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.