Basic CANDU Design

by
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In this Session we will review some of the history which led to the CANDU reactor. We will then look at the basic characteristics which define the distinctive CANDU reactor.

CANDU means CANada Deuterium Uranium.

8.1 History

Neutron-induced nuclear fission was first clearly identified in 1939 by Lise Meitner and Otto Frisch, who correctly interpreted the results of earlier experiments on uranium which had been carried out by Hahn and Strassmann.

The fact that fission released a large amount of energy, and, in addition, that typically 2 or 3 neutrons emerged from the fission process meant that a chain reaction was possible under the right circumstances. The potential for a weapon capable of a hitherto unimaginable explosive power was immediately understood by nuclear physicists.

During the Second World War, the émigré Hungarian physicist Leo Szilard, living in the USA, started worrying seriously about the possibility that the Nazis were working on research into an “atomic bomb”. He convinced Albert Einstein to write a letter to President Roosevelt urging him to initiate an American program of research in order to pre-empt a Nazi bomb. This led to the Manhattan Project in 1942.

In 1943, following a meeting between Roosevelt, Churchill, and Mackenzie King, Canada entered into a wartime collaboration on research into nuclear fission with the UK and the USA. Because fear of a German invasion of Britain was still very real, the UK desired to move its scientists to Canada, out of harm’s way, and consequently a research laboratory was created at the Université de Montréal in 1942. Along with the British scientists came Lew Kowarski, a Russian émigré physicist who had worked in France and then had Fled to England. Kowarski had with him a very valuable cargo: almost the entire world’s supply of heavy water, which he had spirited out of Norway and then out of France. The importance of heavy water as a neutron moderator had begun to be realized, and as a consequence, Canada was given the responsibility for developing a heavy-water reactor to eventually produce plutonium for an atomic bomb for the war effort.

The Montréal Laboratory was moved to Chalk River in 1944, and work on designing and building the research reactor ZEEP (Zero Energy Experimental Pile) was started as a first step in building the production reactor (called NRX). In fact, this work was highly successful, and ZEEP was the **first** man-made nuclear reactor to “go critical” outside the USA, although this was actually a few days after the end of the War, in 1945 September!

NRX was of course not operational yet, so in fact Canada did not produce plutonium for the war.

Following the end of the war and in the early 1950s, several visionaries, among them Bennett Lewis, who headed up the Chalk River Laboratories (which eventually became AECL when the latter was incorporated in 1952), lobbied the Federal Government very hard to apply the nuclear knowledge which had been gained in the War, but now to peaceful ends: the production of electrical power by nuclear fission. And Bennett was able to convince to get the Government to give AECL that mandate.

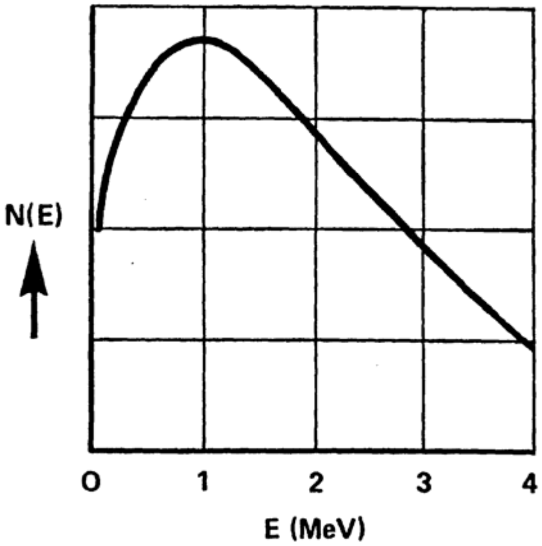
Because of the excellence and success of the work in developing ZEEP, it was extremely natural to continue in that path and decide to use heavy water as the moderator in Canadian reactors. This was in contrast to the US decision to develop light-water reactors for power, a decision which followed from the successful American nuclear-submarine program. Thus, a distinctive, world-class Canadian reactor design was to be born – a proud feat and a great technological success for a country with a small population.

8.2 Basic CANDU Characteristics

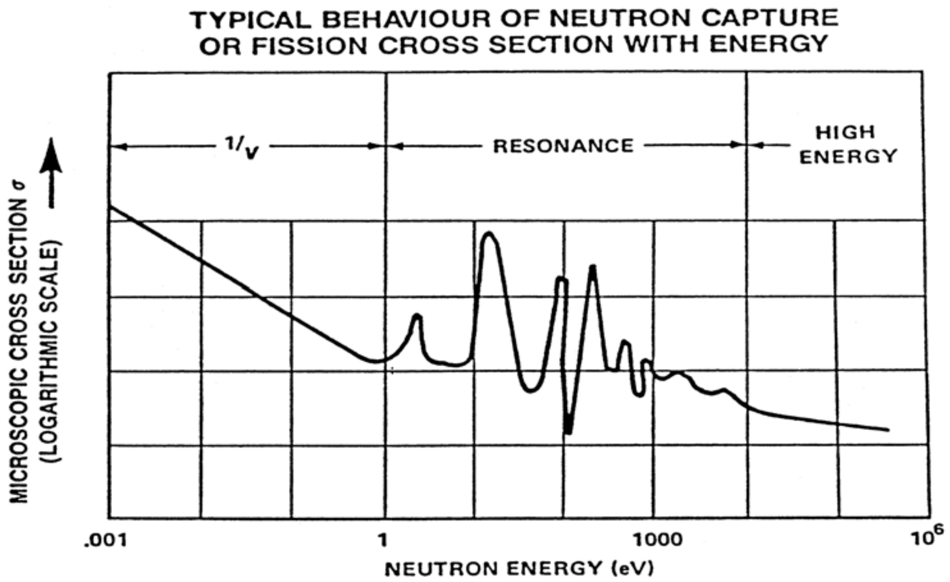
8.2.1 Heavy Water as Moderator

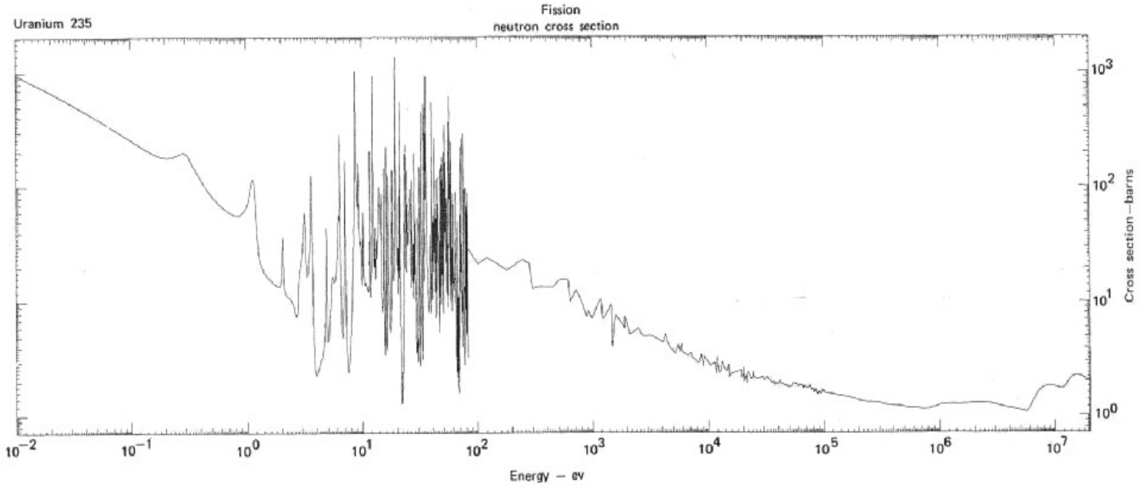
As seen above, this was a natural conclusion, based on Canada's work during World WAR II. However, this decision is also very strongly founded on physics:

The function of the moderator is to slow fission neutrons down. The reason is that neutrons emerge from fission typically with a very high kinetic energy: their energy spectrum (distribution) shows a maximum at ~1 MeV – see Figure.



However, the probability for a neutron to induce fission is orders of magnitude higher at “thermal” energies (~0.025 eV) than in the range of 1-2 MeV [see Figures below, the first showing a sketch of a fission cross section versus energy, and the second showing (rather faintly, admittedly, unless the figure is enlarged) the actual fission cross section of ^{235}U (source: Duderstadt)]. Therefore, a moderator is used to slow the fission neutrons down to thermal energies.





Fission Cross Section of ^{235}U versus Neutron Energy (Source: Duderstadt)

To slow the neutron down in as few collisions as possible, the moderator should have nuclei of mass close to that of a neutron, i.e., it should be a light element. The nuclide with mass closest to that of the neutron is ordinary hydrogen, ^{1}H. Therefore, ordinary (light) water is certainly very effective at slowing down neutrons. And it is in fact used in light-water reactors.

However, ^1H has also a high absorption cross section for neutrons. Thus, it can slow them down, or it can also absorb them (making heavy hydrogen – deuterium: ^2H or D) and take them out of circulation as agents of further fissions.

Other light nuclides, which are by virtue of their mass good at slowing down neutrons, are D (deuterium – in the form of heavy water), C (carbon, in the form of graphite), and Be (beryllium). These have a smaller absorption cross section for neutrons than hydrogen. The one with the smallest absorption cross section is deuterium, and so heavy water is in fact the moderator with the best "neutron economy" – i.e., it leaves neutrons in circulation, to act as agents of further fissions.

Quantitatively, the following 3 quantities are important in determining the properties of a moderator:

Σ_s, the scattering cross section for neutrons. **Larger** is better, because it means that the nuclide is efficient at colliding with neutrons.

ξ, the "lethargy decrement". This is the average energy lost by a neutron in a collision with the nuclide. **Larger** is better, because it means that the neutron is thermalized in fewer collisions.

Σ_a, the absorption cross section for neutrons. **Smaller** is better, because it means that the nuclide is poor at absorbing neutrons.

The quantitative "figure of merit" for moderators is therefore the

$$Moderating\ Ratio = \frac{\xi \cdot \Sigma_s}{\Sigma_a}$$

As can be seen from the following Table, heavy water is indeed the best moderator, as it has the highest moderating ratio.

Slowing down parameters of typical moderators [Source: DUD76, Table 8-1]

Moderator	A	α	ξ	$\rho[g/cm^3]$	Number of collisions from 2 MeV to 1 eV	$\xi\Sigma_s[cm^{-1}]$	$\xi\Sigma_s/\Sigma_a$
H	1	0	1	gas	14	—	—
D	2	.111	.725	gas	20	—	—
H_2O	—	—	.920	1.0	16	1.35	71
D_2O	—	—	.509	1.1	29	0.176	5670
He	4	.360	.425	gas	43	1.6×10^{-5}	83
Be	9	.640	.209	1.85	69	0.158	143
C	12	.716	.158	1.60	91	0.060	192
^{238}U	238	.983	.008	19.1	1730	0.003	.0092

Note that for a batch of heavy water to be used as moderator, its isotopic purity must be extremely high. Reactor-grade heavy water is at least 99.75 weight % pure; i.e., its light-water content cannot be more than 0.25 weight %, otherwise the neutron economy would be significantly impaired.

8.2.2 Natural Uranium as Fuel

The neutron economy of heavy water is such that natural uranium **can** be used as fuel. With light water as moderator, this is not the case: the rate of neutron absorption is sufficiently high that the reactor cannot go critical with natural-uranium fuel; the uranium must first be enriched in the ^{235}U isotope to increase the probability of fission relative to that of absorption.

Thus, natural uranium has been chosen as the fuel for CANDU. This was important for Canada, because it could then use its very large uranium resources in a self-sufficient manner, it did not have to develop the complex and costly enrichment capability or rely on external sources of enriched fuel. [This remains an important factor for any other small country which does not want to depend on foreign sources for its reactor fuel.]

The fuel in CANDU is uranium dioxide. CANDU fuel is manufactured in the form of elements of length ~ 48 cm. Each element consists of uranium-dioxide pellets encased in a zircaloy sheath. A number of fuel elements are assembled together to form a bundle of length ~ 50 cm. The elements are held together by bundle end plates:

The CANDU fuel bundle is short and easy to handle, and it has few different components. As a result, current CANDU fuel is much cheaper than light-water-reactor fuel, and CANDU fuel-manufacturing capability can readily be developed by even small countries which purchase CANDU reactors.

Note that although natural uranium has been the fuel for CANDU since the beginning, the heavy-water moderator does not **demand** natural uranium. In fact, CANDU is extremely flexible in that it can burn enriched uranium, mixed-oxide (uranium/plutonium) fuels, or even irradiated fuel from light-water reactors. The latest CANDU design, the Advanced CANDU Reactor (ACR), will use slightly-enriched uranium.

8.2.3 Pressure-Tube Design

The first CANDU prototype was the Nuclear Power Demonstration (NPD) reactor, which went critical in June of 1962. The first design of NPD was a pressure-vessel design. Now, although NPD was to be a relatively low-power prototype (20 MWe), the pressure vessel would have had to be much larger than that for a light-water reactor of the same power. The reason is the heavy-water moderator: although D_2O is an excellent moderator, the mean free path of neutrons in heavy water is much longer than that in light water, and the number of collisions to thermalize a neutron quite a bit higher. Canada did not at the time have a heavy industry capable of manufacturing a pressure vessel of the required size, so a contract was signed to purchase the vessel from the UK.

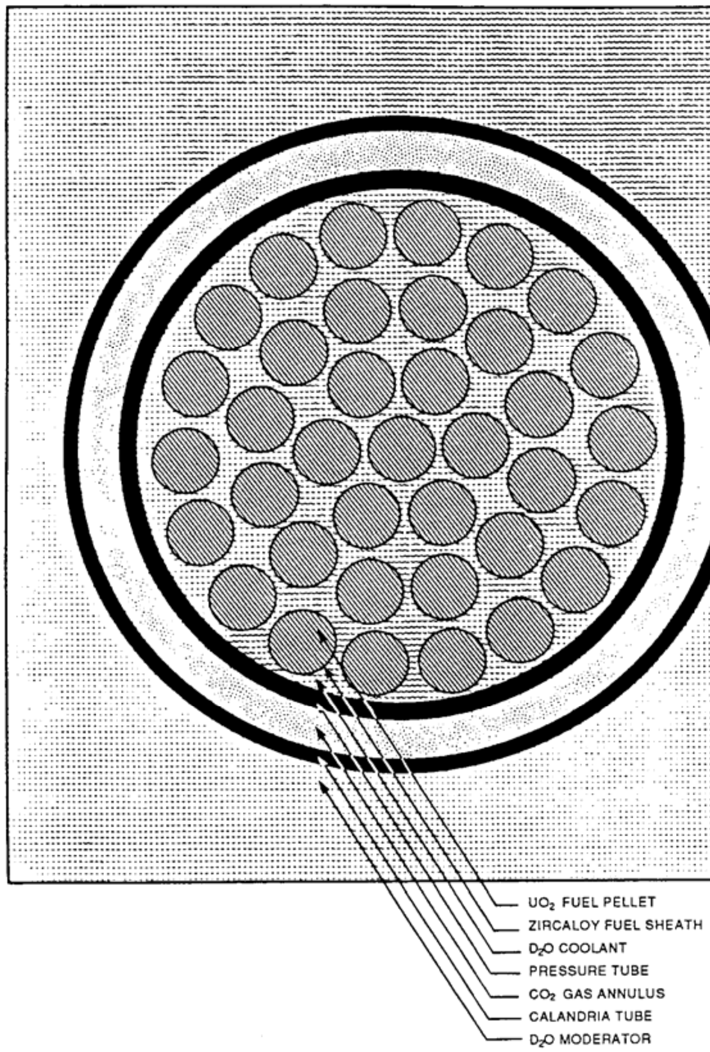
However, the fathers of CANDU then started to be concerned about the size of the pressure vessel, not only for NPD, but even more so for the larger reactors that would follow. The pressure vessels would really have to become enormous. As a result of these misgivings, the pressure-vessel design for NPD was scrapped (a penalty had of course to be paid to tear up the contract for the vessel), and NPD was changed to a pressure-tube design. This meant that the tubes would be the pressure boundary within which the hot coolant would flow. The reactor vessel would not have to operate at pressure, and would therefore be much simpler to manufacture – in fact, it could be manufactured domestically, another important plus for Canada. The CANDU low-pressure reactor vessel has been named a **calandria**.

The designers of NPD, and thereafter of all currently operating CANDUs, opted for horizontal pressure tubes. This was in the interest of symmetry – there would be no "preferred" direction for the coolant flow, as there would be if the pressure tubes were vertical. With horizontal pressure tubes, the coolant could be made to flow in opposite directions in alternate channels, which would further enhance axial symmetry.

It is very important to note, however, that the reason that the pressure-tube concept was viable is zirconium. In the pressure-tube design, there is a large mass of metal **inside** the reactor, which could absorb too many neutrons. This would definitely be the case with steel pressure tubes – the fission chain reaction could not be made self-sustaining, on account of the large neutron absorption by the steel. Fortunately, zirconium, which is a "magic" nuclide with a very low neutron-absorption cross section, came on the scene in time for application in NPD. Incidentally, this "coming to the fore" of zirconium was as the result of materials research in Chalk River for the US nuclear program.

Note that while the pressure tubes are the pressure boundary, they would tend to conduct heat from the fuel out into the moderator. Therefore, in order to provide insulation for the moderator and prevent it from boiling in contact with the hot pressure tube, each pressure tube is surrounded by a concentric calandria tube of larger diameter. The gap between pressure tube and calandria tube is filled with gas (CO_2) and insulates the moderator, allowing it to operate at relatively low temperature (~ 70 ^oC).

See sketch of CANDU basic lattice cell below. This is not to scale.



CANDU Basic Lattice Cell for 37-Element Fuel (Not to Scale)

8.2.4 Heavy Water as Coolant

In the pressure-tube design, the moderator and coolant are separated, in contrast to the situation in the pressure-vessel design. In principle, this allows the moderator and coolant to be different.

In spite of this, all operating CANDUs have heavy water as the coolant. The idea for retaining heavy water as the coolant too is to maximize the neutron economy.

Note that experimentation was performed with other coolants, however:

- Gentilly-1, near Trois-Rivières in Québec, was a CANDU prototype for a vertical reactor. It used boiling light water as coolant. It suffered from control problems, particularly on account of the boiling of the coolant. Its control problems and the success of the "standard" CANDU design resulted in a very short life for Gentilly-1.

- WR-1 at Whiteshell Laboratories was a prototype which used an organic coolant. Although this coolant had a higher operating temperature than heavy water, there was some concern about its flammability. It was therefore never seriously considered for the production reactors.

Note also that the Advanced CANDU Reactor is designed with **pressurized light water** as coolant. This is in conjunction with slightly enriched uranium as fuel, a slightly thicker pressure tube, and a smaller pitch for the lattice.

8.2.5 On-Power Refuelling

With the pressure-tube concept, on-power refuelling becomes possible, since, with an appropriate design, fuel channels can be “opened” individually and at full power to replace some of the fuel. On-power refuelling was therefore adopted for CANDU.

The short CANDU fuel bundle facilitates on-power refuelling, because we can then replace **part** of the fuel in a channel at each refuelling operation. Also, choosing a design with horizontal fuel channels simplifies the refuelling operation, because the bundles need not be “tied” together. In contrast, in Gentilly-1 with its vertical channels, a central tie-rod was needed to hold the entire fuel-string together.