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On CANDU Reactors: History, features and its use around the world

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1. Introduction

A wide variety of reactors was created worldwide. The majority of them used uranium enrichment technology, like the first USA's reactors, and light water to moderate the fast neutrons. However, the isotope Uranium 235 is significantly less abundant than Uranium 238 (natural uranium). For this reason, an alternative was developed, the Heavy water reactor. In Canada, that technology gave rise to the CANDU.[1] CANDU is a Canadian heavy water reactor, and it also uses heavy water as a coolant. Its main fuel is natural uranium (uranium dioxide), but it is versatile and can use others like plutonium thorium or enriched uranium [7,8].

Nuclear fission has been created by the interaction between a fissionable nucleus and neutrons. When a nuclear fission occurs there are neutron releases that can create other fissions. Each fissionable atom has a range of energy when the probability (the named cross section) to occur a fission is bigger, that is the resonance energy, but the Neutrons when created are not in a range of energy which can fission other atoms. Because this moderator was useful to reduce the neutron's energy. Each moderator can reduce the energy of the neutrons when to a range, light water is useful to moderate neutrons to fission Uranium 235, but not Uranium 238 which the energy is bigger than the range of U-235. Because this is used Heavy water which moderates the energy to the range of resonance of the uranium 238.

That work is a study about CANDU and your potential for a future use with Thorium and Uranium 233. CANDU is a reactor of burning and production of radioisotopes [7], and Thorium can be used to produce U-233. There are some studies about use of Thorium in CANDU reactors which have the advantage of not needing enrichment. The project has the objective of reducing the production of plutonium, which is one of the safeguard problems of CANDU, through a production of U-233 which has the properties similar to U-235. Brazil has one of the largest reserves of Thorium in the world, and that was a project of use of thorium with heavy water, the project "TURUNA" [12], but that has been discontinued.

2. History

CANDU rises with the partnership of AECL (Atomic Energy of Canada Limited), Ontario Hydro, and Canadian General Electric Company. That project has been studied since World War II, but the nuclear resources changed to pacific uses worldwide with the war's end.

In 1954, the project was started, and in 1962, the prototype NPD (Nuclear Power Demonstration) was finally completed [1]. That research reactor operated for many years (until 1987) until its lifetime operation ended [1]. However, the NPD was essential for the scientists and engineers to learn and overcome the challenges until a viable technology was born [1].

The heavy water was chosen due to the difficulties of accessing the enrichment. At that time, the fuel was unavailable on the common market [1]. Canada, however, has had a considerable number of uranium reserves [8], and that is why it developed another method. Another significant challenge was to create a system that generates energy and heats the coolant enough to generate electricity on a commercial scale. The solution was using tubes and pressurizing the coolant about 100 atm, and then they could heat above 300 degrees Celsius [1]. Using zircaloy and his transparency to neutrons was essential to the project too [1].

Another feature is the online recharge, which is to recharge the reactor in operation. Online refueling increases the operation time on Reactor and increases the energy extracted from it. The Pickering 7 for example, is a CANDU which operated for 894 without shutdown. [5], and Darlington-1, another CANDU, breaks this record in 2020 [6].

The refueling is based on the decay of elements, the refueling rate is proportional to the degradation rate, so the online recharge can be used with different fuels [11]. Many types of fuels have been developed for CANDU, and it is common to use a mixture of natural uranium with some low-enrichment uranium [7] [9,11].

The next chapter of that history was the Douglas point project, the first reactor called CANDU. That was a project to study the commercial potential of the PHWR. Douglas Point had planned to generate 200 MWe. The project's location was in Douglas point, which will one day be the Bruce Nuclear Generating Station site, the biggest in the world. The project was successful, although some technical problems (which were solved) like losses of coolant and moderator (Heavy water has a significant price to the plant) and operating between 1966 and 1984 [1].

Later, they finally projected a commercial version of the CANDU with 500 MWe [1], competitive with coal-burning plants. Thus, that is how it came to the Pickering plants, a complex with four reactors operating until now. Now we have many CANDU types: CANDU 3, a smaller reactor with approximately 300 MWe; CANDU 6, a 600MWe reactor like the Bruce; and CANDU 9, a 900MWe reactor showing success was the CANDU [1].

3. CANDU around the World

The technology of PHWR is not only in its origin country. CANDU was also exported for many nations like India, China, Argentina, Pakistan, South Korea, and Romania. A particular case is in India; a partnership between these countries was made in the '60s [1].

The project CIRCUS (Canadian-India Reactor) began in 1963, with the construction of RAPP-I (Rajasthan Atomic Power Plant) and after RAPP-II that was made with more autonomy to India. The project was a success, but the result was a diplomatic problem [1]. In 1974, India tested its first nuclear bomb, which showed the danger of CANDU to safeguards. CANDU does not need enrichment uranium, only natural uranium, producing more plutonium per KWe than other reactors [1,11]. Canada and India's partnership was dissolved, and RAPP-II was finished without help.

The same interest surged in Pakistan, and in 1972 the first reactor was on. Maybe the political relationship between India and Pakistan had some influence on the decision to build a weapon. After this case, Canada ended its partnership program and did not export more reactors until the Pickering operation [1].

Table I: Countries, CANDU numbers, and Capacity

Country	Units Number	Net Capacity (MWe)
Argentina	1	600
Canada	19	13,513
China	2	1,280
India	18	3,757
Pakistan	1	125
Romania	2	1,305
. Korea	4	2,579

4. CANDU Features

Although PWR and BWR have been the majority of commercial reactors in operation, CANDO still one of the most. CANDU have some advantages over conventional light water reactors.

Natural Uranium is cheaper and more abundant than the isotope U-235, and CANDU has most efficiently neutron economy CANDU produces about five times the mass per unit of electricity than a PWR, but with not so much different costs in disposal, and CANDU is more efficient leaving less residual fissile material [11].

The online refueling system is one of its most important features. Provides flexibility to use many different fuels, increases the operation time in months (sometimes years), and increases the energy extracted from the fuel about 25% [11]. That reduces the excess of reactivity which reduces the needs of burnable poison and minimizes the absorption in the control materials [11].

CANDU produces about two times the amount of Plutonium than a PWR [1,11] and that is a problem to safeguard. The online refueling makes it possible to produce and get plutonium without shutdown the reactor, and produce a Weapon without enrichment technology. CANDU needs heavy water for coolant and moderation, which is very more expensive than light water and needs more safety measures. When Canada started to build its PHWR, it built installations to produce tons of heavy water [11], that’s a challenge to get a CANDU [7,11].

5. Conclusions

CANDU shows that a PHWR is viable in different countries, it only needs access to a reserve or buying in the regular market. There are some works about the synergy between a CANDU and a regular PWR or BWR, the unenriched fuel can be used on a CANDU, considering the mining is one of the most impactful to the environment, CANDU shows to be an alternative [7,8].

CANDU are safe to safeguard because they do not use enrichment, but the production of plutonium is a problem [1]. But CANDU can use this to produce energy [7,8], and burn the plutonium. The biggest problem with CANDU is the costs of the Heavy water [10] but there are projects trying to reduce the losses [9].

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