Basic CANDU Design

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History

- Neutron-induced nuclear fission first clearly identified in 1939 by Lise Meitner and Otto Frisch - they correctly interpreted results of earlier experiments by Hahn and Strassmann on uranium.
- Large energy release + 2-3 neutrons: chain reaction possible under right circumstances.
- Potential for extremely powerful weapon immediately understood.

History (cont’d)

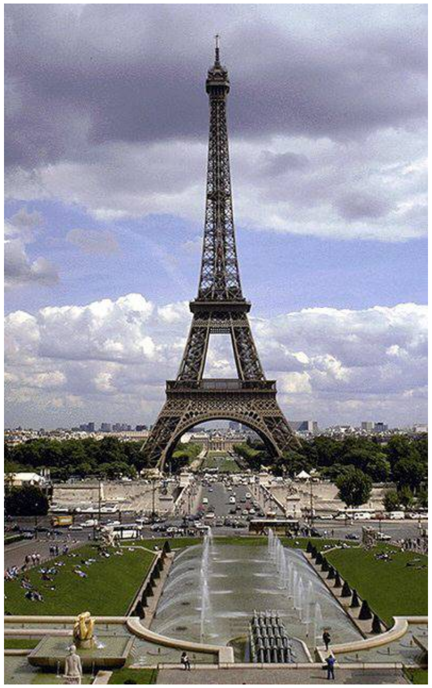
- During the Second World War, émigré Hungarian physicist Leo Szilard, living in USA, convinced Albert Einstein to write a letter to President Roosevelt urging him to initiate an American program of research in order to pre-empt a Nazi bomb.
- This led to the Manhattan Project in 1942.

History (cont’d)

- UK war scientists moved to Canada; research laboratory created at the Université de Montréal in 1942. Also came Lew Kowarski, Russian émigré physicist who had worked in France and then had fled to England.
- Kowarski came with very valuable cargo: almost entire world’s supply of heavy water, spirited out of Norway and then out of France.

1940 … The Heavy-Water Caper

Not-so-gay Paree



Lew Kowarski & Hans von Halban escape from Paris to the U.K. with their D_2O, ahead of the Nazi invasion. Subsequently (1942), they come to Canada.

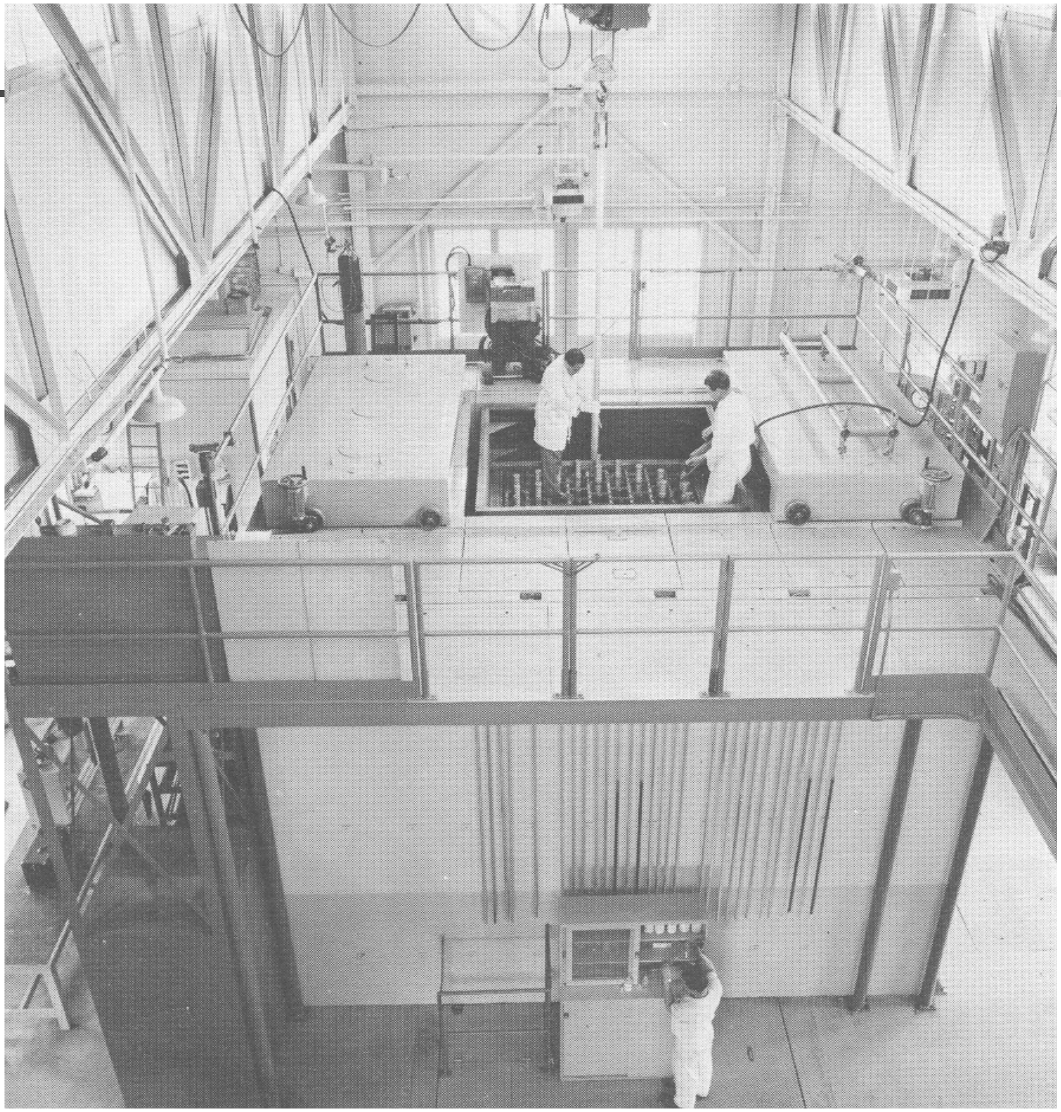
History (cont’d)

- 1943: Meeting between Roosevelt, Churchill, and Mackenzie King. Canada enters into wartime collaboration on research into nuclear fission with UK and USA.
- The importance of heavy water as a neutron moderator was understood, and since Canada now had an inventory of it, Canada was given the responsibility for developing a heavy-water reactor to eventually produce plutonium for an atomic bomb for the war effort.

History (cont’d)

- The Montréal Laboratory was moved to Chalk River in 1944.
- Work began on designing NRX, which was to be the production reactor for plutonium for the war effort.
- However, Lew Kowarski was able to get authorization, as a first step, to build a research reactor: ZEEP (Zero Energy Experimental Pile).

ZEEP



Lew Kowarski’s Baby

60th Anniversary this year!

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History (cont'd)

- Kowarski was successful, and ZEEP was the **first** man-made nuclear reactor to "go critical" outside the USA - a few days after end of the War, in 1945 September!
- NRX was commissioned in 1947.
- So, in fact, NRX did not produce plutonium for the war. Neither did ZEEP!

Chalk River Early Research Reactors

NRU: Provider of radionuclides to the world – then and now.

History (cont'd)

- Following end of war, in the early 1950s, several visionaries, among them Bennett Lewis, head of Chalk River Nuclear Laboratories (which eventually became AECL in 1952), lobbied hard to apply Canada's nuclear knowledge to peaceful ends: the production of electricity.
- Bennett, a man of purpose and eloquence, convinced the Government to give AECL that mandate.

The History

- W.B. Lewis was the driving force behind the application of nuclear science to electricity production.

See excellent book on

early history of Chalk River

"Canada Enters the Nuclear Age"

McGill-Queen's University Press, 1997

Available from AECL & CNS

W.B. Lewis – The father of CANDU

History (cont’d)

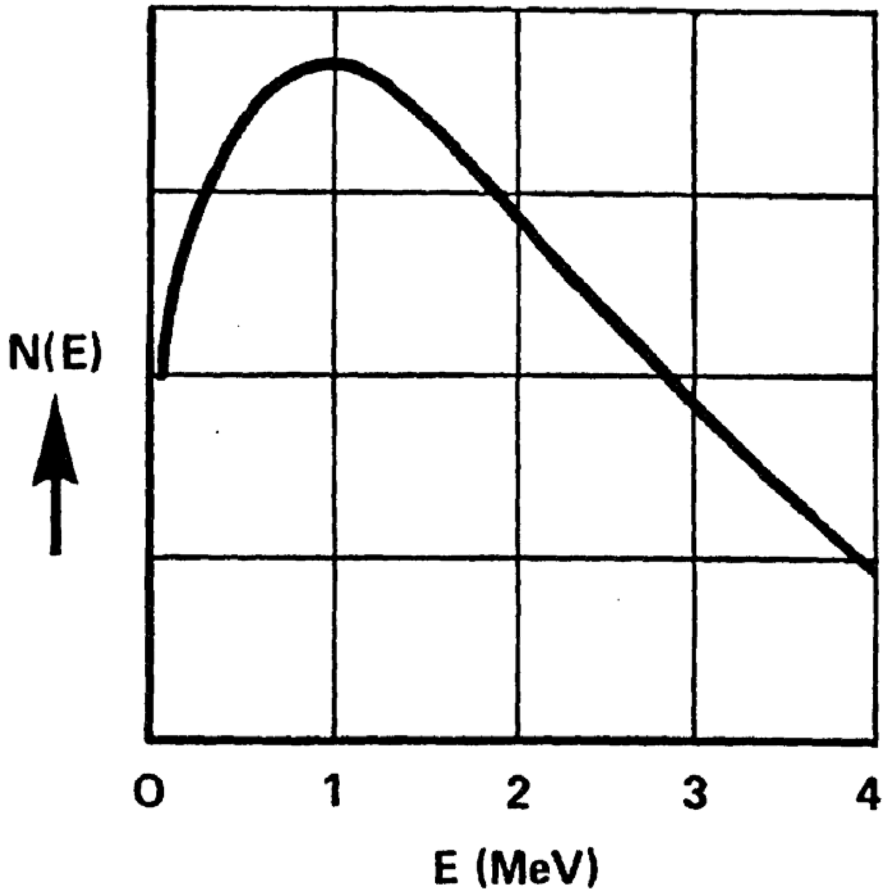
- Excellence and success of ZEEP development made it natural to continue in the heavy-water “path” for the moderator.
- This was in contrast to the US decision to develop light-water reactors for power, which followed from the successful American nuclear-submarine program.
- A distinctive, world-class Canadian reactor design was born – a great technological success and a proud feat for a country with a small population.

Basic CANDU Characteristics – Heavy Water

Heavy Water as Moderator

- A natural conclusion, based on Canada’s work during World WAR II.
- However, a decision also very strongly founded on physics.
- The function of the moderator is to slow down the neutrons which emerge from fission, typically with very high kinetic energy - their energy distribution shows a maximum at ~1 MeV (speed ~ 14,000 km/s!) – see Figure.

Fission-Neutron Spectrum

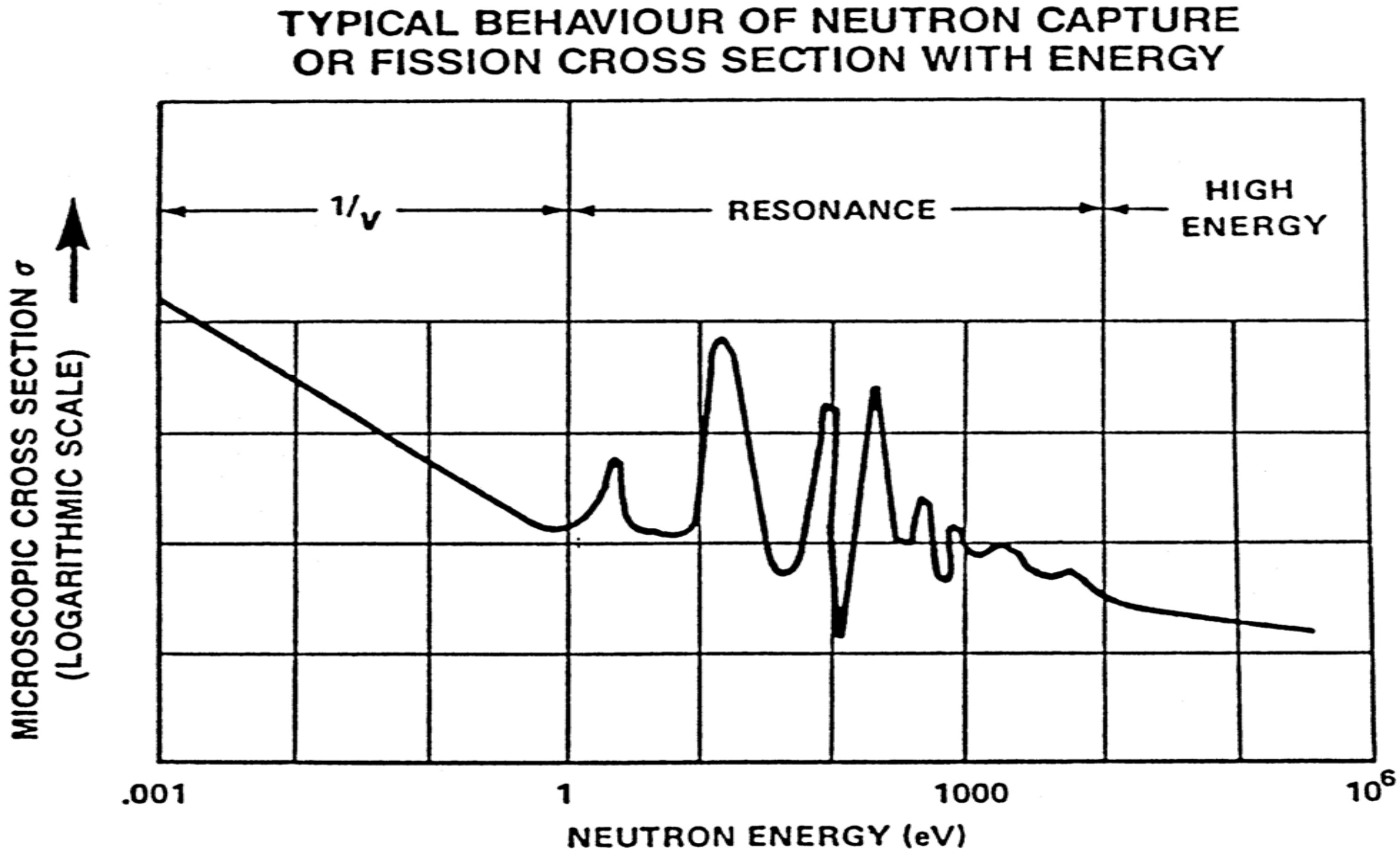


Basic CANDU Characteristics – Heavy Water

Heavy Water as Moderator

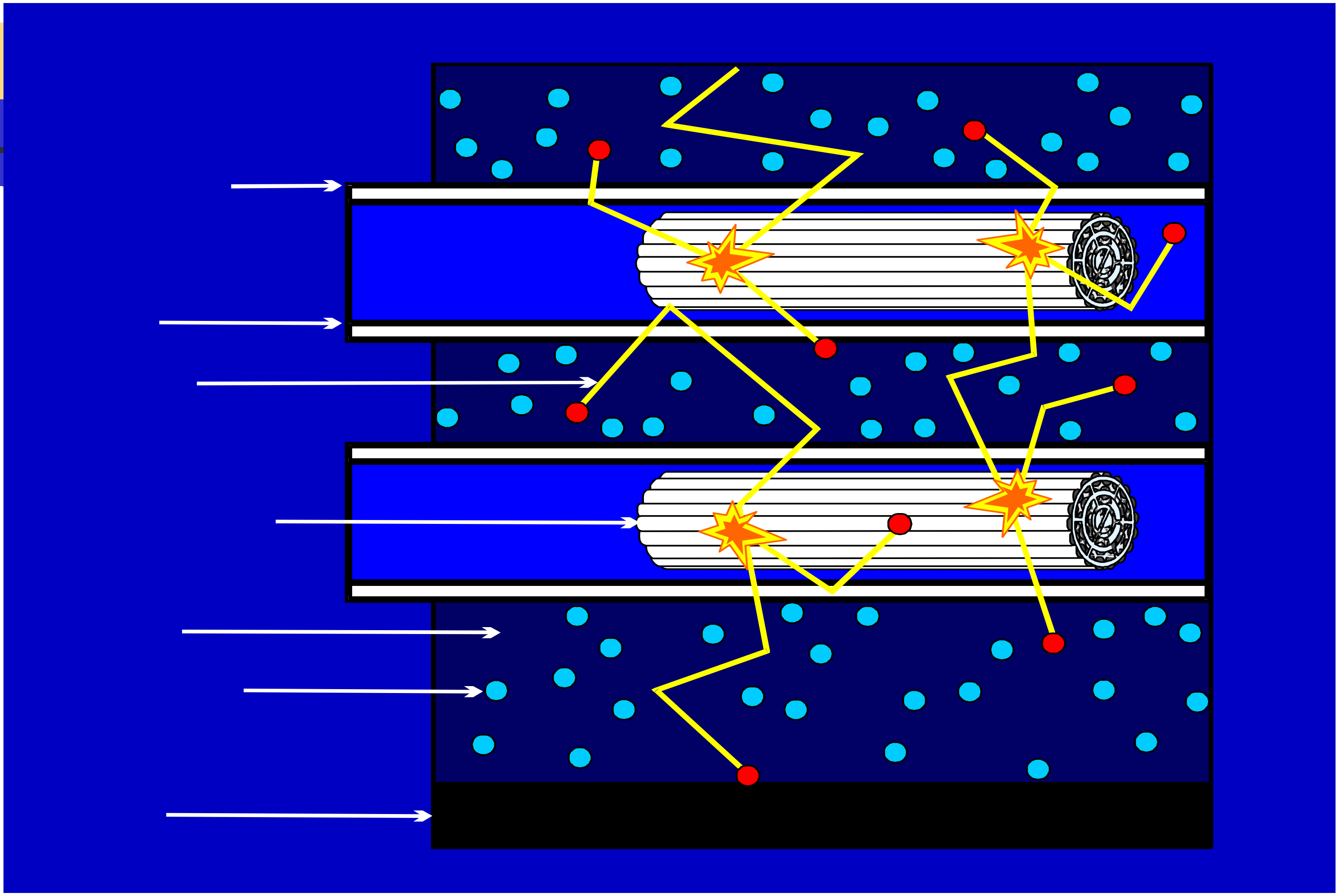
- However, probability for a neutron to induce fission is orders of magnitude higher at “thermal” energies (small fractions eV) than at 1-2 MeV [see Figures below].
- Therefore, a moderator is used to slow the fission neutrons down to thermal energies. At ambient 20^{o}C, most probable neutron energy = 0.025 eV (speed 2.2 km/s).

Capture or Fission Cross Section vs. Energy (Schematic View)



Why Lump the Fuel?

- The Resonance region presents absorption peaks between fast and thermal energies (see previous slide).
- Configuring the fuel in lumps (channels), each surrounded by a volume of moderator, encourages the scenario in which neutrons:
  - exit from fuel into moderator
  - are slowed down through (and below) resonance range away from fuel and resonance absorption
  - re-enter a fuel region as thermal neutrons to continue the chain reaction – see Figure.
- Thus, resonance escape increases dramatically when fuel is lumped. This was recognized early (Fermi's pile, first man-made nuclear reactor).



Fission Neutrons Slowed in Moderator Region

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Desirable Moderator Properties

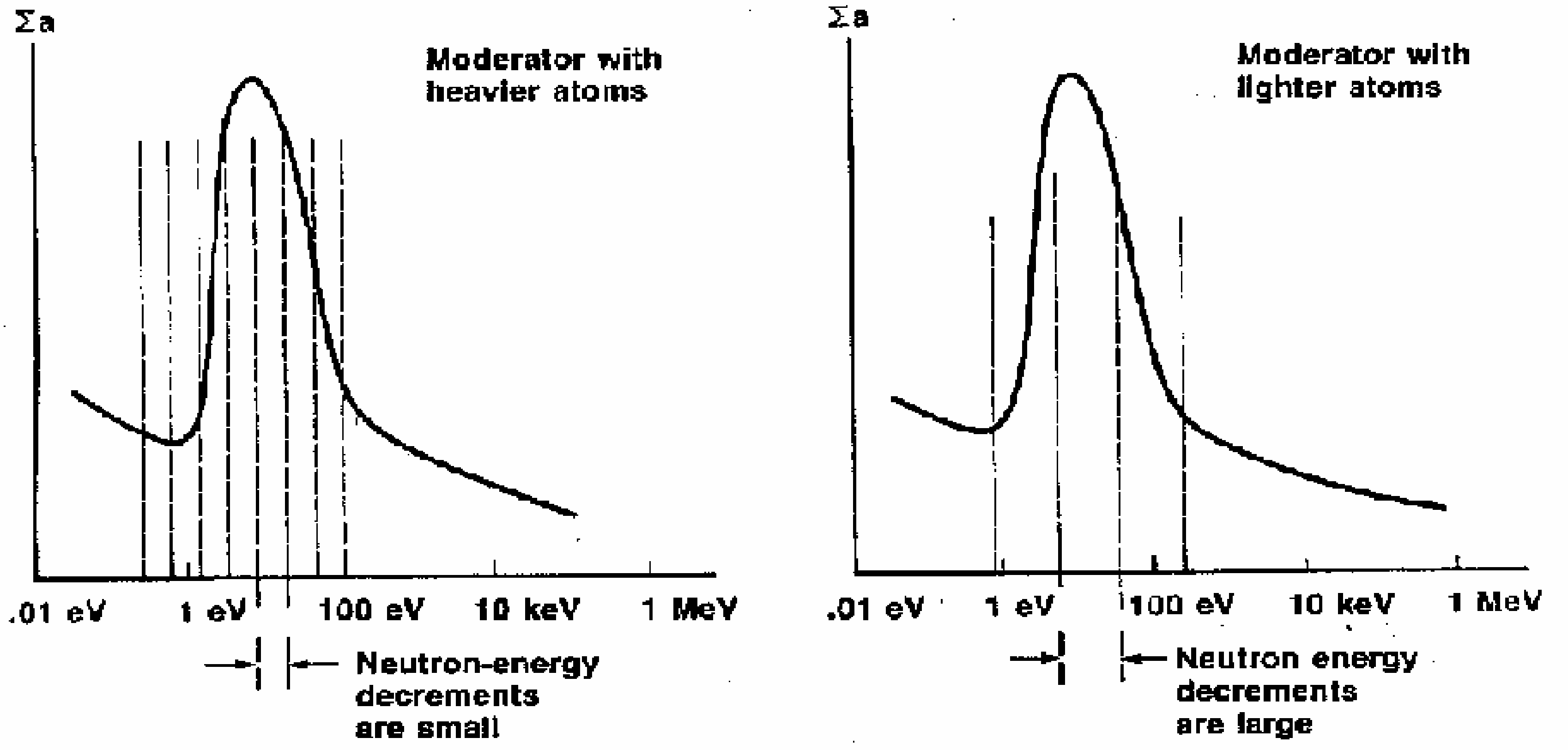
Heavy Water as Moderator

Most efficient moderator has light atoms.

Light atoms will slow neutrons down in fewer collisions.

Small number of collisions enhances resonance-escape probability; see Figure.

EFFECT OF MODERATOR ON NEUTRON ENERGY DURING SLOWING-DOWN



Resonance Escape More Probable when Energy Decrements are Large

Desirable Moderator Properties

- Therefore, 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.

Desirable Moderator Properties

Hydrogen (Light Water) as Moderator

- However, ^{1}H 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: ^{2}H or D) and take them out of circulation as agents of further fissions.

Desirable Moderator Properties

- Other light nuclides, good by virtue of mass:
  - D (deuterium – in the form of heavy water)
  - C (carbon, in the form of graphite)
  - Be (beryllium).
- These have a smaller absorption cross section for neutrons than H. The one with smallest absorption cross section is D.
- Heavy water is in fact moderator with best “neutron economy” – i.e., it leaves neutrons in circulation to induce more fissions.

Basic CANDU Characteristics

- 3 quantities important in determining the properties of a moderator:
- Σ_s, scattering cross section for neutrons. **Larger** is better: nuclide is efficient at colliding with neutrons.
- ξ, "lethargy decrement" = average energy lost by a neutron in collision with the nuclide. **Larger** is better: neutron is thermalized in fewer collisions.
- Σ_a, the absorption cross section for neutrons. **Smaller** is better: nuclide is poor at absorbing neutrons.

Basic CANDU Characteristics

Heavy Water as Moderator

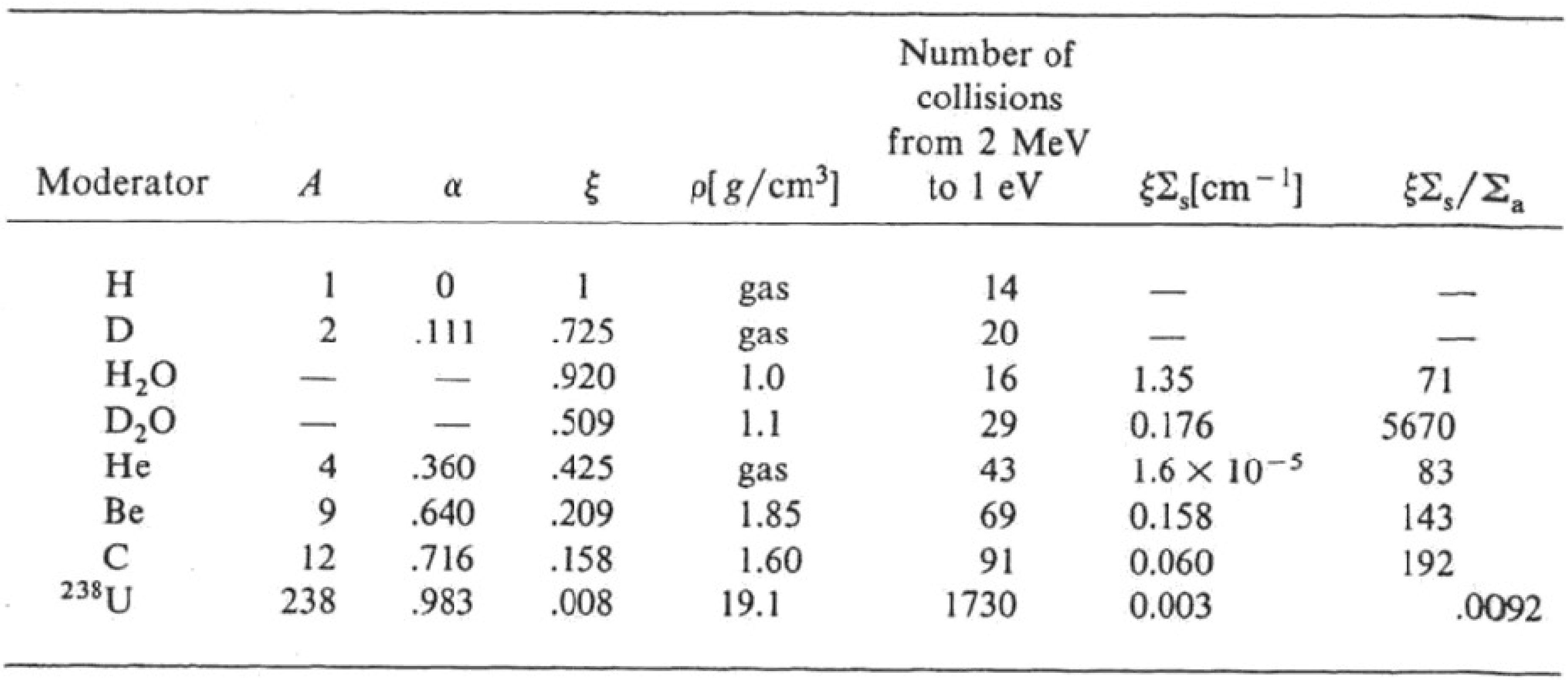
- The quantitative “figure of merit” for moderators is therefore the

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

- The following Table shows that heavy water has the highest moderating ratio, and is indeed the best moderator.

Basic CANDU Characteristics

Moderating Ratios (from Duderstadt)



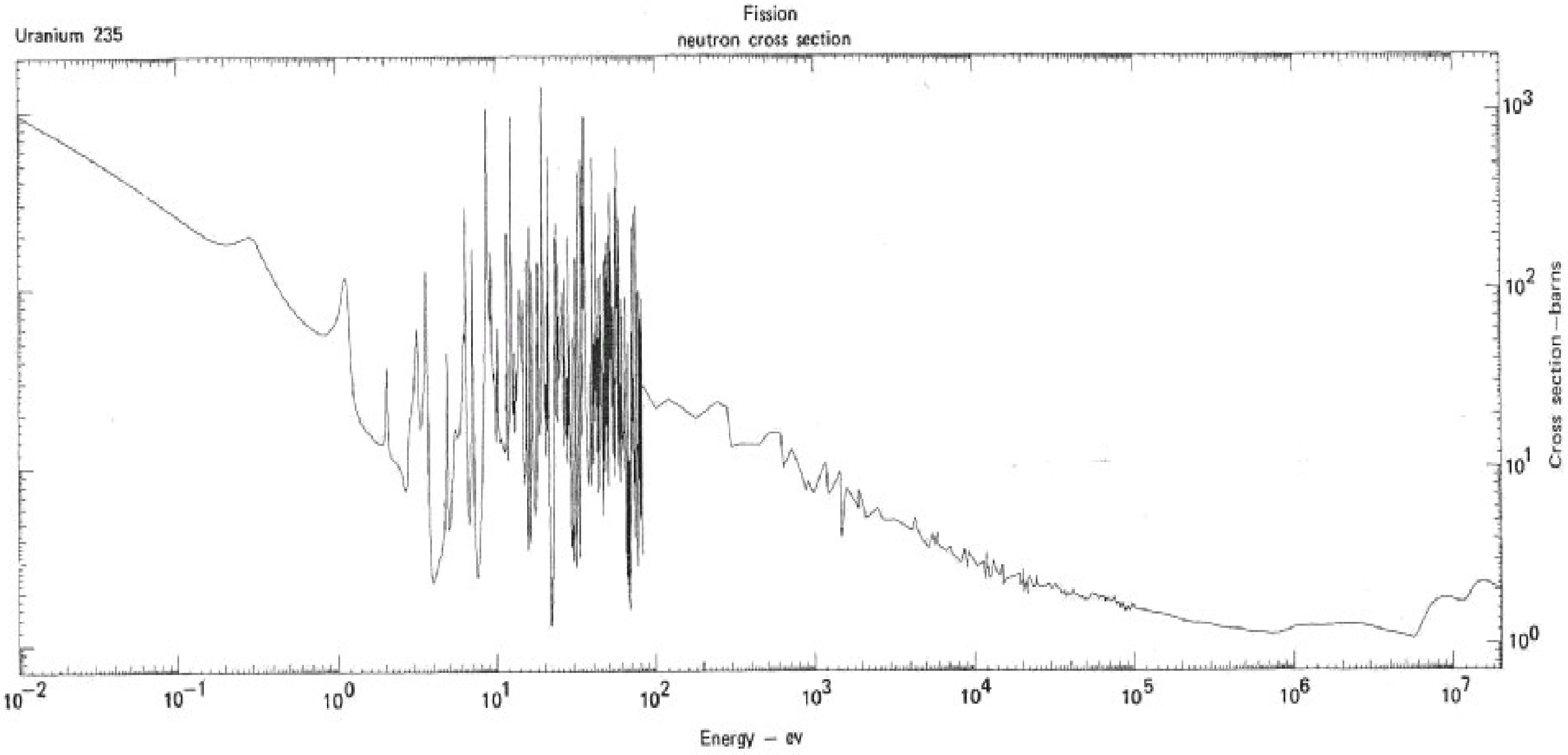
Moderator	A	α	ξ	$\rho[g/cm^3]$	Number of collisions from 2 MeV to 1 eV	$\xi\Sigma_s[cm^{-1}]$	$\xi\Sigma_s/\Sigma_a$
H	1	0	1	gas	14	—	—
D	2	.111	.725	gas	20	—	—
H_2O	—	—	.920	1.0	16	1.35	71
D_2O	—	—	.509	1.1	29	0.176	5670
He	4	.360	.425	gas	43	1.6×10^{-5}	83
Be	9	.640	.209	1.85	69	0.158	143
C	12	.716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

Basic CANDU Characteristics

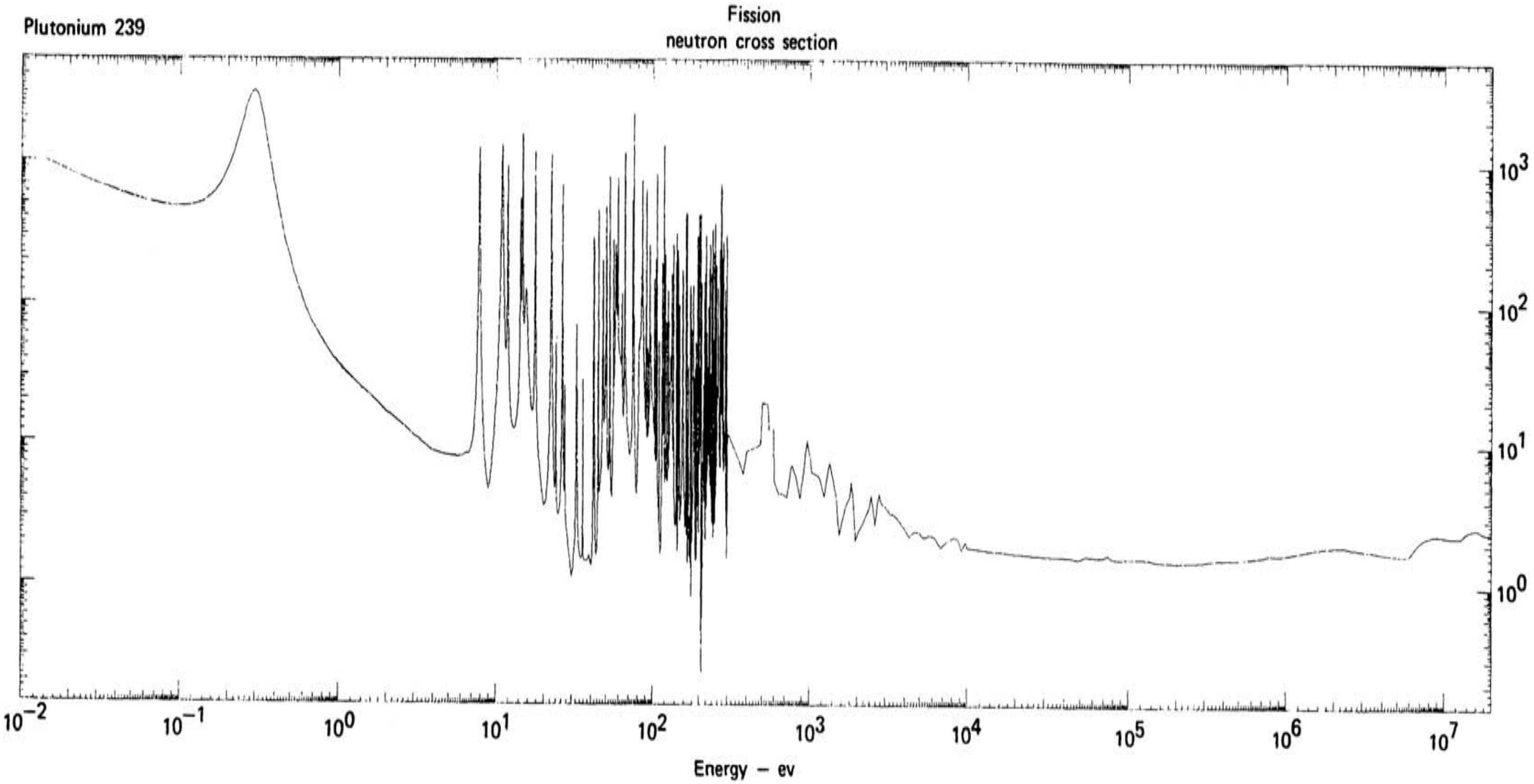
Heavy Water as Moderator

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

Fission Cross Section of U-235 (Duderstadt)



Fission Cross Section of Pu-239



Basic CANDU Characteristics

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.

Basic CANDU Characteristics

Natural Uranium as Fuel

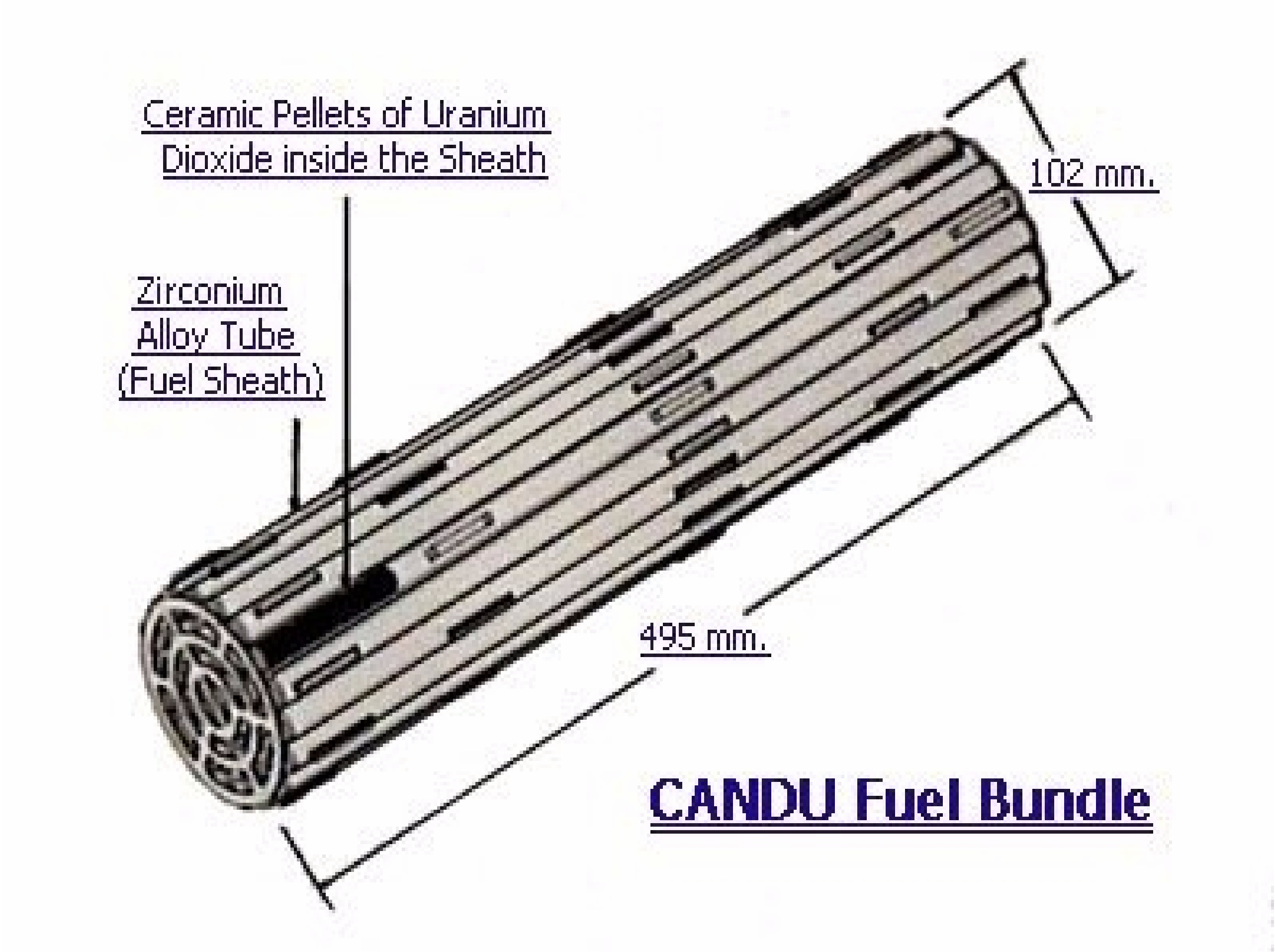
- Thus, natural uranium was chosen as the fuel for CANDU.
- Important for Canada: self-sufficient in its very large uranium resources, it did not have to develop the complex and costly enrichment capability or rely on external sources of enriched fuel.
- Remains important factor for other small countries not willing to depend on foreign sources for reactor fuel.

Basic CANDU Characteristics

Natural Uranium as Fuel

- CANDU fuel is uranium dioxide.
- Manufactured in form of elements of length ~ 48 cm.
- Each element consists of UO_2 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.

CANDU 37-Element Bundle



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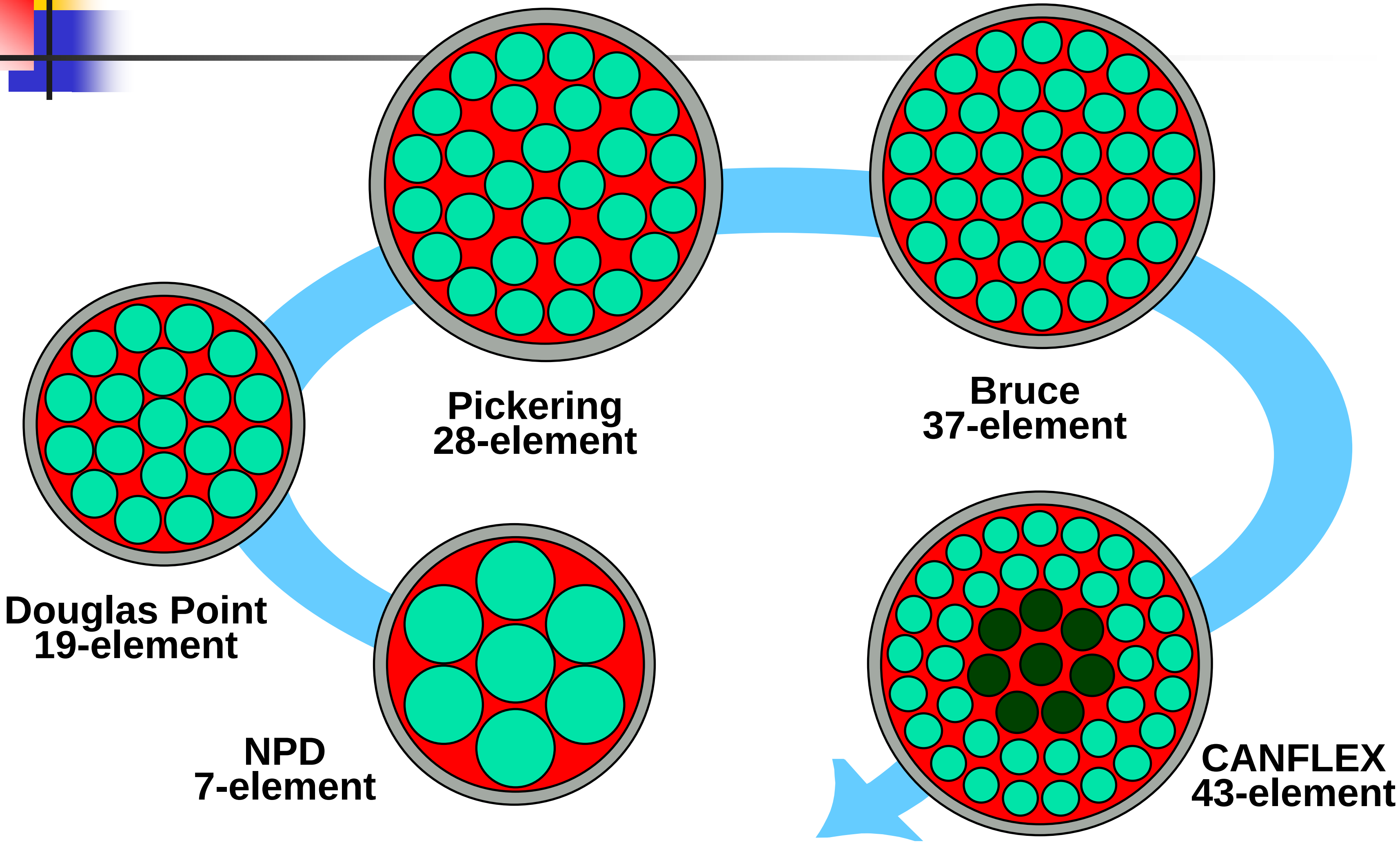
Evolution of CANDU Bundle Designs



Pickering
28-element

Bruce
37-element

Douglas Point
19-element

NPD
7-element

CANFLEX
43-element

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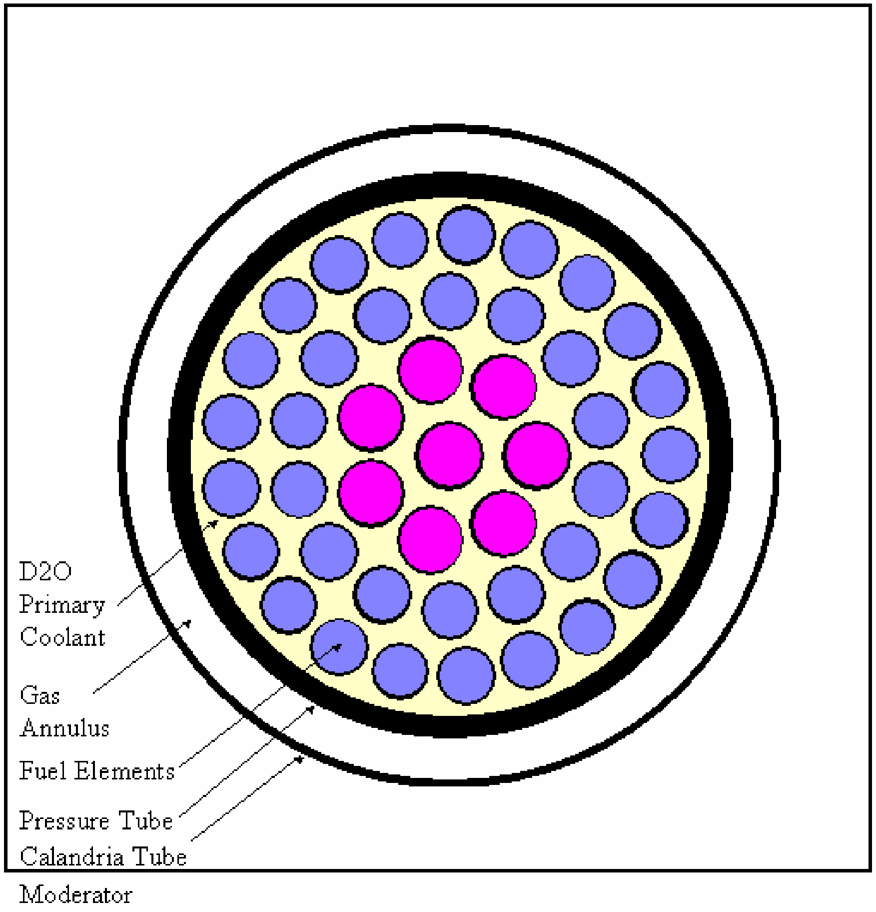
CANFLEX Fuel Bundle



CANDU Fuel Characteristics

CANDU fuel has several advantages:

- The CANDU fuel bundle is short and easy to handle.
- It has few (7) different components.
- CANDU fuel is much cheaper than light-water-reactor fuel
- CANDU fuel-manufacturing capability can readily be developed by even small countries which purchase CANDU reactors.

CANDU Fuel Flexibility

- Note: 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 - can burn enriched uranium, mixed-oxide (U/Pu) fuels, or even irradiated fuel from light-water reactors.
- Latest CANDU design, the Advanced CANDU Reactor (ACR), will use slightly-enriched uranium.

CANDU: Pressure-Tube Reactor

Pressure-Tube Design

- First CANDU prototype was the Nuclear Power Demonstration (NPD) reactor - critical 1962 June.
- First NPD design was a pressure-vessel design.
- Although NPD was 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 (mean free path in D_2O much longer than in H_2O, and number of collisions to thermalize a neutron quite a bit higher).

CANDU: Pressure-Tube Reactor

Pressure-Tube Design

- Canada did not 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.

CANDU: Pressure-Tube Reactor

Pressure-Tube Design

- As a result of these misgivings, the pressure-vessel design for NPD was scrapped (with penalty to tear up contract for vessel).
- NPD was changed to a pressure-tube design - the tubes would be the pressure boundary for the hot coolant, the reactor vessel (renamed a **calandria)**.
- would not be at pressure, and would be much simpler to manufacture.
- In fact, it could be manufactured domestically, another important plus for Canada.

CANDU: Pressure-Tube Reactor

Pressure-Tube Design

- NPD designers, and those 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.

CANDU: Pressure-Tube Reactor

Pressure-Tube Design

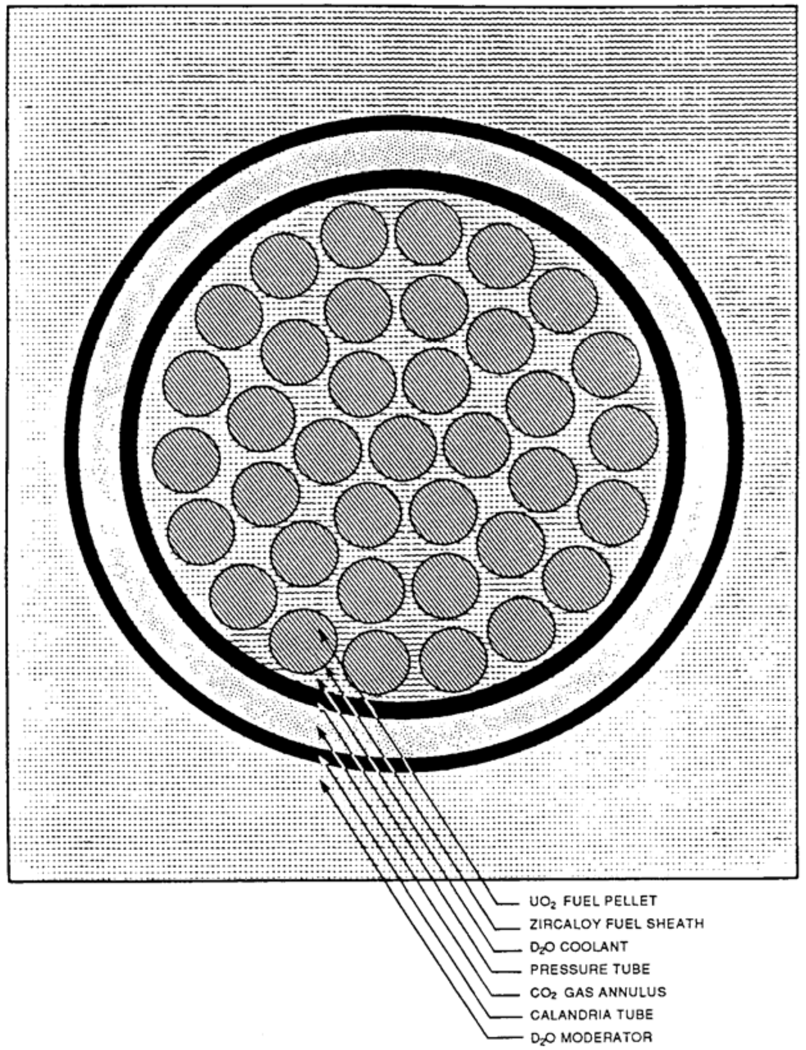
- Very important to note that what made the pressure-tube concept was viable is zirconium.
- The large mass of metal in the pressure-tube design could absorb too many neutrons - definitely the case with steel pressure tubes: the fission chain reaction could not be made self-sustaining.
- Zirconium, “magic” nuclide with a very low neutron-absorption cross section, came on the scene in time. This as the result of materials research in Chalk River for the US nuclear program.

CANDU: Pressure-Tube Reactor

Pressure-Tube Design

- Note: while the pressure tubes are the pressure boundary, they would tend to conduct heat from the fuel out into the moderator.
- 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 insulating gas (CO_2), allowing it to operate at relatively low temperature (~ 70 ^oC).

Basic Lattice Cell for 37-El Fuel



(not to scale – square dimension should be almost twice as large)

CANDU Coolant

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.

CANDU Coolant

Experimentation with other coolants:

- Gentilly-1, near Trois-Rivières in Québec, a CANDU vertical prototype, used boiling light water as coolant. It suffered from control problems, particularly on account of the boiling of the coolant. This, 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 with organic coolant. Although this had a higher operating temperature than D_2O, there was a flammability concern. It was never seriously considered for the commercial reactors.

CANDU Coolant

- 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

CANDU: Refuelling at Power

On-Power Refuelling

- With pressure tubes, on-power refuelling becomes possible - fuel channels can be “opened” individually and at full power to replace some of the fuel. On-power refuelling was therefore adopted for CANDU.
- On-power refuelling also means that “old” fuel is replaced by fresh fuel nearly continuously. Thus, very little excess reactivity is required. Batch refuelling would require a large excess reactivity at the start of each cycle (as in LWR).

CANDU: Refuelling at Power

On-Power Refuelling

- The short CANDU fuel bundle facilitates on-power refuelling - can then replace part of the fuel in a channel at each refuelling operation (e.g., 8-bundle-shift refuelling scheme in CANDU 6).
- Also, horizontal channels simplify refuelling - the bundles need not be "tied" together. In Gentilly-1, with vertical channels, a central tie-rod was needed to hold the entire fuel-string together.
- Horizontal channels allow axial symmetry (no difference in coolant density between the 2 ends).

Safety Advantages of CANDU Design

- Unpressurized calandria - no risk of catastrophic vessel “break-up”
- Reactivity devices in unpressurized environment – no “rod ejection”
- Low excess reactivity – potential for reactivity addition small
- Very long prompt-neutron lifetime
- Redundant, independent safety systems

Safety Advantages of CANDU Design

- Separation between control and safety systems
- Large volume of cool moderator "water" – excellent heat sink in hypothetical severe accidents
- Low fissile content in fuel – no criticality concern outside the reactor