CANDU Fuel-Management Course

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Basic Characteristics of the CANDU Lattice

- **This chapter discusses the basic characteristics of the CANDU lattice. The discussion is largely general but, where necessary, particular reference is made to the CANDU 6 reactor.**

1.1 The CANDU Lattice Cell

- **Figure 1.1: schematic face view of CANDU 6.**
- **CANDU design is modular, with fuel channels set on a square lattice**
- **lattice pitch = 28.575 cm.**

1.1 The CANDU Lattice Cell

- Figure 1.2: face view of basic lattice cell, with:
  - fuel
  - coolant
  - pressure tube
  - gas gap
  - calandria tube
  - moderator
- dimensions shown: 1 lattice pitch by 1 lattice pitch (28.575 cm x 28.575 cm)
- In 3rd direction (perpendicular to paper) dimension of cell is one fuel-bundle length, 49.53 cm.

1.1 The CANDU Lattice Cell

In CANDU 6:

- **12 fuel bundles in each fuel channel**
- **380 fuel channels**
- **total number of fuel bundles = 12 * 380 = 4560**

Total thermal power = 2061 MW

Total fission power = 2156 MW

1.1 The CANDU Lattice Cell

- The next few sections describe the various components of the lattice cell.

1.2 The Moderator

- The CANDU design has opted for heavy water as the moderator: advantage of neutron economy provided by deuterium.
- Allows use of natural-uranium fuel
- Precludes the need for expensive fuel-enrichment technology.

1.2 The Moderator

- The first desirable property for moderator is ability to thermalize neutrons in as few collisions as possible.
- When number of collisions required for thermalization is smaller, average loss of neutron energy per collision is greater, and
- probability is enhanced that neutron will miss the resonance-absorption energy range during moderation (see Figure 1.3).

1.2 The Moderator

- **Figure 1.4 shows the average number of collisions needed for various moderators to thermalize a fission neutron.**

1.2 The Moderator

- **It is also important that moderator have small probability of capturing neutrons (i.e., a small neutron absorption cross section)**
- **otherwise, negative impact on neutron economy**
- **In this respect hydrogen is not best moderator: has relatively high neutron absorption cross section.**
- **Heavy hydrogen, or deuterium, on the other hand, has a very low absorption cross section.**

1.2 The Moderator

- A good index of performance for moderators is the moderating ratio = ratio of slowing-down power of the material to neutron absorption cross section:

$$Moderating\ ratio = \frac{Slowing-down\ power}{Absorption\ cross\ section} = \frac{\xi\Sigma_s}{\Sigma_a}$$

where ξ is the mean logarithmic energy decrement per collision.

1.2 The Moderator

- **The moderating ratio of various moderators is shown in Figure 1.5.**
- **It is clear that by far the best moderator for neutron economy is heavy water (D_2O)**
- **reason chosen as the moderator for CANDU.**

1.2 The Moderator

- Significant probability of neutron capture by any light water present in the heavy-water moderator
- crucial that moderator have very high isotopic purity
- Reactor-grade moderator must be at least 99.75 % D_2O by weight (preferably 99.8 % or even 99.9 %)
- Even a reduction of 0.1% in the isotopic purity has a significant effect on neutron economy of the reactor and on achievable fuel burnup.

1.3 The Fuel

- Natural uranium is used in all currently operating CANDU reactors.
- Very convenient for countries which wish not to have to rely on expensive, and most probably foreign, enrichment technology.
- However, CANDU design is very flexible and allows use of advanced fuel cycles: slightly enriched uranium (SEU), recovered uranium (RU), mixed-oxide fuel (MOX), thorium fuels (Th), and others (DUPIC, actinide burning).
- These can be introduced into CANDU with few or no hardware changes, when option becomes attractive.

1.3 The Fuel

- **CANDU fuel is of very simple design.**
- **It 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.**

1.3 The Fuel

- **The CANDU fuel bundle contains only 7 different components and is short, easy to handle, and economical.**
- **Short bundle means fuel can be added to core in small increments: small reactivity perturbation.**
- **Also means can be handled more easily by fuelling machine.**
- **CANDU fuel is relatively simple to manufacture, and fabrication can easily be localized.**

1.3 The Fuel

- **Various fuel-bundle designs illustrated in Figure 1.6.**

- **Only two bundle types are used in present-generation CANDUs:**

  - **the 28-element bundle (in Pickering), and**

  - **the 37-element bundle (in Bruce, Darlington and the CANDU 6).**

1.3 The Fuel

- **The 28-element bundle has a smaller ratio of sheath mass to fuel mass than the 37-element bundle**
- **Gives the 28-element bundle a reactivity advantage.**
- **On the other hand, the 37-element bundle features better thermalhydraulic properties due to greater fuel subdivision: larger number of pins of smaller diameter provide better heat-removal capability.**

1.3 The Fuel

- Therefore 37-element bundle can operate at higher power than 28-element bundle.

- Higher power then tends to further reduce reactivity of 37-element bundle

- But allows higher total reactor power for the same mass of fuel, an important economic advantage.

1.3 The Fuel

- **The CANFLEX fuel design (Figure 1.7) has been under development for last few years**
- **This is the fuel bundle for the future.**
- **In 1998, a demonstration irradiation of 24 CANFLEX fuel bundles has been initiated at the Pt. Lepreau Nuclear Generating Station in New Brunswick, Canada. It is on-going.**

1.3 The Fuel

- **The CANFLEX bundle has 43 elements**
- **Outer two rings of elements are of smaller diameter than the inner 7 elements.**
- **The CANFLEX bundle features improved thermalhydraulic properties, and 20% lower maximum element-power ratings than 37-element fuel, for the same bundle power.**

1.4 The Coolant

- In all commercial CANDU reactors, heavy water is used as the coolant in the primary heat-transport system, to further improve neutron economy.
- However, prototype CANDUs have been built using boiling light water or an organic liquid as coolant (Gentilly-1 and WR-1 respectively). The organic coolant, in particular, allows higher temperatures and greater efficiency of conversion of heat to electricity.
- Up to now, heavy water has won.

1.5 The Pressure-Tube Concept

- **A major characteristic was selected early in the development of the CANDU reactor: the pressure-tube design.**

- **It is clear that if a liquid is used to remove the large quantity of heat generated inside the reactor, the liquid must be kept at high pressure, otherwise it would boil. The heat-transport-system pressure in CANDU is ~ 100 atmospheres.**

1.5 The Pressure-Tube Concept

- To contain the pressure, the choice is between a pressure-vessel design and a pressure-tube design.
- In the former (e.g. the PWR) the vessel contains all the fuel and the liquid, which is at once both moderator and coolant.
- In the pressure-tube design, moderator and coolant are separate and the coolant flows (at high pressure) through the pressure tubes,

1.5 The Pressure-Tube Concept

- Pressure tubes contain the fuel and in fact comprise the fuel channels.
- The pressure tubes are made of an alloy of zirconium and 2.5% niobium.
- The pressure-tube concept was originally chosen for CANDU because the manufacture of a pressure vessel of the size required for a heavy-water reactor (HWR) would at the time have challenged the capability of Canadian industry.

1.5 The Pressure-Tube Concept

- **However, the pressure-tube concept has many other advantages in relation to the design and safety of the reactor:**
  - **The rupture of one pressure tube is not as catastrophic as the rupture of an entire pressure vessel. Also, in most cases a pressure tube will leak and give ample warning before rupturing.**
  - **Because coolant and moderator are physically separated, the moderator can be kept relatively cool.**

1.5 The Pressure-Tube Concept

- In CANDU the moderator is isolated from the hot pressure tube by a concentric calandria tube.
- A gas annulus separates the pressure and calandria tubes (see Figure 1.2).
- Thus the moderator can be kept at about 70 °C and at near atmospheric pressure.
- Many safety benefits ensue as a consequence.
  - The moderator is a benign, low-pressure and low-temperature environment for interstitial reactivity devices (control rods, etc.)
  - rod-ejection accidents are therefore not a concern.
  - moderator is a potential ultimate heat sink in case of accident.
  - In addition, a cool moderator further improves neutron economy.

1.5 The Pressure-Tube Concept

- **The pressure-tube concept allows the replacement of fuel in the reactor on power, precluding the need for periodic shutdowns for refuelling. Also, on-power refuelling means that the excess reactivity in the lattice is never very high, a safety advantage.**

- **These basic characteristics of CANDU are summarized in Figure 1.8.**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- Fuel burnup is the amount of energy that is obtained per unit mass of uranium in the fuel.
- Fuel burnup can be measured in units of:
  - MW.h/kg(U), or
  - MW.d/Mg(U)
- These units are related by the equation:
- 1 MW.h/kg(U) = 1*1000/24 MW.d/Mg(U)
- = 41.67 MW.d/Mg(U)

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **In CANDU we also speak of fuel irradiation.**
- **In the context of the Westcott convention for fluxes and cross sections (see the section below on the lattice code), the irradiation (ω) is the product of Westcott fuel flux by time:**

$$\omega = \hat{\phi} t$$

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **Burnup and irradiation are closely linked.**
- **Burnup is a monotonic, nearly linear function of irradiation, as shown in Figure 1.9.**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **Note: for a given type of fuel and reactor, fuel burnup is essentially the inverse of:**
- **fuel consumption, i.e., amount of fuel used to produce a given quantity of energy (electricity)**
- **Fuel consuption is measured for example in units of Mg(U)/GW(e).a.**
- **For a given fissile content, a high burnup signifies low fuel consumption, and therefore a small refuelling cost component.**
- **High fuel burnup is good, low fuel consumption is good.**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **However, note:**
- **When comparing different fuels or reactors, a higher fuel burnup does not necessarily mean a lower uranium utilization.**
- **For instance, fuel burnup attained in PWRs is much higher than that attained in CANDU**
- **This is the result of fuel enrichment, not of higher fuel efficiency.**
- **Even though PWR fuel burnup may be 3 to 6 times the value in CANDU, uranium utilization is lower by ~ 25-28% in CANDU, due to neutron economy.**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **A typical fuel burnup attained in the CANDU 6 is 7500 MW.d/Mg(U), or**
- **175-180 MW.h/kg(U).**

- **However, the burnup attained depends on the operational parameters of the core.**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **The fuel burnup is of course influenced by any quantity which affects the core reactivity.**
- **Any neutron loss or parasitic absorption which reduces the lattice reactivity will have a negative effect on the attainable fuel burnup.**
- **The relationship between reduction in core reactivity and loss of burnup is found to be:**
- **1 milli-k reduction in core reactivity**
  - **= 2.88 MW.h/kg(U) loss in burnup**
  - **= 120 MW.d/Mg(U) loss in burnup**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **Examples of factors which affect the reactivity, and therefore the attainable fuel burnup, are as follows:**
- **higher moderator purity increases burnup**
  - **(moderator-purity coefficient = ~ 34 milli-k/atom % purity)**
- **higher coolant purity also increases burnup (but much less than moderator purity)**
  - **coolant-purity coefficient = ~ 3 milli-k/atom % purity**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **operating the reactor with moderator poison decreases burnup**
  - **boron reactivity coefficient = ~ 8 milli-k/ppm(B)**
- **a reflector decreases leakage and increases burnup**
- **thicker pressure or calandria tubes decrease burnup**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **a higher ratio of fuel-sheath mass to fuel mass in a bundle (everything else being equal) decreases burnup**
- **a lower moderator temperature increases burnup**
- **flattening the power distribution increases leakage and decreases burnup.**

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- Of course, the lower fuelling cost associated with higher burnup must be weighed against other, possibly opposite, cost components in the total unit energy cost.

- For instance, a thicker reflector will increase burnup, but beyond a certain point, the cost of the additional reflector may outweigh the benefit in burnup.

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- Similarly, the 37-element bundle is preferred over the 28-element bundle, despite its lower burnup
- because can be operated at a higher power, and
- it therefore allows a lower reactor capital cost per installed kW.
- (A bundle with greater fuel subdivision, i.e., a greater number of thin pencils rather than a smaller number of thick pencils, can produce higher power for same pencil rating, measured as kW per m of pencil).

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- Using the 37-element fuel bundle,
- licensed maximum bundle power in CANDU 6 =
- 935 kW
- This corresponds to a fuel rating in the hottest (outermost) element of ~ 60 kW/m.

- By comparison, licensed maximum bundle power in Pickering (using the 28-element fuel bundle) =
- about 750 kW.

1.6 Fuel Burnup and Irradiation and Effect of Operating Conditions

- **The CANDU 6 has adjuster rods (see next chapter) with a reactivity worth of approximately 15 milli-k.**
- **A CANDU reactor which is designed without adjusters has a higher excess reactivity and therefore provides higher burnup.**
- **On the other hand, a design with adjusters has the advantage of providing xenon-override capability and the ability to compensate, for a time, for fuelling-machine unavailability.**