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CANDU: STUDY AND REVIEW

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ABSTRACT

The CANDU (Canadian Deuterium Uranium) is a nuclear reactor developed by AECL (Atomic Energy of Canada Limited). The first small-scale reactor is known as NPD and was made in 1955 and commenced operation in 1962. It is a pressurized heavy water reactor and uses D2O as moderator and coolant and therefore uses natural uranium as fuel. There have been two major types of CANDU reactors, the original design of around 500 MWe that was intended to be used in multi-reactor installations in large plants, and the rationalized CANDU6 which has units in Argentina, South Korea, Pakistan, Romania and China. Throughout the 1980s and 90s the nuclear power market suffered a major crash, with few new plants being constructed in North America or Europe. Design work continued through, however, and a number of new design concepts were introduced that dramatically improved safety, capital costs, economics and overall performance. These Generation III+ and Generation IV machines became a topic of considerable interest in the early 2000s as it appeared a nuclear renaissance was underway and large numbers of new reactors would be built over the next decade. The present work aims to study the reactors of the CANDU type, exploring from its creation to studies directed to G-III and G-IV reactors.

1. INTRODUCTION

In a typical fission reaction, a neutron strikes the nucleus of an atom, producing lighter elements, thermal energy, gamma rays, and more neutrons, which go on to strike other atoms and so on:

$$ {}_{0}^{1}n + {}_{92}^{235}U \longrightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3\,{}_{0}^{1}n \qquad (1) $$

The neutrons produced in this reaction have a mean energy of 2 MeV, therefore travel at high speeds and are called fast neutrons. The likelihood of fission between an incident neutron and a target nucleus, its *fission cross section*, is larger when the neutron has a substantially small energy (on the order of 0.025 eV – a thermal neutron). To achieve a successful chain reaction, it is necessary to lower the kinetic energy of the produced neutrons using a *moderator*.

If a neutron hits a particle of similar mass, a significant part of its momentum is transferred to that particle, analogously to billiard balls hitting each other. The most common type of nuclear reactor, the Pressurized Water Reactor (PWR), uses light water as moderator. Light water has hydrogen atoms in its composition (which have a mass approximately equal to that of a neutron) and therefore it is an excellent moderator. However, hydrogen's capture cross section is large, so the fuel has to be enriched to increase the amount of fissionable material and consequently the number of neutrons in the reactor to compensate those absorbed by the water.

The Canadian Deuterium Uranium (CANDU) as its name implies, utilizes heavy water as moderator and coolant. Even though heavy water is a weaker moderator than light water, its deuterium atoms have a smaller capture cross section (since they already contain an extra neutron, compared to hydrogen) allowing the use of non-enriched, natural uranium as fuel [1][2][3]. Furthermore, heavy water has a near identical chemical behavior to that of light water, permitting the use of cooling solutions of light water reactors.

CANDU reactors are of paramount importance in nuclear engineering. In fact, this is quite noticeable when looking at the extensive literature about this type of reactor, which involves its early history all the way to state-of-the-art studies about fuel cycles and new generation designs. Their incredible versatility, robust safety, exclusive features and capability of using advanced fuels, such as thorium, which will likely power the reactors of the future, make them an excellent topic of discussion.

In this work we present an overview of CANDU reactors inner workings and history, as well as an analysis of their fuel cycles and an examination of future designs.

2. A CANDU STUDY

2.1. Anatomy of a CANDU Reactor

The basic working principle of a CANDU reactor is the same as the majority of nuclear fission reactors: thermal energy generated by the reactions heats up the coolant, which then transfers its heat to water, which turns to steam that proceeds to spin a turbine, passes through a condenser and goes back into the system, as shown in Fig. 1.

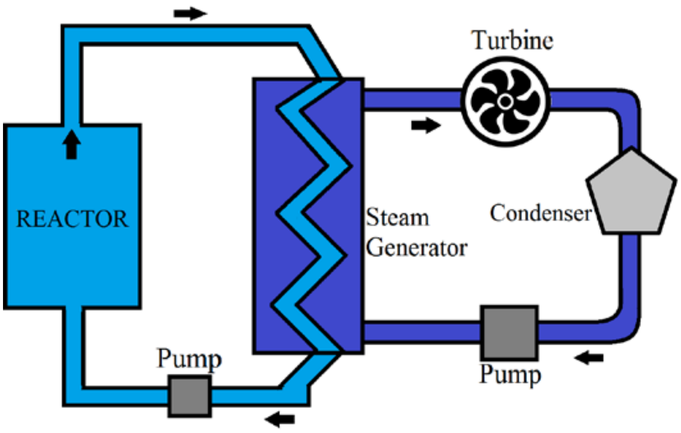

Figure 1: Basic reactor schematic.

Despite appearing to work with century old reactor design when looked from a superficial standpoint, CANDU reactors have a number of features that are not present on most reactors.

In a CANDU reactor (Fig. 2), cylindrical zircaloy fuel bundles (typically UO_2) (item 1 in Fig. 2) are contained within horizontal tubes with pressurized heavy water, part of the primary cooling loop. These tubes are immersed in a tank of low pressure heavy water, known as *calandria* (item 2 in Fig 2). To keep the hot coolant from boiling the moderator, a calandria tube surrounds each pressure tube, with insulating carbon dioxide gas in between. The moderator is actually a large heat sink that acts as an additional safety feature. Adjuster rods (item 3 in Fig. 2) are used to control the rate of fission. Hot pressurized heavy water transfers its heat to light water in the steam generator (item 5 in Fig. 2), part of the secondary cooling loop.

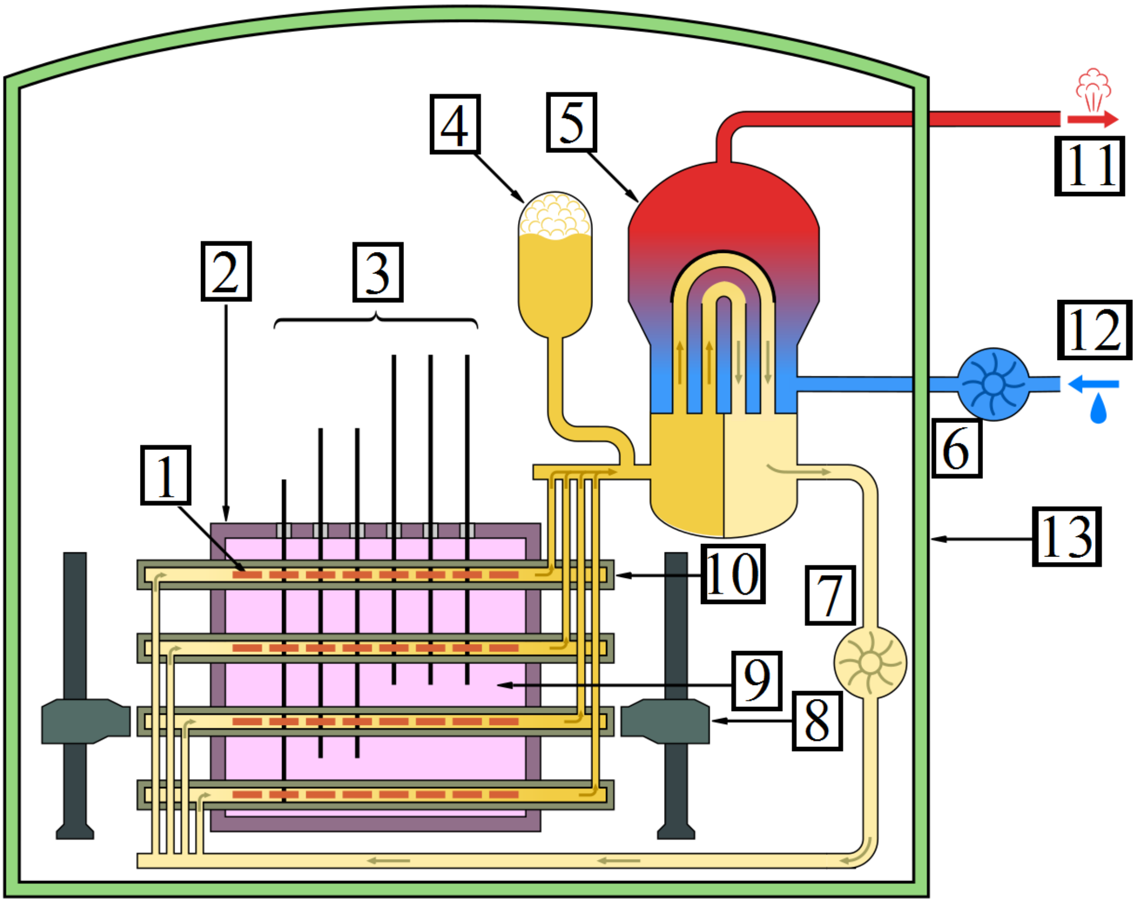

Figure 2: Basic CANDU reactor schematic. Items, in order: 1 – Fuel bundle; 2 – Calandria; 3 – Adjuster rods; 4 – Heavy water pressure reservoir; 5 – Steam generator; 6 – Light water pump; 7 – Heavy water pump; 8 – Fueling machines; 9 – Heavy water moderator; 10 – Pressure tube; 11 – Steam going to a turbine; 12 – Cold water returning from the turbine; 13 – Containment building made of reinforced concrete [26].

This design allows refueling with the reactor online. The reactor pressure vessel is shut down, the pressure consequently drops and the lid is removed. A considerable fraction of the fuel is then replaced at once by the fueling machines (item 8 in Fig. 2), which insert new fuel into one end of the channel while the other receives the discharged fuel at the opposite end [2].

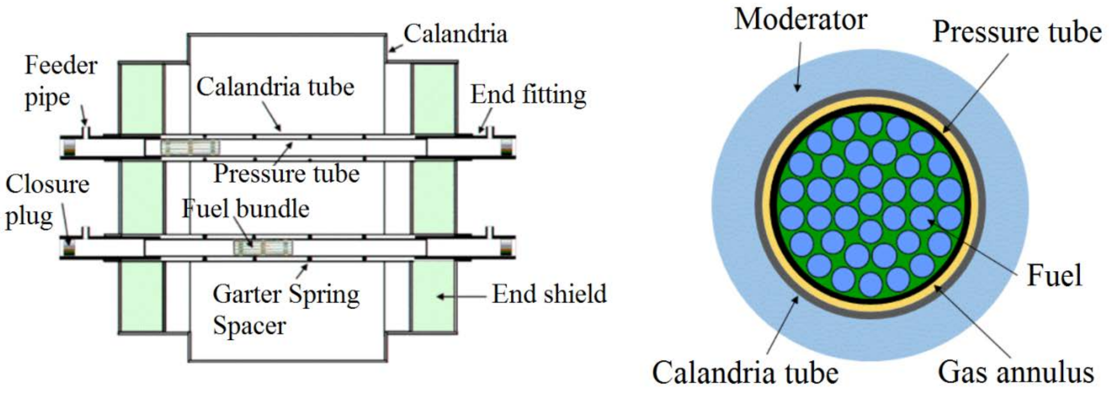

Figure 3: Calandria and fuel channel schematics [27].

2.2. A Brief History of CANDU Reactors

By the early 1940’s, nuclear chain reactions and their potential as a power source were well understood. Initially, in a joint effort between Canadian, British and French scientists, the Zero Energy Experimental Pile (ZEEP) was developed at Chalk River Laboratories to test the use of heavy water as a moderator and to produce plutonium [4]. It went live on September 5, 1945, and became the first reactor to sustain a chain reaction outside of the United States [2][5][6][7]. ZEEP was instrumental in the development of the National Research Experimental (NRX) and National Research Universal (NRU) reactors, that were the foundation of the Nuclear Power Demonstration (NPD) reactor, the prototype for the CANDU design [2][6][7].

The NRX achieved criticality on July 22, 1947, being able to generate 10 MW of thermal power (increased to 42 MW by 1954) and at the time was the most powerful nuclear research reactor and most intense source of neutrons in the world [2][6][7]. NRU was a more advanced version of NRX (with a designed thermal output of 200 MW), achieved criticality on July 22, 1957 and at that time was also the most intense source of neutrons available [2][7]. Due to this fact, it became the world’s leading supplier of radioactive isotopes [2][7]. It was also the first reactor capable of online refueling, a feature that is now a standard part of CANDU design [2][7].

The NPD reactor was designed in 1955 as a joint venture between Atomic Energy of Canada Limited (AECL), Ontario Hydro and Canadian General Electric (CGE) [7]. Several improvements had to be made to the NRU design in order for the reactor to generate electricity: the fuel was changed from uranium to uranium dioxide (a ceramic) in order to sustain higher temperatures; the fuel cladding was changed from aluminum to zircaloy (a material “invisible” to neutrons) to protect the fuel from corrosion without blocking the passage of neutrons; the pressure of the heavy water coolant was increased to allow higher operating temperatures, enabling the use of a steam turbine at a reasonable efficiency; the orientation of the pressure tubes was changed to horizontal, facilitating online refueling; the incorporation of a number of safety features, including functional and physical separation of the safety systems from the systems utilized for normal plant operation, safety shutdown of the reactor by "fail-safe" logic and gravity (passive) actuation, etcetera [2][7]. It operated from 1962 until 1987, when its pressure tubes reached the end of their service life.

The Douglas Point power plant was the first full-scale CANDU generating station, created by AECL and Ontario Hydro, built on what is today the Bruce Nuclear Power Complex and achieving criticality on November 16, 1966 [7]. Capable of 200 MWe, it was in essence a scaled-up version of the NPD and provided valuable experience to future projects. It began operations in 1967 and was taken out of service in 1984, when the replacement of its pressure tubes was not economically justifiable due to its small power output [2][7].

The basis for subsequent power plants was the Pickering-A Generator Station, a four unit plant that came into service in 1971, with each unit capable of 500 MW. There was an increase in the number of fuel elements per bundle from 19 to 28 along with a raise in the pressure tube internal diameter, from 8 cm to 10 cm [2][7].

In December of 1963, AECL entered an agreement with the Indian Department of Atomic Energy (DAE) to build CANDU reactors in India. This type of reactor was of particular interest to India since the country does not possess enrichment capabilities but has a large reserve of nuclear fuel (thorium). Thus began the Rajastan Atomic Power Plant (RAPP) project, which resulted in the construction of RAPP-1 plant, and the beginning of the RAPP-2 plant. However, due to a nuclear weapon test made by India in 1974, Canada withdrew support from the country’s nuclear program [7].

By 1964 the Pakistan Atomic Energy Commission, due to similar reasons to those of India negotiated with CGE the construction of the Karachi Nuclear Power Plant (KANUPP), a 132 MWe version of NPD. The plant commenced operation in December of 1972 [7].

The next generation of CANDU units, due to the reduction in fuel element diameter, had the number of fuel elements in each bundle raised from 28 to 37, increasing heat transfer surface and consequently boosted power from 500 MWe to 600 MWe. Experience in steam generator design allowed a reduction in the number of pumps and steam generators, and a gain in coolant efficiency. This type of unit is known as CANDU 6 [2][7].

This improved design along with the marketing efforts of AECL led to the sale of several reactors domestically and internationally, as shown in Table 1 [2][7].

Table 1: CANDU-6 reactors capacity and service date

Country	Station Name	Gross (MWe)	Net (MWe)	Service Date
Argentina	Embalse 1	648	600	1984
Canada	Point Lepreau	680	635	1983
Canada	Gentilly 2	675	635	1983
China	Quinshan 4	700	640	1984
China	Quinshan 5	700	640	2002
Romania	Cernavoda 1	706	655	1996
Romania	Cernavoda 2	706	655	2007
South Korea	Wolsong 1	679	629	1983
South Korea	Wolsong 2	700	650	1997
South Korea	Wolsong 3	700	650	1998
South Korea	Wolsong 4	700	650	1999

An important trend in CANDU design progression was the increase in pressure tube diameter and decrease in element diameter. This trend implies an increase in the number of fuel bundle elements, as can be seen in Fig. 4.

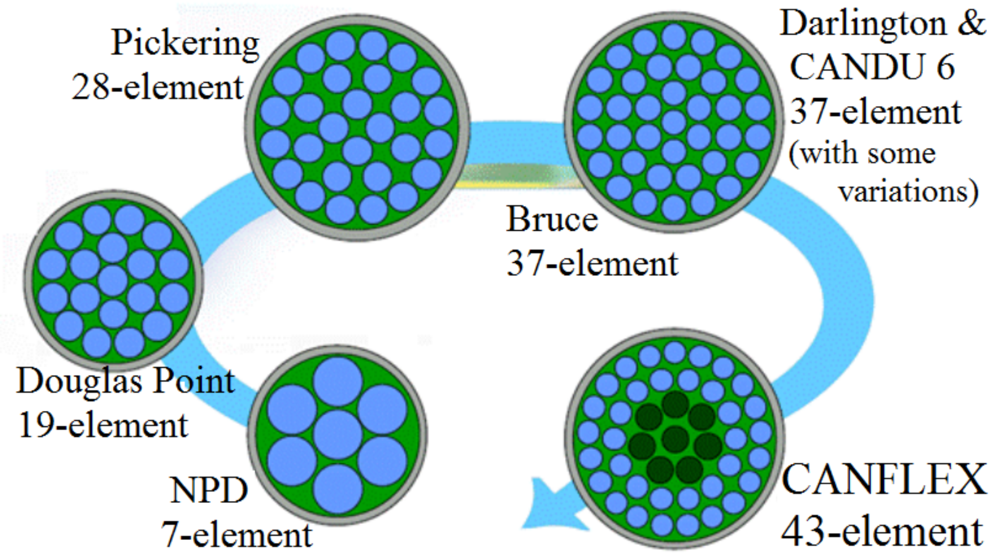

Figure 4: Fuel bundle evolution [27].

An upscaling of the reactor design led to the larger 800+ MWe units of the Bruce Nuclear Generating Station and Darlington Nuclear Generating Station. The popularity of 900 MW designs of the late 1980's and early 1990's, combined with the success of the aforementioned stations led to the design of the single unit, 935 MWe CANDU 9 (Fig. 5) [2][8][9]. While a reactor of this type has yet to be built, its current design features include: reduced site area requirements; improved containment, coolant system, safety, operability and maintainability; increase in fuel channels from 390 to 480 [8][9].

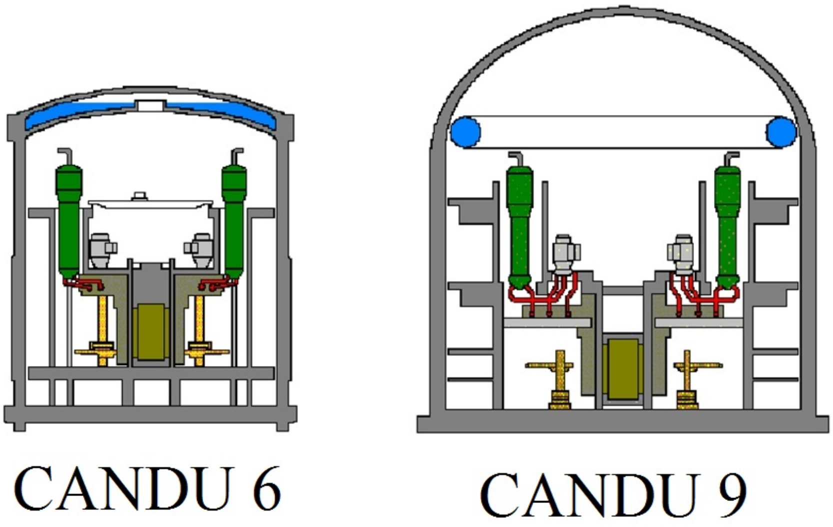

Figure 5: CANDU 6 and CANDU 9 reactor building layout [27].

3. CANDU FUEL CYCLES

In this section we take a look at all the available fuel cycles of existing and future reactors (Fig. 6). The high neutron economy of CANDU reactors along with the simplicity of its fuel bundles (Fig. 7) allow easy manufacture and utilization of advanced fuels [3][10].

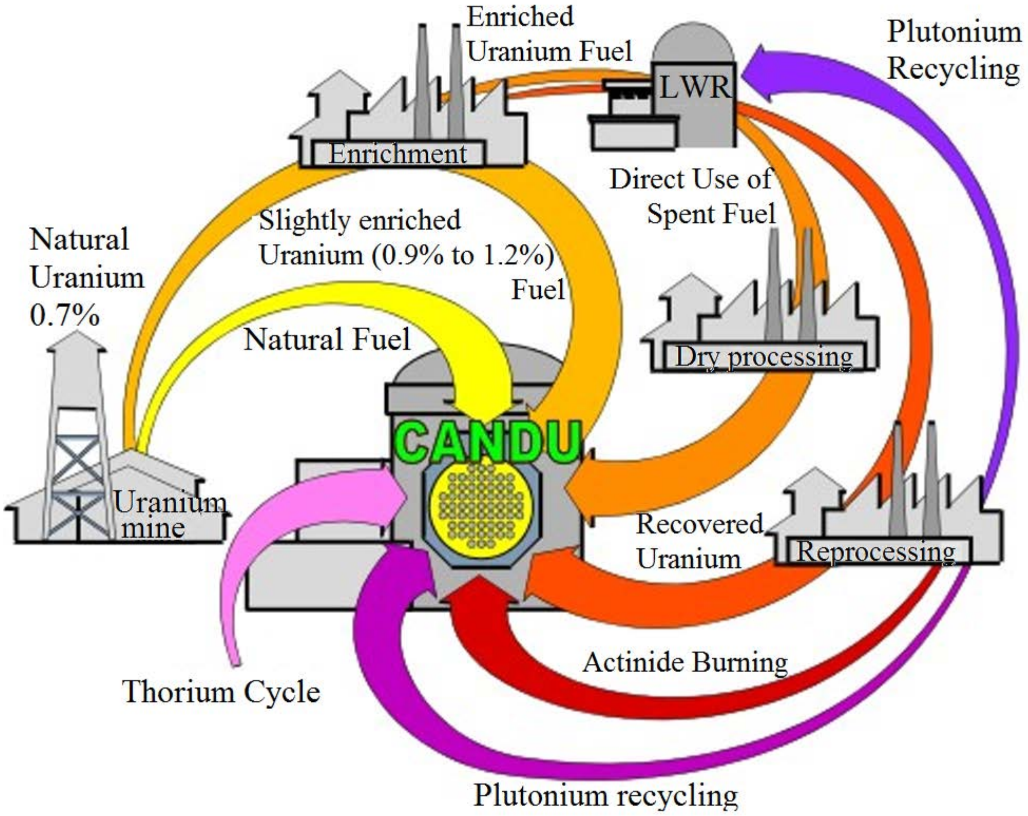

Figure 6: CANDU fuel cycles [26].

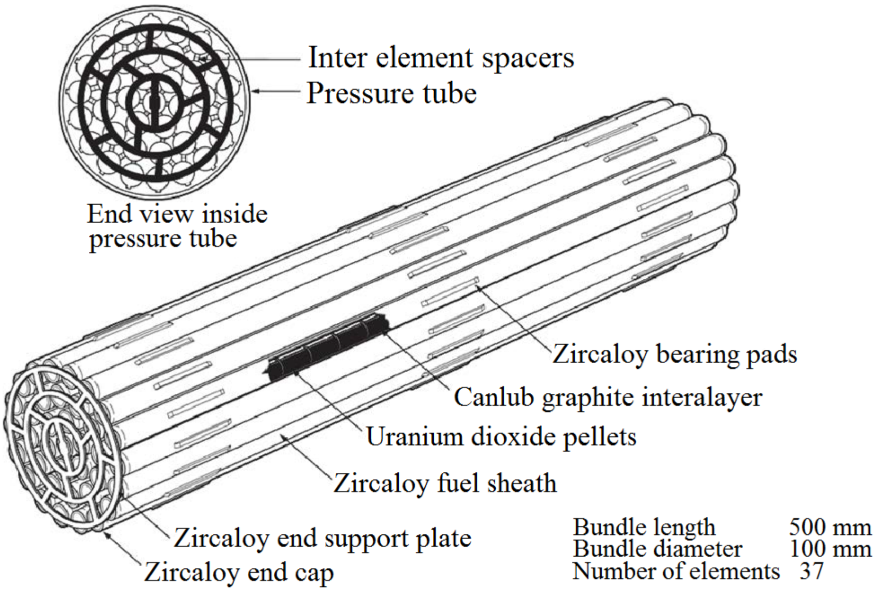

Figure 7: CANDU 6 fuel bundle (37 elements) [3].

3.1. Natural Fuel, Slightly Enriched Uranium (SEU) and Recovered Uranium (RU)

3.1.1. Natural fuel

This type of fuel is the one already used in CANDU reactors around the world. Its simplicity and non-requirement of enrichment capabilities still make it an attractive choice. An improvement on the use of natural uranium and other fuels is the CANFLEX bundle, which contains 43 elements. It has improved operating and safety margins; improved critical heat flux and critical channel power; better thermalhydraulic performance; reduced fission gas released to the free inventory and higher power capability [3][10].

3.1.2. SEU/RU

The CANFLEX bundle can also be used with these fuels. A mere 0.9% enrichment (compared to the 0.72% found in natural uranium) is capable of doubling fuel burnup to 14 MWd/kg, and a 1.2% can triple it. 0.9% SEU also implies a 45% lower uranium consumption and a 30% increase in uranium utilization, as well as a 20-30% reduction in fuel cycle costs [3][10][11].

3.2. Direct Use of Spent Fuel, Plutonium Recycling and Actinide Burning

Mixed oxide fuel, also known as MOX fuel, is nuclear fuel that contains more than one oxide of fissile material, usually consisting of plutonium blended with natural uranium, reprocessed uranium, or depleted uranium [12]. They are used in these fuel cycles.

3.2.1. DUPIC

Direct **U**se of Spent **P**WR Fuel **I**n **C**ANDU (DUPIC) is a fuel cycle that utilizes non-separated, non-enhanced waste products of LWR directly as CANDU fuel, using only thermal and mechanical processes to recycle the spent fuel [3][10][11]. This offers several benefits, such as: reduction in LWR spent fuel storage requirements, reduction in quantity of fuel requiring disposal, reduction in heat load of the spent fuel (per unit of electricity produced), high degree of proliferation resistance, etc. [10]. CANDU MOX fuel can be manufactured through the Oxidation and REduction of OXide fuels) process (“OREOX”), a series of oxidation/reduction cycles that convert used PWR pellets into a ceramic-grade powder that are pressed and sintered as CANDU pellets, and loaded into standard sheaths that are assembled into fresh bundles [3].

3.2.2. Disposition of weapons-grade plutonium

A tripartite agreement between Canada, the United States and Russia, known as the Parallex Project, is researching the feasibility of disposing of weapons-derived plutonium in CANDU MOX fuel [10]. With plutonium concentrations betwixt 1% and 5%, using two reactors in Ontario, Canada, it was predicted that 50 tons of ex-weapons plutonium could be processed in 15 to 25 years [11]. To completely annihilate the plutonium, an inert matrix (non-fertile material) can be used as carrier, or alternatively, a mixture of plutonium and thorium dioxide (thoria) can be used as fuel [12].

3.2.3. Actinide burning

An inert matrix containing ^{237}Np, ^{241}Am, ^{243}Am, ^{244}Cm and plutonium from spent PWR fuel can be used to burn these actinides in a CANDU reactor. The lack of ^{238}U in the matrix implies that no more of them will be produced in the reaction [3]. 60% of the actinides are destroyed, along with 90% of the plutonium [12].

3.3. Thorium Cycle

The possibility of peak uranium, conjoined with thorium's greater abundance, superior physical and nuclear properties, reduced plutonium and actinide production, and better resistance to nuclear weapons proliferation when used in a traditional light water reactor, has motivated the creation of innumerous studies about this fuel [3][10][11][13]. The thorium used in the cycle (^{232}Th), however, is not the actual fuel burned in the reaction (Eq. 2), it is transmuted into the fuel (^{233}U), and therefore a neutron source is needed.

$$ {}_{0}^{1}n + {}_{90}^{232}Th \longrightarrow {}_{90}^{233}Th \xrightarrow{\beta^-} {}_{91}^{233}Pa \xrightarrow{\beta^-} {}_{92}^{233}U \tag{2} $$

One option is to use spent LWR fuel [13][14][15][16] as well as weapons-derived plutonium as the source. Another, simpler option is to use natural uranium.

By reason of the breeder nature of the thorium cycle, it is heavily dependent on the reactor neutron economy, and thus CANDU reactors, which have excellent neutron economy, are a natural candidate. There are different possible thorium cycles available for this type of reactor [13][17][18][19]. They are:

- Once-through cycle, where ^{233}U is generated and incinerated *in situ*;
- Direct self-recycle of irradiated ThO_2 elements following the once-through cycle (no reprocessing);
- Reprocessing and other types of recycling;
- The self-sufficient equilibrium thorium cycle, in which ^{233}U concentration in the recycled fresh fuel matches the ^{233}U concentration in the spent fuel.

For the once-through cycle, an idea is to use SEU as the "driver" fuel (source of neutrons). In a mixed channel approach, channels would be filled with interleaved thoria and SEU bundles. To work properly, a combination of feed rates, burnups, uranium enrichment and neutron flux level would have to be carefully chosen. Another option is to use a mixed fuel bundle, with thorium elements at its center and driver elements encompassing them [17][18][19].

Direct self-recycling bring about notable improvements in uranium utilization, with uranium requirements being 35% lower than those of a natural uranium cycle and 10% lower than those of a SEU cycle [17][18][19].

Separating the thorium and uranium from the other fission products before recycling would significantly increase the burnup and energy obtained from thoria elements[17][18][19].

Thorium cycles are also of our particular interest due to the large reserves of thorium in Brazil, contained in monazitic sands [20][21].

4. NEW GENERATION CANDU REACTORS

Like other fields of technology, nuclear engineering continues to develop. With the increasing global energy demand, traditional methods of energy generation, such as fossil fuels and hydro, will not be enough to supply the world, while solar and wind power are too expensive and nuclear fusion is still decades away from being able to produce electricity commercially. Therefore nuclear fission is the only option capable of meeting the energy needs of humanity in the near – and likely long – term. To that end, new generation reactors are being developed [22]. Fig. 8 shows a timeline of reactor generations, with a focus on CANDU reactors.

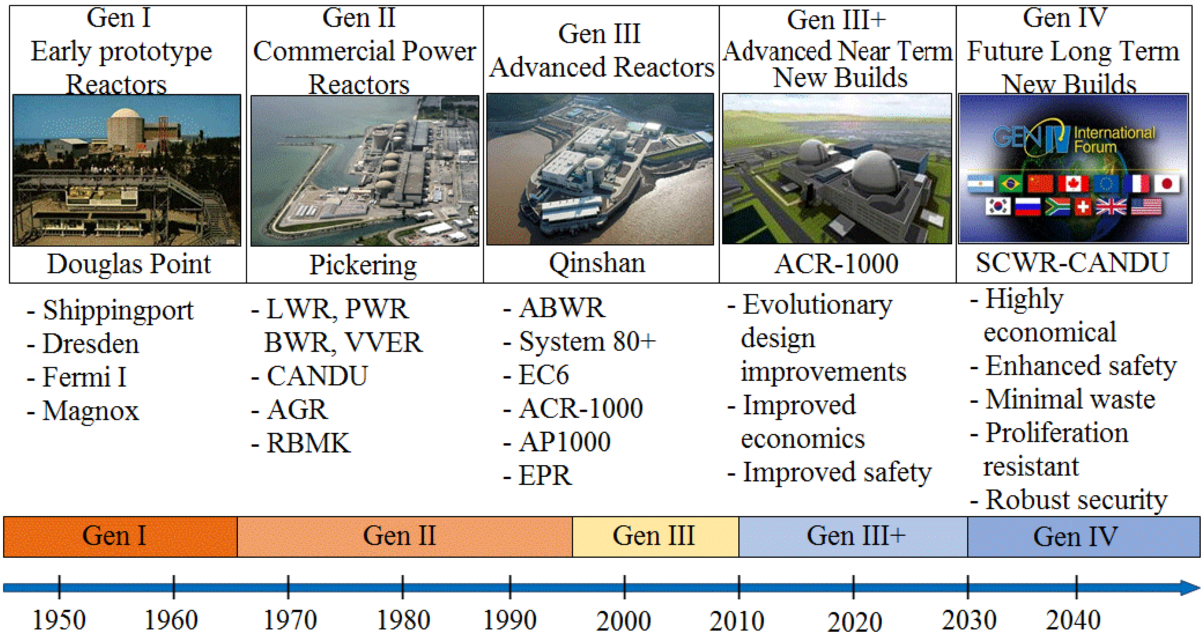

Figure 8: Timeline of nuclear reactor generations [27].

4.1. ACR-1000

The Advanced CANDU reactor (ACR), or ACR-1000, is a Generation III+ nuclear reactor designed by AECL. The name refers to its design power in the 1,000 MWe class, with the baseline around 1,200 MWe. It combines features of the existing CANDU reactors with features of light-water cooled advanced pressurized water reactors (APWR). The heavy water cooling loop is replaced with one containing conventional light water, greatly reducing costs, while still maintaining the majority of features provided by traditional CANDU reactors [23].

Another difference is the use of low-enriched uranium (LEU) CANFLEX fuel. Both of these features along with other evolutionary changes enable a more compact core design, reducing heavy water inventory; a higher burnup; improved overall turbine cycle efficiency through the use of higher pressures and higher temperatures in the coolant and steam supply systems; reduced emissions, through the elimination of tritium production in the coolant and other environmental protection improvements; enhanced severe accident management by providing backup heat sinks; improved performance through the use of advanced operational and maintenance information systems; etc. [23].

4.2. SCWR – CANDU

The supercritical water cooled reactor (SCWR) is a concept Generation IV reactor that operates at supercritical pressure. This allows for higher net electrical efficiency, reduction of flow rate of water for cooling the reactor allowing the adoption of smaller pipelines and pumps, high power density, a small core, and a small containment structure [24].

The CANDU X program aims to study and design feasible G-IV reactors, including a SCW CANDU reactor. To have a greater power output, a G-IV CANDU would likely utilize SEU/RU CANFLEX fuel. To be able to withstand the higher temperatures and pressures of SCW, stronger pressure tubes will be needed, for that end a high temperature channel named CANTHERM is being developed [25].

Even though SCWR – CANDU shows great potential, due to the cutting edge nature of this type of reactor, development is still in its early stages. A commercial version will probably be available in between 2025-2080, if a prototype is developed before this period [24].

5. CONCLUSIONS

In summary, CANDU reactors have experienced many changes and evolutions. On one hand, they require a large core and thus have higher construction costs. On the other, their ability to use natural uranium and online refueling results in lower operational costs. Their capability of easily running different fuel cycles, alongside their high neutron economy make them an attractive option as a thorium burner. The improvements brought about by new generation reactors will likely make CANDU reactors more competitive when compared to their current status.

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