5. General Discussion on CANDU Fuel Management

5.1 General Description

- **Refuelling operations in CANDU reactors are carried out with the reactor at power.**
- **This feature makes the in-core fuel management substantially different from fuel management for reactors which must be refuelled while shut down.**

5.1 General Description

- **The CANDU on-power refuelling capability also means that long-term reactivity control can be achieved by an appropriate rate of fuel replacement.**
- **Therefore, excess core-reactivity requirements are very small:**
- **Current CANDU reactors use natural-uranium fuel, and the lattice has much smaller excess reactivity than enriched-fuel lattices**
- **The CANDU fuel bundle (~50-cm long and containing ~19 kg of uranium) allows adding fuel in small increments (cont'd)**

5.1 General Description

- For continuous or short-term reactivity control, a capability of only a few milli-k is necessary; this is provided in the light-water zone-control compartments
- Other than in the initial core, there are no large batches of fresh fuel,
- and therefore no need for burnable poison or large amounts of moderator poison to compensate for high excess reactivity;
- in the initial core, when all fuel is fresh, only ~2-3 ppm of moderator boron are required

5.1 General Description

- **These factors lead to excellent neutron economy and low fuelling costs.**
- **Also, since power production is not interrupted for refuelling, it is not necessary to tailor the refuelling schedule to the utility’s system load requirements.**

5.1 General Description

- To refuel a channel, a pair of fuelling machines latch onto the ends of the channel.
- A number of fresh fuel bundles are inserted into the channel by the machine at one end,
- and an equal number of irradiated fuel bundles are discharged into the machine at the other end of the channel.

- [Note: the fuelling machines are very high-tech machines, they must “break into” the heat-transport system at full pressure, with no (or small) leaks]

5.1 General Description

- **For symmetry, the refuelling direction is opposite for neighbour channels.**
- **In the CANDU-6 reactor, the refuelling direction is the same as that of coolant flow in the channel.**
- **In some other CANDU reactors (e.g., Bruce) the refuelling direction was designed to be against coolant flow.**
- **Refuelling with flow presents advantages in some kinds of hypothetical loss-of-coolant accidents.**

5.1 General Description

- Figure 5.1 illustrates the 8-bundle-shift scheme,
- where the eight bundles near the outlet end of the channel are discharged,
- and the four bundles previously nearest the inlet end are shifted nearest to the outlet end.
- Thus, the four low-power bundles are in-core for two cycles, and
- the high-power bundles are in-core for only one cycle.

5.1 General Description

- **Several refuelling operations are normally carried out daily,**
- **so that refuelling is almost continuous.**

- **CANDU reactors offer extreme flexibility in refuelling schemes:**
- **The refuelling rate (or frequency) can be different in different regions of the core,**
- **and in the limit can in principle vary from channel to channel. (cont’d)**

5.1 General Description

- **By using different refuelling rates in different regions, the long-term radial power distribution can be shaped and controlled.**
- **The axial refuelling scheme is not fixed; it can be changed at will. It can be different for different channels.**
- **It need not even be the same always for a given channel: it can vary at every visit of the channel. Eight-, 4-, or 10-bundle-shift refuelling schemes have been used.**

5.1 General Description

- A channel can be refuelled without delay if failed fuel exists or is suspected.
- In such a case, when there is concern that replacing all fuel bundles in the channel would drive its power too high, some depleted-uranium bundles can be mixed with standard bundles to limit the power.
- This is made possible by the subdivision of the fuel in a CANDU channel into short bundles.

5.2 Overall Objectives

- The primary objective of fuel management is to determine fuel-loading and fuel-replacement strategies
- to operate the reactor in a safe and reliable fashion while keeping the total unit energy cost low.

5.2 Overall Objectives

- **Within this context, the specific objectives of CANDU fuel management are as follows:**
- **The reactor must be kept critical and at full power. On-power fuelling is the primary means of providing reactivity. If the fuelling rate is inadequate, the reactor eventually has to be derated.**
- **The core power distribution must be controlled to satisfy safety and operational limits on fuel power.**

5.2 Overall Objectives

- **The fuel burnup is to be maximized within the operational constraints, to minimize the fuelling cost**
- **Fuel defects are to be avoided. This minimizes replacement fuel costs and radiological occupational hazards.**
- **The fuel-handling capability must be optimized. This minimizes capital, operating and maintenance costs.**

5.3 Periods During Operating Life of Reactor

- **From the point of view of fuel management, the operating life of a CANDU reactor can be separated into three periods.**
- **The first two are short, transitional periods,**
- **while the third, the "equilibrium core", represents about 95% of the lifetime of the reactor.**

From First Criticality to Onset of Refuelling

- The first period is from first criticality until onset of refuelling.
- It is of limited duration, about 100 to 150 full-power days (FPD) long.
- The reactor is initially loaded with natural-uranium fuel everywhere,
- except for a small number of depleted-fuel bundles at specific core locations, designed to help flatten the power distribution.

From First Criticality to Onset of Refuelling

- Consequently, at this time, for the only time in the life of the reactor, there is a fair amount of excess reactivity.
- This is compensated by adding boron poison to the moderator.

From First Criticality to Onset of Refuelling

- **At about 40-50 FPD of reactor operation, the core reaches its "plutonium peak"**
- **At this time the core reactivity is highest,**
- **due to the production of plutonium by neutron capture in ^{238}U, and the as-yet relatively small ^{235}U depletion and fission-product concentration.**
- **Following the plutonium peak, the plutonium production can no longer compensate for the buildup of fission products, and the excess core reactivity decreases.**

Onset of Refuelling and Transition to Equilibrium Core

- **When the excess core reactivity has fallen to a small value, refuelling begins in order to maintain the reactor critical.**
- **During the transitional period which follows, the reactor gradually approaches the final or "equilibrium" state.**
- **The average refuelling rate and in-core burnup are transitional but start to converge towards steady values.**

Equilibrium Core

- Approximately 400 to 500 FPD after initial start-up, a CANDU reactor has reached a state which may be termed an “equilibrium core”.
- The overall refuelling rate, the in-core average burnup, and the burnup of the discharged fuel
- have become essentially steady with time.

Equilibrium Core

- The global flux and power distributions can be considered as having attained an equilibrium,
- "time-average" shape
- The refuelling of individual channels leads to local "refuelling ripples" about the time-average shape.
- These ripples are due to the various instantaneous values of fuel burnup in the different channels,
- which are the result at any given instant of the specific sequence of channels refuelled.

Equilibrium Core

- **With some refuelling operations taking place essentially every day,**
- **the equilibrium core contains, at all times, fuel with a range of burnups, from 0 to some average exit-burnup value.**
- **The exit-burnup value is the long-term burnup of fuel at discharge from the reactor.**
- **The average in-core burnup at any time is approximately one half of the exit burnup.**

5.4 Infinite-Lattice Multiplication Constant

- **The infinite-lattice multiplication constant k_{inf} is a measure of the multiplicative properties of the lattice,**
- **in the absence of leakage from the lattice cell.**
- **The k_{inf} is provided by a cell code, such as POWDERPUFS-V, and applies to the “ideal” situation of an infinite array of identical cells.**

5.4 Infinite-Lattice Multiplication Constant

- Fig. 5.2 shows the k_{inf} as a function of irradiation for the standard CANDU 6 lattice fuelled with natural uranium.
- The figure shows that the lattice is ~ 80 milli-k supercritical for fresh fuel (i.e., at zero irradiation).

- Important note: the figure shows k_{inf}, the reactivity for the "infinite", bare lattice. An estimate of the k_{eff} for a finite reactor can be obtained by subtracting about 50 milli-k (30 milli-k for leakage and 20 miili-k for in-core devices - zone controllers and adjusters)

5.4 Infinite-Lattice Multiplication Constant

- **The reactivity increases at first with increasing irradiation, reaching a maximum at approximately 0.4-0.5 n/kb, a phenomenon due to the production of plutonium from neutron absorption in ^{238}U.**
- **This reactivity maximum is consequently known as the plutonium peak.**

5.4 Infinite-Lattice Multiplication Constant

- Beyond the plutonium peak, the reactivity starts to decrease with increasing irradiation.
- This is due to the continuing depletion of ^{235}U and the increasing fission-product load.
- From Fig. 5.2, k_{inf} reaches a value of 1.050 (which means an approximately critical reactor) at an irradiation of about 0.9 n/kb.

5.4 Infinite-Lattice Multiplication Constant

- **This means the reactor is critical when the *average in-core* irradiation is about 0.9 n/kb.**
- **About twice this value, i.e., ~1.8 n/kb, marks a natural exit irradiation, the point at which the fuel can be targeted for removal from the core,**
- **since at higher irradiations the average lattice becomes increasingly subcritical, i.e., an increasing net absorber of neutrons.**

5.4 Infinite-Lattice Multiplication Constant

- **Thus, channels containing fuel approaching or exceeding an irradiation of ~1.7-1.8 n/kb become good candidates for refuelling. (This is a very general statement, which is made more specific in a later section.)**
- **The corresponding exit burnup is in the range 7,300-7,500 MWd/Mg(U) [175-180 MW.h/kg(U)] - however, note that this can vary with lattice conditions, especially the moderator purity.**

5.4 Infinite-Lattice Multiplication Constant

- **It is instructive to examine also the infinite-lattice multiplication constant for the depleted-uranium lattice.**
- **This is shown in Fig. 5.3 for depleted uranium with an initial fissile content of 0.52 atom % (as opposed to 0.72 atom % for natural uranium).**
- **Note that the plutonium peak is even more pronounced for depleted uranium.**
- **This is easily explained by the fact that the role of ^{238}U conversion to plutonium is relatively greater when the smaller ^{235}U content.**

5.4 Infinite-Lattice Multiplication Constant

- **Note also, however, that the depleted-uranium lattice is subcritical at all irradiations,**
- **i.e. it is always a neutron absorber.**
- **This explains the use of depleted fuel to reduce excess reactivity, and also flatten the flux distribution, in the initial core.**
- **Depleted fuel is also occasionally used to reduce the power ripple on refuelling.**