Chapter 5

HEAVY WATER REACTOR

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5.1 INTRODUCTION

The Heavy Water Reactor (HWR) concept allow the use of natural uranium as a fuel without the need for its enrichment, offering a degree of energy independence, especially if uranium is available for mining or for extraction as a byproduct of another industry such as gold mining or phosphate fertilizer production. However, it needs the installation of a heavy water D_2O production capability, which is a much simpler endeavor anyway, since separating the light isotopes (D from H) is much simpler than separating the heavy isotopes (U^{235} from U^{238}).

HWRs have become a significant proportion of world reactor installations, second only to the Light Water Reactors (LWRs). They provide fuel cycle flexibility for the future and can potentially burn the recycled fuel from LWRs, with no major reactor design changes, thus extending resources and reducing spent fuel storage.

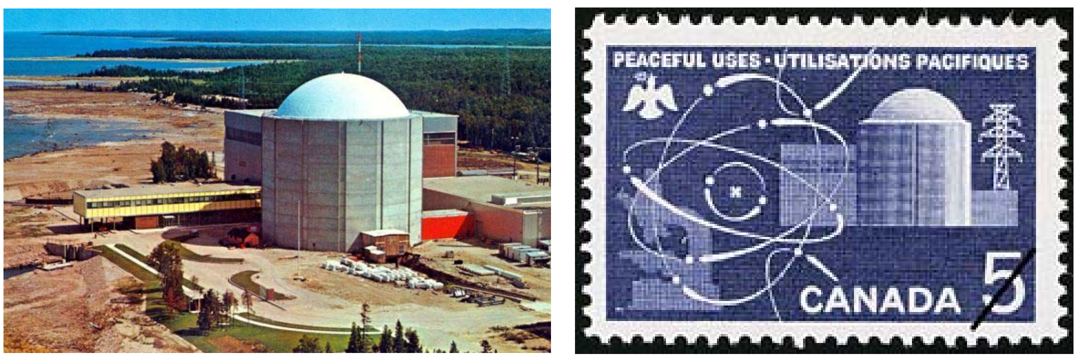

Figure 1. First Generation Douglas Point on a stamp face, first HWR of the Candu design, now decommissioned, was part of a nuclear complex including the Bruce HWRs.

5.2 EVOLUTION OF THE CANDU HWR DESIGN

The HWR concept is primarily represented by the CANDU design which is an acronym for CANada Deuterium Uranium. The CANDU system uses pressurized heavy water D_2O as moderator and coolant and natural uranium as fuel in the form of uranium dioxide UO_2.

The HWR design, because of its relative technical simplicity is in vogue in developing countries. New HWR designs are being developed mainly in Canada and India.

HWR reactors are currently operated in Canada at Ontario, New Brunswick and Québec, in Korea, Argentina and Romania. Other similarly designed Pressurized Heavy Water Reactors (PHWRs) are operated in India and Pakistan.

In China, the Qinshan project, a partnership between Atomic Energy of Canada Limited (AECL), Canada and the Third Qinshan Nuclear Power Company (TQNPC), included two units that went into commercial operation in 2002 and 2003 respectively.

In India, a continuing process of evolution of the HWR design has been carried out since the Rajasthan I and II projects. Tarapur 4, an evolutionary 500 MWe HWR achieved criticality in March 2005 and another 500 MWe unit Tarapur 3.

Figure 2. Bruce HWRs Reactors complex, Canada.

Figure 3. Second generation Point Lepreau, Atomic Energy of Canada Limited (AECL) Candu 6 power plant.

A boiling light water cooled, heavy water moderated Advanced HWR was under development in India. This design is a thermal breeder using the thorium and U^{233} fuel cycle and incorporates many passive features, including natural circulation cooling.

In Canada, AECL continues to evolve the basic CANDU design to develop the Advanced CANDU Reactor (ACR), focusing on improvements in economics, inherent safety characteristics and performance, while retaining the features of the earlier family of PHWR nuclear power plants that are now decommissioned such as the Douglas Point HWR. The stated goals include lower plant capital and operating costs, plus reduced project schedules, through the use of improved design and construction methods and operational improvements. The design uses Slightly Enriched Uranium (SEU) fuel to reduce the reactor core size, which also reduces the amount of heavy water required to moderate the reactor and allows the use of light water in place of heavy water as the reactor coolant.

At the leading edge of the ongoing AECL program for evolutionary improvements in the CANDU line of reactors is a research and development program, designated as CANDU-X, or innovative CANDU reactors operating at higher thermal efficiencies, which implies a high temperature coolant or supercritical water as a coolant. Such reactors would also incorporate passive high temperature fuel channels, natural circulation heat removal, and passive containment heat removal.

5.3 CANDU 6 HEAVY WATER REACTOR DESIGN

The core of the nuclear steam supply system of a CANDU 6 power plant is a large cylindrical vessel called the calandria. This vessel is filled with cool, low-pressure D_2O. The vessel houses 380 horizontal tubes, loaded with natural uranium fuel bundles.

Each fuel channel consists of a 104 mm diameter, 4.3 mm thick zirconium niobium alloy pressure tube, inserted into a slightly wider calandria tube, and two stainless steel end fittings at the ends of the fuel channel. The tubes are 6.3 m in length. Garter Spring spacers separate the two tubes.

Heavy water flows through the pressure tubes in a secondary pressurized circuit, removing heat from fuel bundles and transferring it to the steam generators, where secondary circuit light water is being heated and converted into steam to drive the steam turbine and the electrical generator. During reactor operation, the pressure tube material is subject to high pressure at 11.3 MPa and high temperature reaching 310 °C.

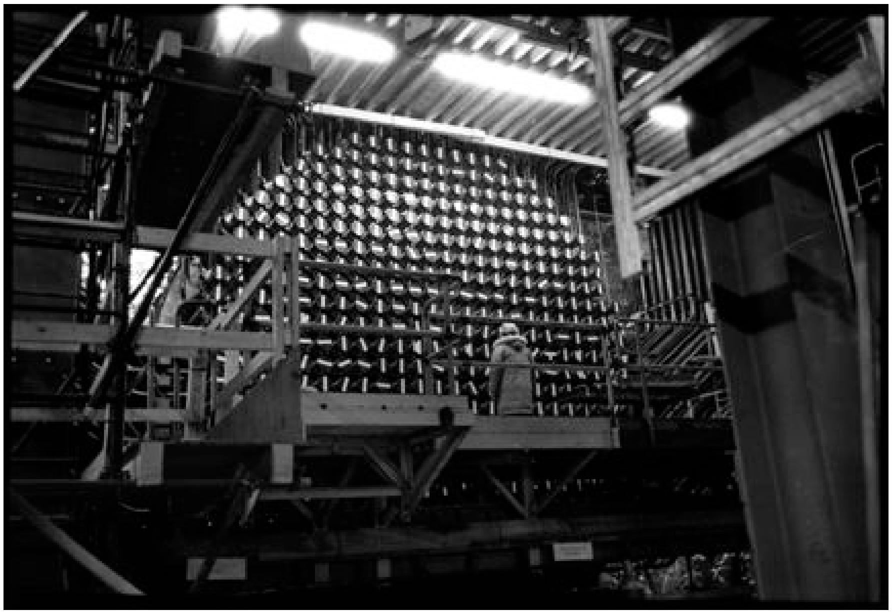

Figure 4. Darlington CANDU reactor face showing the horizontal pressure tubes.

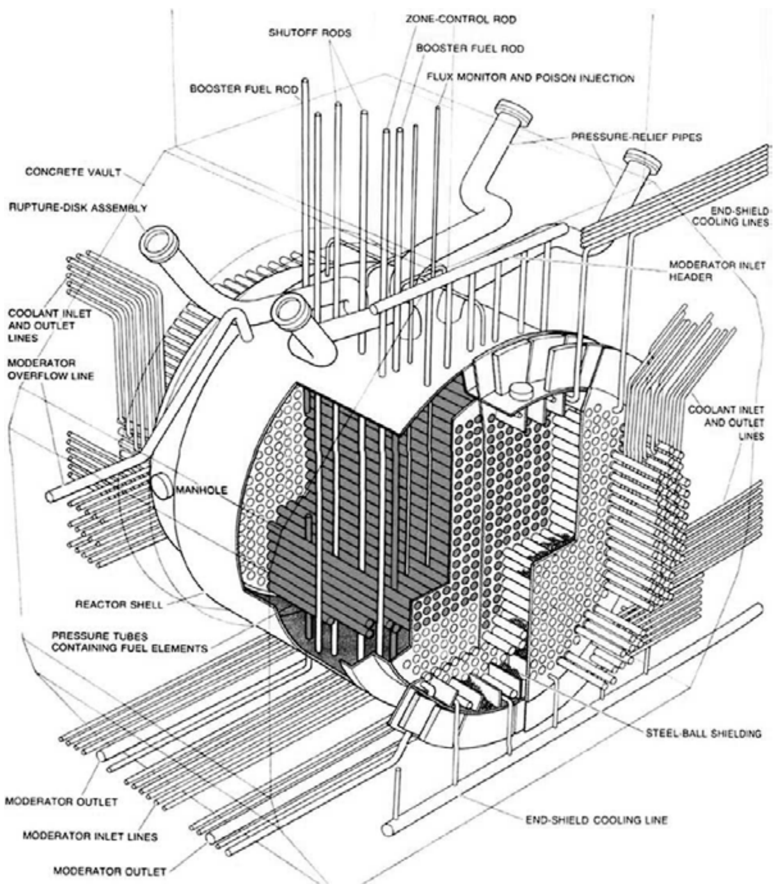

Figure 5. Horizontal calandria of HWR showing its components.

Figure 6. Fuel pellets, tube and bundle used in the HWR design.

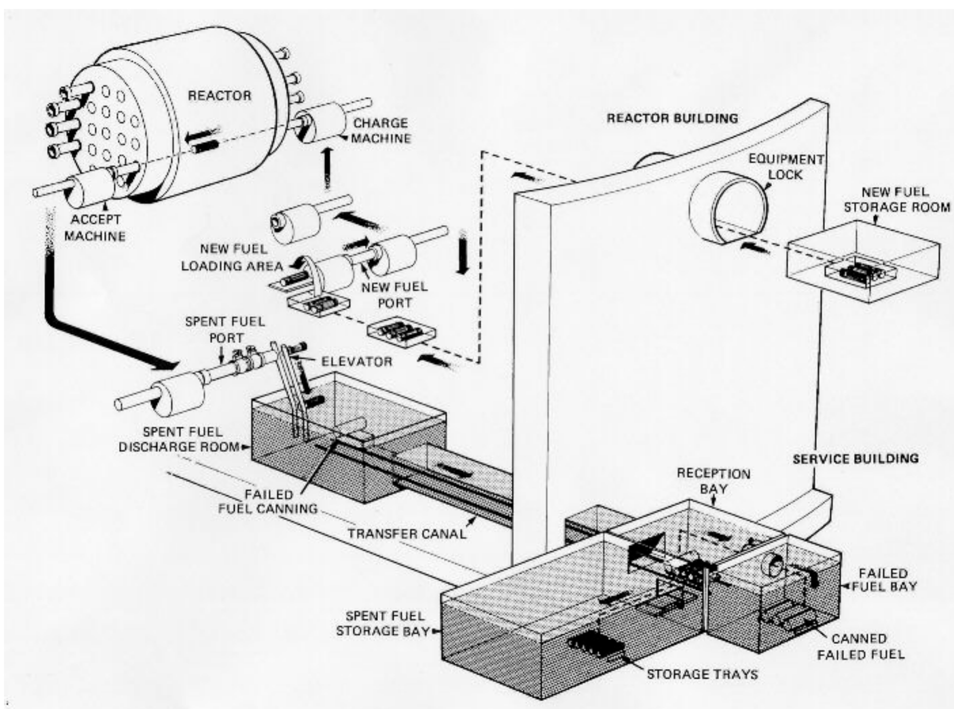

Figure 7. On line refueling machine in horizontal tubes CANDU design.

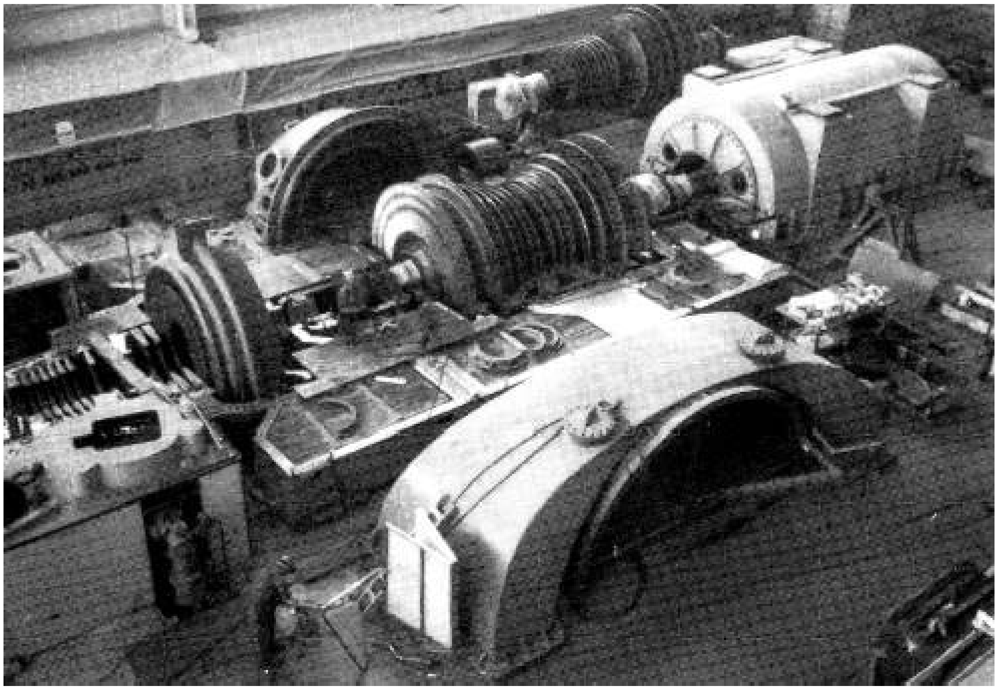

Figure 8. Electrical generator and disabled steam turbine in the Douglas Point plant.

5.4 CANDU PERFORMANCE

The CANDU 6 reactor design possesses the highest performance rating of all other reactors concepts and is able to be refueled at full power using an online refueling machine. This leads to a power generating capacity factor of 75 percent, even after 13 years of operation making it a more reliable system than other energy options.

The Lifetime Capacity Factor (LCF) is the Total Gross Generation (TGG) figure divided by the capacity (CF) divided by the total number of hours (H) from the time of first synchronization, multiplied by 100:

$$LCF = \frac{TGG}{CF.H} \times 100 \ [\frac{MWe.hrs}{hrs}] \quad (1)$$

The CANDU 6 units are reported as having the highest lifetime capacity factors within their class.

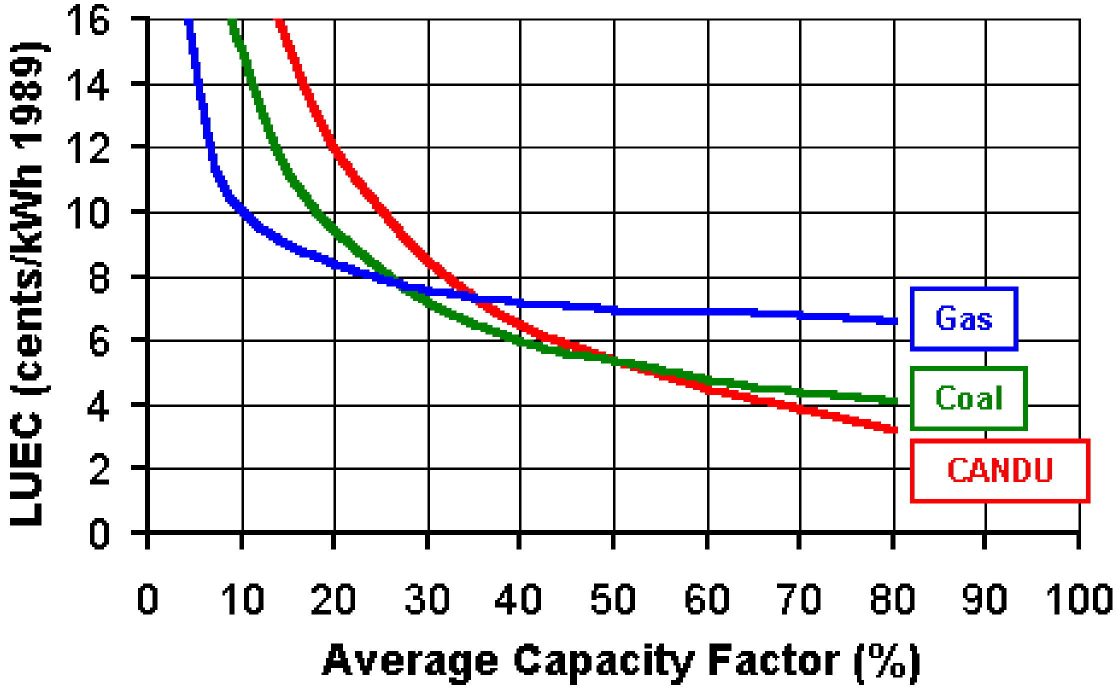

Figure 9. Levelized Unit Energy Cost (LUEC) of gas, coal and nuclear sources in Ontario, Canada, for units placed in service in 2002, in 1989 Canadian dollars. Ontario Hydro.

5.5 SAFETY ASPECTS

Originally licensed in Canada, the CANDU 6 design has also been licensed in every country where it has been installed over the past two decades. With the Wolsong 2, 3 and 4 plants in the Republic of Korea, it met all requirements for licensing in both Canada and Korea, the latter having licensed both PWR and Candu systems.

The Canadian regulator, the Atomic Energy Control Board (AECB), generally plays a role in the transfer of expertise to international regulatory bodies. Part of the licensing acceptability is its approach to safety. Long operating experience under a wide range of demanding conditions bears this out. The unique defense-in-depth design incorporates tri-level passiveness. Preventative boundaries and independent shut-down systems are built into the design at multiple levels.

The design has established a long history of minimizing radiation doses to the operating staff. This has contributed to ease of plant maintenance which, in turn, has contributed to operating reliability and lower operating costs.

The power plants are highly automated, requiring only a minimum of manual operator action. Each plant has two independent digital computers which operate continuously, one operating and one on standby.

The safety systems include two independent and fully capable shutdown systems. To provide maximum safety, the systems are separated physically and functionally.

The moderator operates at low pressure and temperature, completely separate from the primary heat transport coolant circuit, providing a large body of water capable of absorbing excess heat.

Power plants have an emergency core cooling system and a containment system. In the event of a Loss Of Coolant Accident (LOCA), the reactor safety system will automatically shut down the reactor, isolate the defective primary heat transport coolant circuit, and assure a supply of cooling water over the fuel.

5.6 ENVIRONMENTAL ASPECTS

A CANDU 6 reactor produces about 24 cubic meters of used fuel bundles per year, a volume that would fit into a small room. The design of the power plant is such that these wastes are controlled and represent no threat to station personnel or to the public at large.

Figure 10. Concrete silos temporarily store the used fuel elements allowing cooling before final recycling or disposal.

The 700 MWe class nuclear power plant saves the burning of about 84 million metric tonnes of coal or about 330 million barrels of oil over a 40-year period and the millions of tonnes of acid-producing NO_x and SO_x atmospheric pollutants these fossil fuels would generate. It avoids the release of 196 million tonnes of carbon dioxide over its lifetime, an amount that would be produced by a fossil-fuelled plant of equal size.

Air and water discharges are free of such contaminants as heavy metals, organic compounds and acid gases. Radioactivity releases in any form are closely monitored, and are consistently less than 1 percent of those permitted by regulatory standards.

Power stations occupy relatively little land since space is not required for large coal storage and ash disposal areas. As an example, the CANDU 6 at Point Lepreau produces about 300 kgs of used fuel per day. An equivalent coal-fired station produces eight metric tonnes of fly ash and 1,440 metric tonnes of solid ash per day.

5.7 WASTE MANAGEMENT

The overall waste handling philosophy and strategy, which has been the subject of 50 years of continuing research and development, is to provide interim storage at the reactor site, followed by permanent disposal underground in geologically stable formations.

Used nuclear fuel has been stored in water filled pools at HWR nuclear generating stations for 25 years and can be stored in this way for many decades. The use of concrete canisters or silos for dry storage of used HWR reactor fuel is now coming into wide use because it provides safe storage at lower cost than water filled storage pools.

At the Point Lepreau plant, after at least seven years under water, the spent fuel which would have seen a decrease in radioactivity of about 99 percent is moved to on-site dry storage canisters, where each year's discharge fills about 10 canisters.

The MACSTOR above-ground dry storage system for spent HWR fuel, suitable as well as fuel from other reactor types such as the PWR, BWR and VVER, has been developed. It features cooling and shielding, easy fuel retrievability for future off site disposal, resistance to earthquakes and tornadoes, and low construction and operating costs. A MACSTOR unit was installed in a record five and a half months at Hydro Quebec's Gentilly-2 CANDU station in 1995.

5.8 DISCUSSION

The four reactors built at Darlington, east of Toronto, Canada experienced a cost overrun from a projected $2.5 billion to $14.4 billion each in 1993. Part of the cost overrun is blamed on political interference.

The reactors were also plagued by technical problems largely related to their complex pressure systems, which were wearing out far earlier than expected. It was a problem of the 20 reactors built in Ontario. Eight were shut down after 25 years in operation. Four of the reactors were refurbished and placed back into operation. The other 4 have been out of commission. Two of them at the Pickering station are expected to be decommissioned.

On the bright side, some later 2002 CANDU reactors built in China were built on budget. They appear to be in the $3-4 billion range.

The HWR concept has evolved over the past 3 decades into a proven design with high reliability and worldwide acceptability. As more HWR units enter service, operator and customer feedback will continue to be the major contributions to its evolution.

Figure 11. Cutout diagram showing a Candu 9 plant setup.

The HWR remains a world leader in terms of reliability, high capacity factor and power production. There were as of 2005, 39 HWRs in operation worldwide and 8 under construction. The number of countries operating HWRs were 7, with a total generating capacity of 20 GWe and a substantial history of operating experience of 775 reactors.years.