7. *Ongoing Reactor Operation with Channel Refuellings*

- After the initial period following first reactor startup, on-power refuelling is the primary means of maintaining a CANDU reactor critical.
- Thus, a number of channels are refuelled every day, on the average.
- Refuelling is not necessarily done every calendar day; some stations prefer to concentrate all refuelling operations to 2 or 3 days within each week.

7. Ongoing Reactor Operation with Channel Refuellings

- **Replacing irradiated fuel with fresh fuel has immediate consequences on the local power distribution,**
- **and on the subsequent period of operation of the reactor.**
- **These must be well understood and are discussed in the following subsections.**

7.1 The Channel-Power Cycle

- **The “refuelling ripple” is the consequence of the daily refuelling of channels and the “irradiation cycle” through which each channel travels. This cycle may be described as follows.**
- **When a channel is refuelled, its local reactivity is high, and its power will be several percent higher than its time-average power.**

(cont’d)

7.1 The Channel-Power Cycle

- The fresh fuel in the channel then initially goes through its plutonium peak as it picks up irradiation.
- This means that in fact the local reactivity increases for about 40 to 50 FPD, and the power of the channel tends to increase further.
- The higher local reactivity tends to promote a (smaller) power increase in the neighbouring channels also.

(cont’d)

7.1 The Channel-Power Cycle

- **Following the plutonium peak, the reactivity of the refuelled channel starts to decrease, and its power drops slowly.**
- **Approximately half-way through its dwell time, the power of the channel may be close to the power suggested by the time-average model.**
- **The reactivity of the channel and its power continue to drop.**

(cont'd)

7.1 The Channel-Power Cycle

- **Eventually, the channel becomes a net “sink” or absorber of neutrons, and the time comes nears when the channel must be refuelled again.**
- **At this time the power of the channel may be 10% or more below its time-average power.**
- **When the channel is refuelled, its power may jump by 15 to 20% or even more.**

7.1 The Channel-Power Cycle

- What has just been described is a cycle where
- the power of each channel goes through an "oscillation" about its time-average power.
- This cycle repeats every time the channel is refuelled,
- that is, with a period approximately equal to the dwell time suggested by the time-average model.

7.1 The Channel-Power Cycle

- The cycle length is not exactly equal to the dwell time,
- because channels are not refuelled in a rigorously defined sequence.
- Instead, channels are selected for refuelling based on instantaneous, daily information about the core power and irradiation distributions.
- So there is quite a degree of variability, as the fuelling engineer reacts to the specific core parameters day after day (flux shape, zone-controller fills, etc.)

7.1 The Channel-Power Cycle

- **In addition, the CANDU fuelling engineer always has much flexibility in deciding how the core should be managed,**
- **and can in fact decide to modify the global power distribution by changing the refuelling frequency (dwell time) of various channels.**
- **Such decisions may have to be made if, for instance, tilts appear to be developing in the power distribution, for any reason.**
- **The flexibility it provides to react to such occurrences is one of CANDU’s strong points.**

7.1 The Channel-Power Cycle

- As individual channels are refuelled and go through their channel-power cycle, the specific sequence of these discrete refuellings results in variability in the instantaneous peak channel and bundle powers in the core.
- This is illustrated in Figure 7.1, which shows schematically the maximum channel power versus time.

7.1 The Channel-Power Cycle

- The figure illustrates the difference between:
  - the maximum time-average channel power, which comes from the time-average calculation, lacks refuelling ripple, and therefore is relatively low,
  - the average maximum instantaneous channel power, which is a "historical" mean peak channel power,
  - and the absolute maximum channel power, the very highest value reached.
- The fuelling engineer tries to ensure that the absolute maximum channel power is not much higher than the historical mean.

7.2 Channel-Power Peaking Factor

- At any given time, there are several channels in the core which are at or near the maximum power in their cycle.
- Therefore, the maximum instantaneous channel power is always higher than the maximum time-average channel power, as was evident from the earlier Figure 7.1.

7.2 Channel-Power Peaking Factor

- **Because many safety analyses are normally carried out in a time-average model,**
- **it is very important to quantify how much higher the instantaneous power distribution peaks above the time-average distribution.**
- **The Channel-Power Peaking Factor (CPPF) is defined to capture this concept.**

7.2 Channel-Power Peaking Factor

- **It's the maximum, over channels (m), of the "individual peaking factor", ratio of instantaneous to time-average channel power (CP):**

$$CPPF = \underset{m}{Max}\left[\frac{CP_{instantaneous}(m)}{CP_{time-average}(m)}\right] \qquad (7.1)$$

- **where m runs over all channels in the core, or at least over all channels except perhaps the channels with the very lowest power, i.e., except the last two outermost rings of channels.**

7.2 Channel-Power Peaking Factor

- The CPPF value varies from day to day, as the various channels which have fairly recently been refuelled go through their cycle.
- The average CPPF value obviously depends on the axial refuelling scheme used.
- The greater the number of bundles replaced at each operation, the greater the reactivity increment, and therefore also the refuelling ripple (and CPPF).
- With 8-bundle-shift refuelling, a typical value for the CPPF is in the range 1.08-1.10. With a 4-bundle-shift scheme, the typical CPPF is likely to be 1.04-1.05.

7.2 Channel-Power Peaking Factor

- **The exact value of the CPPF is extremely important, because it is used to calibrate the in-core ROP detectors.**
- **The hundreds of flux shapes that are used in the ROP safety analysis (to determine the ROP detector positions and setpoints) are all calculated in the time-average model, assuming many different core configurations.**

(cont'd)

7.2 Channel-Power Peaking Factor

- **But because the real instantaneous channel powers are higher than the time-average powers used in the ROP analysis,**
- **channels would reach their "critical channel power" (power at which there is fuel dryout) earlier than in the time-average model.**
- **To take this into consideration and ensure proper safety coverage in the instantaneous power shape, the in-core ROP detectors are calibrated to read more than 100% at full reactor power.**
- **The instantaneous value of CPPF is used for the calibration.**

7.2 Channel-Power Peaking Factor

- **Since the margin to trip is the “distance” between detector reading and detector setpoint,**
- **then in order to maximize the margin to trip, it is obviously important that the CPPF be kept as low as possible.**
- **This is why a careful selection of channels to be refuelled needs to be made always.**
- **A way in which CPPF can be kept low by design is by using, say, 4-bundle-shift refuelling instead of 8-bundle-shift refuelling, or using a mixed 4- and 8-bundle-shift scheme, where the 4-bundle shifting is done in the inner core (high-power region).**

7.2 Channel-Power Peaking Factor

- **Another way in which poor refuelling strategy could impact on reactor operation is as follows.**
- **Concentrated refuelling in the vicinity of an ROP detector will increase its reading, even though this *may* not increase the CPPF value.**
- **The high detector reading may lead either to spurious trips,**
- **or to power deratings (to restore operating margin), both of which lead to loss of power production.**

7.2 Channel-Power Peaking Factor

- **Determining the daily CPPF value,**
- **and ensuring detectors are calibrated to the correct value,**
- **are very important on-going duties of the fuelling engineer or reactor physicist at a CANDU nuclear generating station.**

7.3 Criteria for Selecting Channels for Refuelling

- **One of the main functions of the fuel engineer (or site reactor physicist) is to establish a list of channels to be refuelled during the following period (few days) of operation of the reactor.**

7.3 Criteria for Selecting Channels for Refuelling

- **Suppose a list is needed for one week of operation.**
- **And suppose the time-average calculation indicated that the average refuelling rate should be ~ 2 channels/FPD (with 8-b.s. fuelling).**
- **Then the list would need about 14 channels.**
- **Perhaps slightly more or fewer than 14 channels may be needed, depending on the total amount of reactivity the refuelling of the specific channels selected generates.**

7.3 Criteria for Selecting Channels for Refuelling

- **To draw up this list, information on the current status of the reactor core is gathered from:**
  - **RFSP simulations of reactor operation (which provide the instantaneous 3-d flux, power and burnup distributions, and also the reactivity increase expected from each channel) ,**
  - **the on-line flux mapping system (another indication of the core flux shape),**
  - **the ROP and RRS in-core detectors (an indication of the operating margin to trip, in various reactor zones),**
  - **and the zone-control-compartment water fills (another indication of where refuelling is needed, to drive the water fills to their reference (mid-range) values).**

7.3 Criteria for Selecting Channels for Refuelling

- **Normally, the process of selecting channels for refuelling will begin by quickly *eliminating* channels which are poor candidates for refuelling.**
- **With experience, a fuelling engineer will develop a personal set of rules for eliminating channels.**

(cont’d)

7.3 Criteria for Selecting Channels for Refuelling

- **A typical (but by no means unique) set of rules may eliminate:**
  - **channels with an instantaneous power within 10% of the maximum licensed channel power, as well as their 4 closest neighbours - refuelling these would almost certainly result in a channel power higher than the licensed power!**
  - **channels refuelled recently, say < 10 FPD prior, as well as their 8 closest neighbours (the "square around the channel") - refuelling channels too close on the heels of their neighbours would eventually result in a "hot spot".**

(cont'd)

7.3 Criteria for Selecting Channels for Refuelling

- **More channels on a typical "elimination" list:**
    - **channels with a high value of peaking factor (>, say, 1.07), as well as their 4 closest neighbours - again, refuelling neighbours of such channels would aggravate the CPPF**
    - **channels with low average value of burnup in the bundles which would be discharged (<, say, 75% of the time-average exit burnup for that channel) - these channels are still too "young", refuelling them would penalize burnup.**

7.3 Criteria for Selecting Channels for Refuelling

- Once channels inappropriate for refuelling have been eliminated, possible lists can start to be developed from the remaining channels.
- Good combinations of channels for refuelling in the few days to follow will typically contain:
  - channels "due to be refuelled", i.e., channels for which the time interval since the last refuelling is approximately equal to the channel's dwell time - the time-average calculation says it's about time to refuel these
  - channels with high current value of exit burnup, relative to their time-average exit burnup - obvious choices

(cont'd)

7.3 Criteria for Selecting Channels for Refuelling

- **More channels which may be good candidates:**
  - **channels with low power, relative to their time-average power - these channels may be at the end of their "cycle"**
  - **channels in (relatively) low-power zones (compared to the time-average zone-power distribution) - the power of such zones needs to be moved towards the time-average value**
  - **channels which, taken together, promote axial, radial and azimuthal symmetry and a power distribution close to the reference power shape - the list must always consider the channels as a group: there must not be too many from one zone or one core region, or an imbalance in the number of channels fuelled from one end as compared to the other**

(cont'd)

7.3 Criteria for Selecting Channels for Refuelling

- More channels which may be good candidates:
  - channels which provide sufficient distance to one another and to recently refuelled channels (to avoid hot spots) - again, channels must be considered together
  - channels which will result in acceptable values for the individual zone-controller fills (20%-70% range), - information on the effect of individual channel refuellings on zone fills needed here, and
  - channels which, together, provide enough reactivity to balance the daily loss due to burnup (and will, therefore, tend to leave the zone-controller fills in the desired operational range: average zone fill between 40 and 60%) .

7.3 Criteria for Selecting Channels for Refuelling

- Typically, the fuelling engineer may find a large number of candidate channels, and will usually have to use judgment to draw up the list, from many options available.
- Channels may be good candidates individually, but may "conflict" with one another, e.g. may be too close together, or may be too many from one side of the core, etc.
- Thus, the list must be assessed as a whole.

7.3 Criteria for Selecting Channels for Refuelling

- **An experienced fuel engineer can probably rely on good judgment alone,**
- **but, in general, a good way of being confident about a channel selection is to perform an RFSP pre-simulation of the expected core status following the refuelling of the channels chosen.**
- **This pre-simulation (especially if it invokes bulk- and spatial-control modelling) will show whether the various power, burnup, and zone-fill criteria are likely to be satisfied, or whether the channel selection should be changed.**

7.4 Initial Fuel Load and Transient to Onset of Refuelling

- Let us now return to the period which marks the beginning of reactor operation.
- In the initial core, fresh fuel is present throughout the core.
- There is no differential burnup which can assist in flattening the power distribution.

7.4 Initial Fuel Load and Transient to Onset of Refuelling

- **Consequently, the power of the central core region would be unacceptably high if no alternate means of flattening the radial power distribution were provided.**
- **However, an alternate means is readily available: depleted fuel.**
- **As we have seen earlier, this depleted fuel is a net absorber of neutrons.**

7.4 Initial Fuel Load and Transient to Onset of Refuelling

- **In the initial core of the CANDU 6 (i.e., the initial fuel load), two depleted-fuel bundles (of 0.52 atom % ^{235}U content) are placed in each of the central 80 fuel channels.**
- **This is shown in Figure 7.2.**
- **The bundles are located in positions 8 and 9, where the numbering is from the channel refuelling end.**
- **In these axial positions, the depleted-fuel bundles are removed from the core in the first 8-b.s. refuelling visit of each of these channels.**

7.4 Initial Fuel Load and Transient to Onset of Refuelling

- Even with some depleted fuel in the core, the fact that all fuel is fresh results in a net excess reactivity in the core.
- The core reactivity starts at approximately 16 milli-k at full power on FPD 0, and then varies with time as shown in Figure 7.3.
- Because all the fuel goes through its plutonium peak at about the same time, the excess reactivity initially increases, from about 16 mk to a maximum of about 23 mk between FPD 40 and FPD 50.

7.4 Initial Fuel Load and Transient to Onset of Refuelling

- The excess reactivity is compensated by soluble boron in the moderator.
- The boron coefficient of reactivity is about -8 milli-k per ppm of boron.
- Thus the boron concentration (at full power) is initially approximately 2 ppm, rising to about 3 ppm at the plutonium peak.
- Following the plutonium peak, boron must be removed (by ion exchange) as the excess reactivity drops gradually to zero at about FPD 120.

7.4 Initial Fuel Load and Transient to Onset of Refuelling

- **During this entire first period in the reactor life, refuelling is not necessary since there is already excess reactivity.**
- **Actually, refuelling is started about 10 or 20 FPD before the excess reactivity reaches 0, i.e. around FPD 100,**
- **because the refuelling rate would be too great if one waited until the last possible moment to start.**

7.4 Initial Fuel Load and Transient to Onset of Refuelling

- Figures 7.4 to 7.6 show representative bundle-power distributions in the horizontal radial direction at FPD 0 (initial core), FPD 40, and FPD 100 respectively.
- The main feature to be noted is the initial “dishing” of the power distribution in rows containing some channels with depleted fuel.

7.4 Initial Fuel Load and Transient to Onset of Refuelling

- The dishing of the power distribution is quite pronounced at FPD 0, but flattens out with increasing fuel burnup, since the inner core actually goes through its plutonium peak earlier than the outer core, and the depleted-fuel plutonium peak is in fact more pronounced, as pointed out earlier.
- Beyond the plutonium peak, the overall power distribution flattens out, and the maximum bundle power drops.

7.5 Period from Onset of Refuelling up to Equilibrium

- **When refuelling begins, the inner core region has the highest burnup and the lowest power relative to the equilibrium power distribution.**
- **Refuelling begins in this region, causing power to rise, both because of the addition of fresh fuel and of the simultaneous discharge of irradiated and depleted fuel.**
- **Only some of the channels in this region can be refuelled, however, otherwise the power would rise excessively.**

7.5 Period from Onset of Refuelling up to Equilibrium

- **Refuelling of outer-region channels follows.**
- **In this region, channel burnup decreases with increasing distance from the core centre (i.e., decreasing power).**
- **Therefore, the refuelling tends to proceed generally from the central core region towards the periphery.**

7.5 Period from Onset of Refuelling up to Equilibrium

- **However, not all channels at a given radius can be refuelled at the same time.**
- **Some channels in each “ring” are initially bypassed for two reasons:**
- **first, it is desirable not to refuel adjacent channels simultaneously, because this would cause a local power peak (“hot spot”);**
- **and second, it is desirable to have a distribution of burnup in each ring when equilibrium is reached.**

7.5 Period from Onset of Refuelling up to Equilibrium

- **Channels missed on the first refuelling of a ring will be refuelled later, until,**
- **when the last channels are visited, the burnup in each ring is uniformly distributed between zero and discharge value.**
- **Because there has to be a selection from among many channels, and refuelling the channel with the highest burnup may lead to a hot spot, this channel is not always the one which is refuelled first!**

7.5 Period from Onset of Refuelling up to Equilibrium

- **After refuelling begins, the rate of refuelling rapidly approaches its equilibrium value (approximately 16 bundles per FPD for the CANDU 6).**
- **Over short periods, there may be considerable variation from this average rate.**
- **For example, if, for a few days, only the outermost channels were being refuelled, a very high rate (almost 6 channels/FPD) would be required to keep up with the reactivity loss, since these channels introduce less reactivity than central channels.**

7.5 Period from Onset of Refuelling up to Equilibrium

- **It is not possible for the fuelling machines to maintain this rate, and therefore refuelling of outermost channels has to be intermingled with the refuelling of high-worth, inner-region channels.**
- **Fortunately, the outermost-channel region does not have to be visited very often - about 4 or 5 times per month on the average.**

7.5 Period from Onset of Refuelling up to Equilibrium

- Figure 7.7 shows a plot of refuelling rate vs. time, obtained from a simulation of the CANDU 6 reactor from the onset of refuelling to FPD 400.
- The corresponding maximum channel powers and bundle powers are shown in Figures 7.8 and 7.9.
- The variability with time is evident, and is something that can essentially not be avoided, no matter what channel selection is made.
- The best that can be hoped for is to keep the variability in peak powers relatively small.

7.5 Period from Onset of Refuelling up to Equilibrium

- **Figures 7.10 and 7.11 show the gradual increase in average discharge burnup and in cumulative discharge burnup through this period of operation.**
- **The average discharge burnup climbs quickly.**
- **[Note, this slide comes from a very early study, where the absolute burnup was low because of a low moderator purity; however, the general dependence on time is typical].**

7.5 Period from Onset of Refuelling up to Equilibrium

- **Fig. 7.11 also shows how it is possible to increase the discharge burnup of the initial fuel load, by reshuffling some fuel into the core.**
- **Fuel bundles in positions 11 and 12 in a channel are in low flux, but normally these bundles have been in positions 3 and 4 before (before the 8-bundle shift), and so have non-negligible burnup.**
- **However, the first-charge bundles to be discharged from positions 11 and 12 have never been in positions 3 and 4, and so will have low burnup at discharge.**

(cont'd)

7.5 Period from Onset of Refuelling up to Equilibrium

- **However, if the “swing-8” refuelling scheme is adopted, the low burnup of the original bundles 11 and 12 can be avoided.**
- **The swing-8 scheme, shown in Figure 7.12, features the reshuffling of bundles 11 and 12 back into their same positions in the channel on refuelling.**
- **The swing-8 scheme is used at the first visit (only) of each channel, because, afterward, position-11 and 12 bundles have remained in core for two cycles, not just one.**

7.6 Consequences of Fuelling-Machine Unavailability

If refuelling were to stop for any reason, core reactivity would continuously decrease.

- The rate of reactivity decay is about 0.4 mk/FPD in the CANDU-6 core.
- The reactor regulating system (RRS) would of course attempt to maintain criticality.
- The first action that the reactor regulating system (RRS) would take to maintain criticality is to lower the level of water in the liquid zone-control compartments.

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7.6 Consequences of Fuelling-Machine Unavailability

- Eventually, the water would be drained to the lower limit of the control range.
- Since the desirable operating range of the zone controllers is between 20% and 70% (i.e., a range of 50%),
- and since the full reactivity range of the zone controllers (from 100% down to 0%) provides about 7 milli-k of reactivity,
- the number of days which can be "survived" without refuelling is typically

  ~ 3.5 mk/(0.4 mk/FPD) = ~ 8 FPD.

7.6 Consequences of Fuelling-Machine Unavailability

- The operator would also ensure that any poison which might exist in the moderator at the time would be removed.
- Every ppm of boron is worth about 8 milli-k, however the operating license usually limits the amount of boron in the core in full-power operation to about 0.625 ppm (5 milli-k).
- If present, this amount would, upon withdrawal, allow another ~12 FPD without refuelling.

7.6 Consequences of Fuelling-Machine Unavailability

- Continued lack of refuelling would lead to withdrawal of the adjuster rods in their normal sequence.
- This would permit operation to continue for several weeks (~15 mk/0.4 mk/FPD = ~37 FPD).
- However, as the adjuster rods are withdrawn, the reactor power must be gradually reduced because of changes in the power distribution associated with spatial changes in the distribution of absorption cross section.

7.6 Consequences of Fuelling-Machine Unavailability

- In effect, withdrawal of the adjusters results in a radially “peaked” power distribution,
- i.e., higher channel and bundle powers at the center of the core,
- which forces a power derating in order to remain in compliance with the licensed channel and bundle powers (7.3 MW and 935 kW respectively).
- The amount of derating necessary increases with the number of adjusters withdrawn.

7.7 Core-Follow Calculations with RFSP

- **In this section the application of RFSP to core-follow is discussed.**

7.7.1 Instantaneous (Snapshot) Diffusion Calculations

- The main application of RFSP at CANDU sites is in tracking the reactor's operating history.
- This function is performed with the *SIMULATE module of RFSP.

7.7.1 Instantaneous (Snapshot) Diffusion Calculations

- **The core history is tracked by a series of instantaneous snapshots, which can be calculated at any desired frequency.**
- **Steps of 2-3 FPD are typically convenient for the site physicist.**
- **The code advances the in-core irradiation and burnup distributions at each step, in accordance with the time interval. [For each bundle, $\omega = \phi t$.]**
- **Individual channel refuellings within a time step are taken into account at the actual time at which they occur.**

7.7.1 Instantaneous (Snapshot) Diffusion Calculations

- At each code execution, the zone-control-compartment fills corresponding to the time of the snapshot are input to the code,
- together with the concentration of moderator poison
- and any other device movement,
- so that the instantaneous reactor configuration is captured.

7.7.1 Instantaneous (Snapshot) Diffusion Calculations

- **The spatial distribution of ^{135}Xe can be modelled in the calculation (see chapter 8); this has an effect on the calculated flux and power distributions.**
- **Bulk and spatial control can also be modelled (see Section 7.7.3), so that the zone-controller fills cans be predicted.**

7.7.1 Instantaneous (Snapshot) Diffusion Calculations

- The presence of in-core detectors in the CANDU 6 allows the validation of the diffusion calculation against actual in-core measurements.
- Validation, using Pt. Lepreau measurements, has given very good results:
- The standard deviation of differences between calculated and measured detector fluxes is typically in the range of 2 to 3 %.

7.7.1 Instantaneous (Snapshot) Diffusion Calculations

- **The site reactor physicist can also elect to do core tracking using the flux-mapping method in RFSP.**
- **The detector fluxes at the time of the snapshot are input to the code to derive the 3-d mapped flux distribution.**
- **This is used to advance the irradiation and burnup distributions from one snapshot to the next.**
- **Even in this option, the diffusion calculation is performed in any case, because results are optimized when the diffusion solution is used as the fundamental mode in the mapping process.**

7.7.2 History-Based Methodology for Lattice Properties

- **This section describes a recent improvement in the method of calculation of lattice properties for application to core-tracking calculations.**

7.7.2 History-Based Methodology for Lattice Properties

- **Lattice properties are typically calculated by interpolating in irradiation (or, equivalently, in burnup) within “fuel tables” computed by the cell code,**
- **assuming core-average values of such parameters as the fuel temperature and the coolant density.**
- **In this method, the only independent parameter is the irradiation (or burnup).**
- **This conventional methodology is here labelled the “uniform-parameter” method.**

7.7.2 History-Based Methodology for Lattice Properties

- However, lattice properties certainly do depend on the local values of these parameters, and also on the history of quantities such as the moderator poison concentration.
- To take this into account, the “local-parameter history-based” methodology has been developed within RFSP for use specifically in core tracking.

7.7.2 History-Based Methodology for Lattice Properties

- **In this method, fuel tables are not employed.**
- **Instead, at each core-follow snapshot, an individual POWDERPUFS-V calculation is performed within RFSP for each fuel bundle, to update its properties over the incremental burnup step (only),**
- **using locally appropriate values of parameters (flux level, fuel temperature, coolant density, whatever parameters the user specifies) for that instant in the core history.**
- **This is made possible by the speed of POWDERPUFS-V calculations.**

7.7.2 History-Based Methodology for Lattice Properties

- **The use of bundle-specific values of parameters (in addition to irradiation) gives the method its local-parameter label.**
- **The history-based label originates in the fact that changes in lattice parameters are captured when and only when they actually occur.**
- **As a result, the evolution of the nuclear properties of each individual bundle is more properly tracked.**

7.7.2 History-Based Methodology for Lattice Properties

- Following the individual-bundle calculation of the lattice properties, the diffusion equation is solved as usual.
- Validation of the history-based methodology using, once again, Pt. Lepreau in-core-detector readings,
- has shown a significant improvement (reduction) of ~ 0.2-0.5 in the per cent standard deviation of differences between simulated and measured readings.
- The improvement is relative to the conventional (uniform-parameter) method.

7.7.3 Modelling of Bulk and Spatial Control

- **In RFSP, the asymptotic bulk-control and spatial-control functions of the Reactor Regulating System can be modelled.**
- **The label asymptotic indicates that the calculation is not in the time domain,**
- **but rather that the code attempts to find the long-term equilibrium (time-independent) values to which the zone-controller water fills tend.**

7.7.3 Modelling of Bulk and Spatial Control

- **Bulk and spatial control are modelled by modifying the zone-control-compartment water fills by computed increments every few iterations in the course of the solution of the diffusion equation.**
- **The following subsections describe how the incremental water fills are computed.**

7.7.3.1 Bulk Control

- Here the zone fills are moved uniformly up or down,
- depending whether the current value of k_{eff} is higher or lower than the desired (reference) value.

- The fractional water fill Z_i of each controller i is changed according to

$$Z_i = Z_i + \alpha_i (k_{eff} - k_{eff,ref}) \qquad i = 1, \ldots ,Nz$$

- where α_i is a user-supplied coefficient (usually with a value ~ 140 for the CANDU 6)

7.7.3.2 Spatial Control

- In the simplest approximation (selected by setting an input variable, ISPCTL, to 1 or 2 in the code),
- spatial control is modelled by requiring the flux distribution by zone to be proportional to the reference (or target) core flux distribution:
- in zones where the ratio of flux to reference flux is higher (lower) than the average value, the zone fill is increased (decreased).
- This has the effect of driving the flux distribution towards the target distribution.

7.7.3.2 Spatial Control

- **The fractional water fill Z_i of each controller i is changed according to**

$$Z_i = Z_i + \alpha_i \left[\frac{\phi_i}{\phi_{iref}} - \left\langle \frac{\phi}{\phi_{ref}} \right\rangle \right] \qquad i = 1, \ldots, Nz$$

- **where** $\left\langle \frac{\phi}{\phi_{ref}} \right\rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{\phi_i}{\phi_{iref}}$ **is the average ratio over all zones**
- **and (cont'd),**

7.7.3.2 Spatial Control

ϕ_i = detector (or zone) flux for detector (or zone) i,

- $\phi_{i,ref}$ = reference detector (or zone) flux for detector (or zone) i
- Nz = number of zone controllers
- α_i = user supplied coefficient (usually 2.0)
- N = Nz
- The reference or target zone (or detector) flux used in the above equation is normally obtained from a time-average calculation (by interpolating in the time-average mesh flux at the detector location, or - better - by averaging over the whole zone for the reference zone flux).

7.7.3.2 Spatial Control

- **In a more sophisticated approximation (selected by ISPCNTL = 3),**
- **the modelling includes "phase-out" factors in the individual "differential lifts"**
- **when the corresponding zone fills reach values that are too high (> 80%) or too low (< 10%).**
- **There is also a term which drives each zone fill towards the average zone fill.**

Summary

- RFSP is used at site to track the entire operating history of the reactor, snapshot by snapshot.
- The frequency of calculations is determined by user demand, but is typically 2-3 runs per week.
- RFSP offers many calculational options, including
  - diffusion
  - flux-mapping
  - history-based calculations of lattice parameters (best-result method)
  - saturating-fission-product modelling
  - bulk- and spatial-control modelling.