors.]

El-Wakil, M.M. (1982) *Nuclear Energy Conversion*, American Nuclear Society, Illinois, USA. [Provides description and technical data of all major types of nuclear reactors as well as other nuclear related methods of power production.]

Knief, R.A. (1992) *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*, Second Edition, Hemisphere Publishing Corporation, Washington. [Provides coverage of application of theory to practical aspects of commercial nuclear power and makes use of instructional objectives].

Steed, R.G. (2007) *Nuclear Power in Canada and Beyond*, General Store Publishing House, Renfrew Ontario, Canada [Provides a comprehensive description of CANDU nuclear plants and their operation. Includes many diagrams and photographs as well as detailed descriptions of fuel handling mechanisms.]

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.