LECTURE 8: POWER DISTRIBUTION CONTROL

OBJECTIVES:

At the end of this lecture, you will be able to:

1. **Describe the power distribution effects of changes in the channel selection rules for fuelling.**
2. **Identify the critical performance assumptions in a simulation of fuelling.**
3. **Suggest specific improvements that could be made.**

INTRODUCTION

The primary objective of fuel management is to determine fuel loading and fuel replacement strategies which will result in minimum total unit energy cost while operating the reactor in a safe and reliable fashion. Within this context, the specific objectives of CANDU fuel management are as follows:

1. 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.
2. The core power distribution must be controlled to satisfy safety and operational limits on fuel and channel powers.
3. The fuel burnup is to be maximized within the operational constraints, to minimize the fuelling cost.
4. Fuel defects are to be avoided. This minimizes replacement fuel costs and radiological occupational hazards.
5. The fuel-handling capability must be optimized. This minimizes capital, operating and maintenance costs.

Initial Fuelling up to Equilibrium

- When refuelling begins, the inner region of the reactor will have the highest burnup and the lowest power relative to the equilibrium power distribution.
- Fuelling begins in this region, causing power to rise both because of the addition of fresh fuel and the discharge of irradiated and depleted fuel.
- Only some of the channels in this region can be refuelled, however, otherwise the power would rise above the equilibrium value.
- After the selected central channels have been refulled, refuelling of outer region channels begins.
- In this region, channel burnup decreases with increasing radius (i.e. decreasing power).
- Refuelling would tend to proceed generally from the inside towards the outside.
- However, not all channels at a given radius are 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; and
  - ⇒ second, it is desirable to have a distribution of burnups in each ring when equilibrium is reached.
- Channels missed on the first refuelling of a ring will be refuelled later until, when the last channels are visited, the burnups in each ring will be uniformly distributed between zero and discharge.
- Note that this means that the most burned-up channel is not always the one which is refuelled.

Initial Fuelling up to Equilibrium (continued)

- After refuelling begins, the rate of fuelling rapidly approaches its equilibrium value (approximately 18 bundles per FPD for the CANDU 6).
- Over short periods, there will be a considerable variation from this average rate.
- Figure 8-1 shows a plot of fuelling rate vs. time obtained from a simulation of the CANDU 6 reactor from the onset of fuelling to almost 400 FPD.

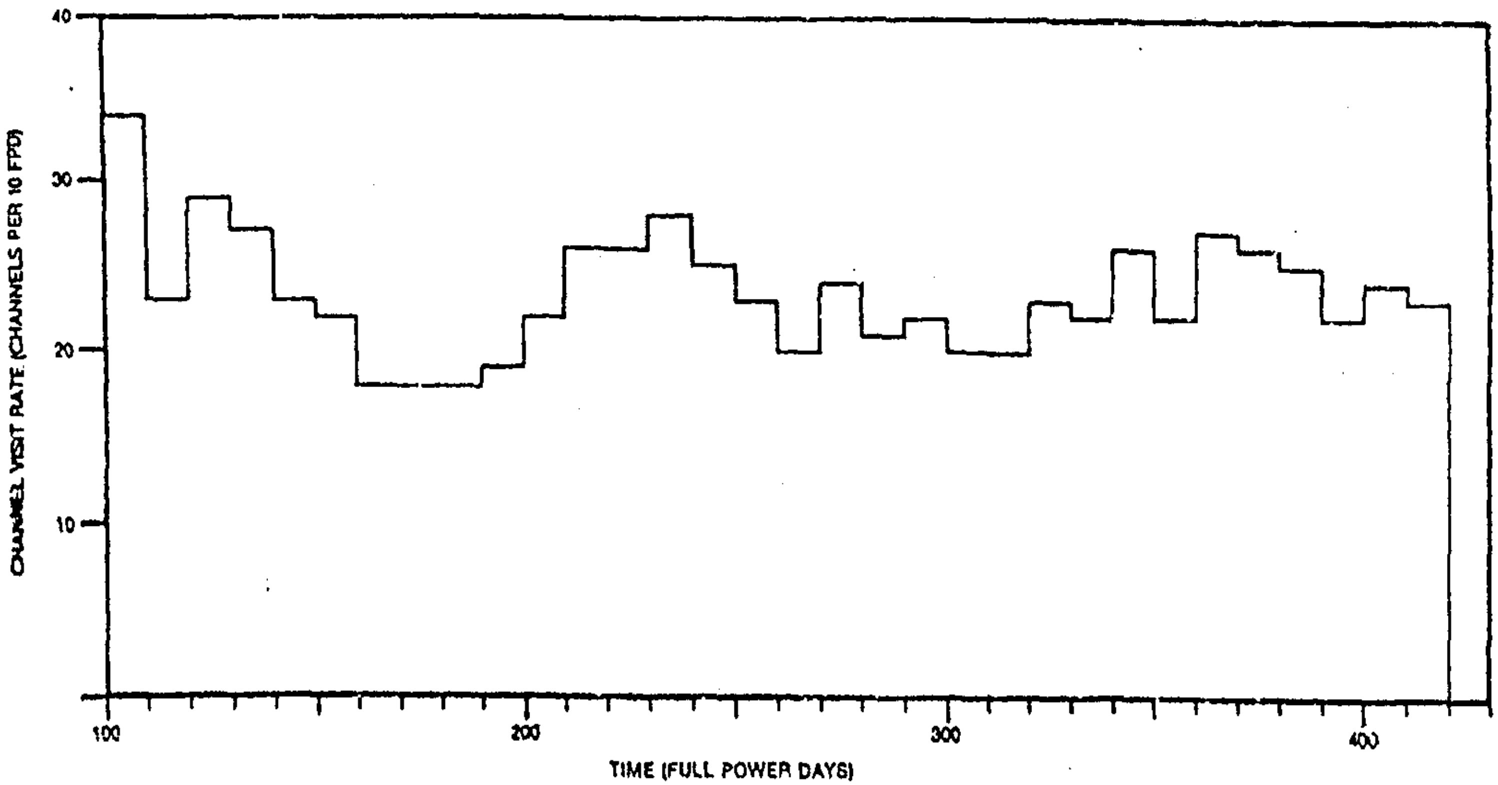


Figure 8-1: Fuelling Machine Visit Rate per 10 FPD Interval.

Initial Fuelling up to Equilibrium (continued)

The maximum channel and bundle power variations for the refuelling strategy shown in Figure 8-1 as obtained in the simulation are shown in Figures 8-2 and 8-3.

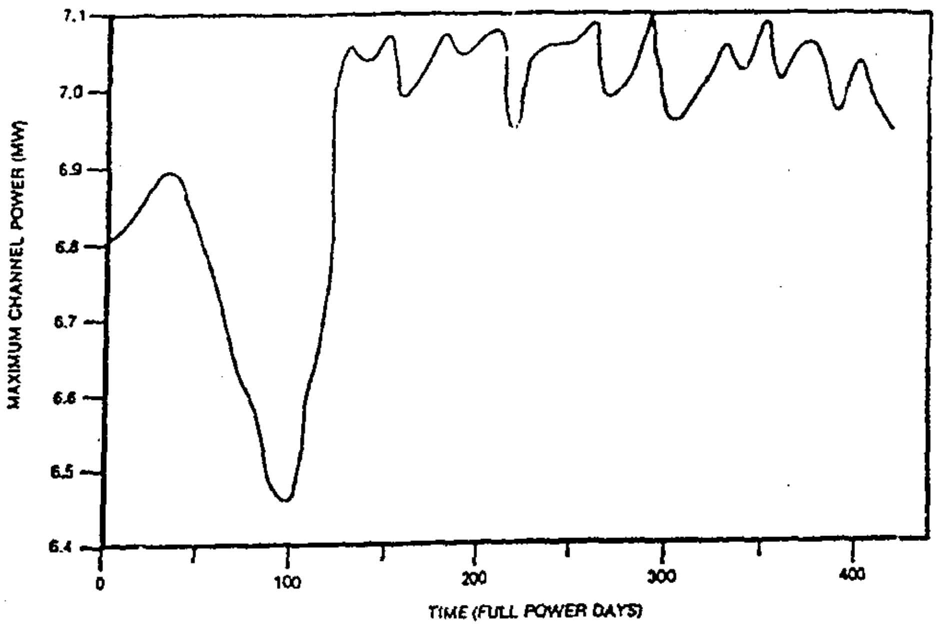


Figure 8-2: Maximum Channel Power.

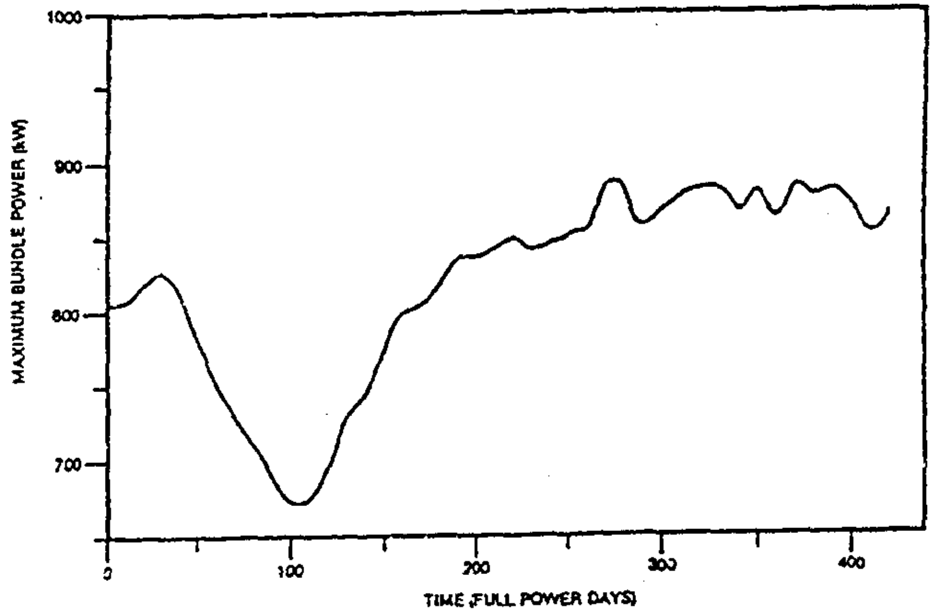


Figure 8-3: Maximum Bundle Power.

EQUILIBRIUM FUEL MANAGEMENT

- Although fuelling rates quickly approach equilibrium values, an equilibrium burnup distribution is attained after about 500 FPD.
- The fuel discharged from the reactor will not reach its equilibrium burnup value until some time after the fuelling rate has reached its equilibrium value.
- Once equilibrium is reached the core average characteristics (e.g. burnup and power distributions) change very little with time.
- Refuelling is the primary method of reactivity addition and of maintaining a satisfactory power distribution in the core.
- The rate of refuelling is adjusted to compensate for the reduction in core reactivity caused by burnup.
- Fuelling rates in different regions are adjusted to control the power distribution - a lower fuelling rate increases average burnup in a region, and reduces its relative power.

Control of Radial Power Distribution

- The presence of adjuster rods for xenon override in the centre of a typical CANDU core reduces the reactivity in this region, producing a flattened radial and axial power distribution.
- If the fuel were irradiated to a uniform average burnup throughout the core, the channel power would be unnecessarily high in the inner channels.
- Consequently the core is divided into two regions radially, the inner region having higher burnup than the outer. This decreases reactivity in the inner region, providing additional flattening to the flux distribution. The inner fuelling region comprises the innermost 124 fuel channels in the CANDU 6 reactor.
- The calculated "time-average" channel power distribution for the CANDU 6 reactor is shown in Figure 8-4. This distribution is calculated using averaged fuel parameters at each bundle location in the core.

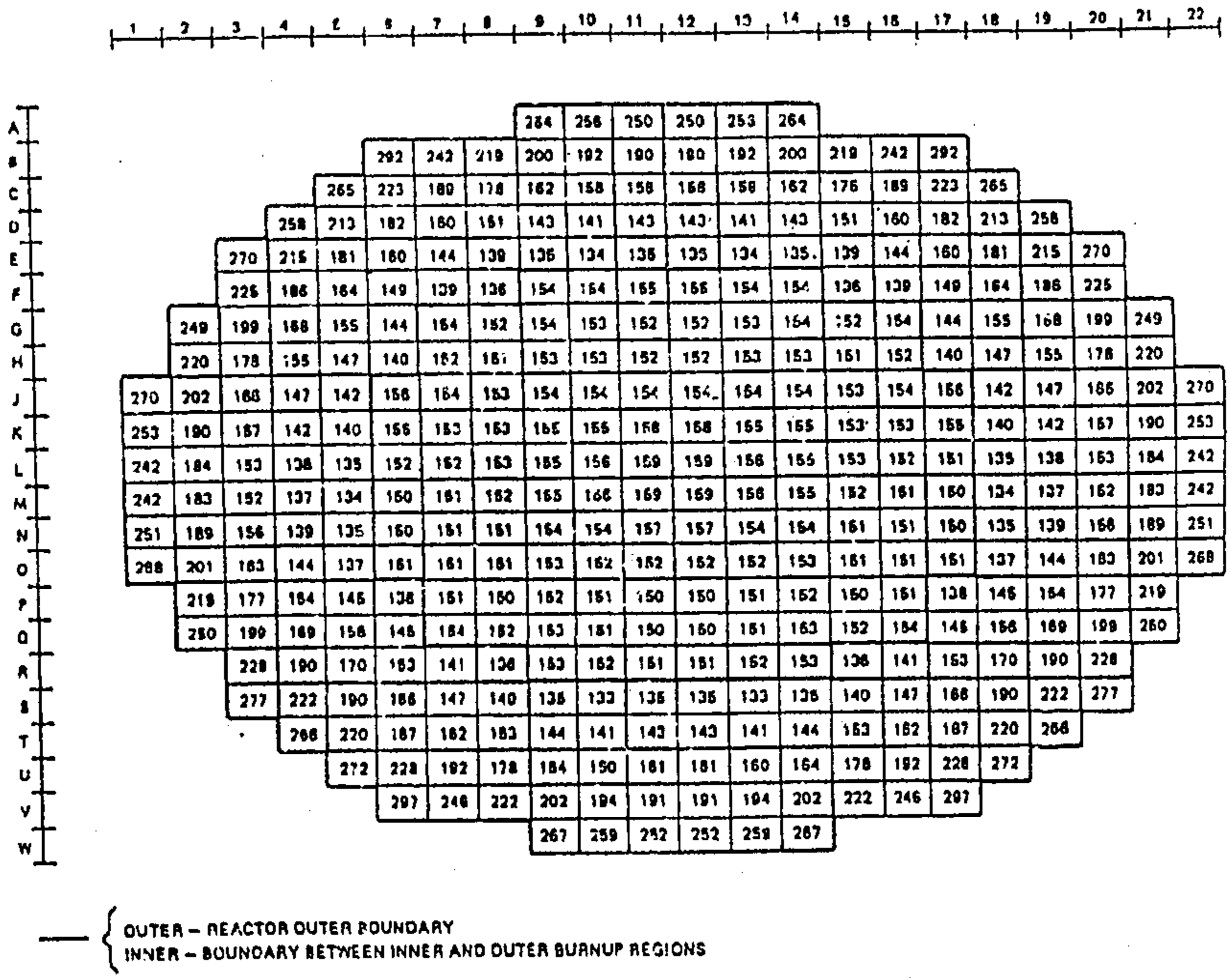


Figure 8-4: Time Averaged Channel Powers.

Control of Radial Power Distribution (continued)

- The power distribution in a channel is time varying.
- Power increases in a channel when it is refuelled for several weeks due to the buildup of plutonium isotopes in the fuel.
- Eventually, the increasing fission product load and decreasing fissionable isotopes cause a reduction in reactivity and power until the minimum power is reached just before refuelling.
- The fuel is said to pass through a "plutonium peak".
- Neighbouring channels will also be affected, with their power increasing slightly when the channel is refuelled, and decreasing as the local neutron source decreases.
- Over larger areas of the core these local effects will average out and the mean power distribution will remain steady, provided the fuelling rates are adjusted correctly in each region.
- Without refuelling, power in the high-power inner region would decrease, and would increase in the outer region, since burnup proceeds more rapidly in the high-power region.
- Refuelling rates in the two regions are adjusted to maintain a constant steady-state power distribution.

Control of Azimuthal Power Distribution

- It is desirable to maintain the power distribution fairly uniform azimuthally.
- The average fuelling rates in areas of the core which have excess loads would have to be slightly higher to keep the power distribution azimuthally uniform.
- If we neglect this small effect, we can compute the mean refuelling rate for every channel in the core based on its power and discharge burnup.
- Figure 8-5 4.12 shows the mean dwell time (the reciprocal of fuelling rate) for each channel in the CANDU 6 reactor in full power days corresponding to the time-average power distribution given in Figure 8-4.
- Note that the dwell time for any given channel is directly proportional to the average burnup of the fuel which is discharged from that channel, and inversely proportional to the channel power. Since the inner channels have higher burnup than the outer channels, we find that the outer channels in the high-power region of the core have shorter dwell times than the inner channels. However, as we move to the outside edge of the core, the dwell times increase rapidly due to the decreasing channel power.

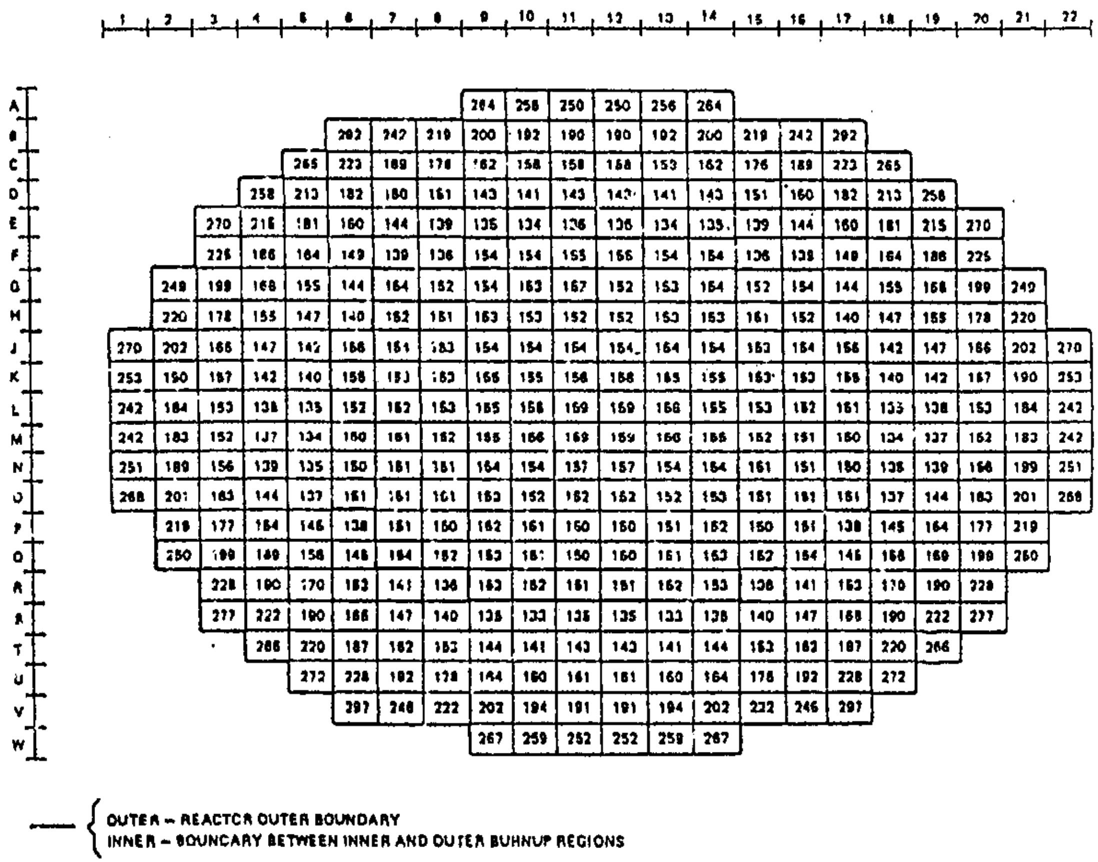


Figure 8-5: Average Channel Dwell Times in Full Power Days.

Axial Fuel Management

- During a fuelling operation, new fuel bundles are added to one end of a channel, and old fuel bundles are moved along the channel to new positions.
- If a small number of bundles are added to the channel at each refuelling, the burnup more closely approaches that for the ideal "continuous" refuelling.
- Replacing up to eight bundles per refuelling has very little effect on the attainable average discharge burnup, although 10- and 12-bundle shifts produce a significant loss in burnup.
- Increasing the number of bundles loaded per refuelling reduces the number of visits that the fuelling machine has to make to the core, which, in turn, reduces operating and maintenance costs for this very important system.
- There is an incentive to refuel as many bundles as possible per refuelling to reduce the load on the fuelling machine.
- The eight-bundle-shift fuelling scheme is the reference fuel-management scheme for the CANDU 6.

Channel Selection for Fuelling

- During reactor operation, one of the main functions of the fuel engineer is to establish a list of channels to be fuelled during the following period of operation.
- To achieve this, the reactor core status is determined from computer simulations of reactor operation, the on-line flux mapping. system, the ROP and RRS in-core detectors and zone control levels.
- The computer simulations of reactor operation produce neutron flux, power and burnup of each fuel bundle and channel as a function of reactor history.
- The simulations also provide maximum bundle and channel powers in the reactor, so that the proximity to operational limits can be assessed.
- The channel selection is usually made on the basis of the following often conflicting requirements:
  - ⇒ highest burnup to minimize fuelling costs,
  - ⇒ power distribution to be controlled so that axial, radial and azimuthal symmetry is maintained and the distribution remains close to the reference power shape,
  - ⇒ maximum separation between fuelled channels to avoid hot spots, and
  - ⇒ high reactivity gain.

FUEL MANAGEMENT CALCULATIONS

- The core of a CANDU reactor which has been operating sufficiently long for all channels to have been-fuelled at least once will contain fuel with different irradiations varying from fresh to discharge.
- This distribution of irradiation (or burnup) in the core will change with time as the fuel is irradiated and channels are refuelled, producing a time-varying flux and power distribution.
- However, if the flux for each bundle location is taken over a sufficiently long period of time, we obtain a unique "time-average" distribution of the core.
- This distribution is useful for various types of fuel management analysis such as calculating discharge burnup in the inner and outer regions, calculating residence times and fuelling rates, and obtaining reference power distributions.
- Ideally, the time-average distribution of the core is calculated by simulating a long period of reactor operation and then averaging. This, however, is not practical. Two approximate procedures are employed, namely, the homogeneous and the time-average models.

Homogeneous Calculations

- This is the simplest procedure and is based on the continuous bidirectional fuelling approximation. The fuel properties (cross sections) are assumed constant along the channel and constant within given regions of the core (e.g. inner core and outer core). They can be obtained directly from a lattice reaction-rate-averaged calculation.
- This procedure is simple, but the continuous fuelling assumption does not take into account the detailed effects of the fuelling scheme.

Time-Average Calculations

In this procedure, the fuel cross sections are averaged over the residence (dwell) time of the fuel at each point in the core. This allows the effect of different fuelling schemes (e.g. 4-bundle shift, 8-bundle shift) to be investigated.

Briefly, the flux and power distributions are calculated based on the assumption that each bundle has an average property determined by:

$$\bar{\Sigma} = \frac{1}{\Delta\omega} \int_{\omega_1}^{\omega_2} \Sigma(\omega)\, d\omega$$

where S is the macroscopic cross section, ω_1, and ω_2 are the irradiations at the beginning and at the end of the dwell time, and, $\Delta\omega = \omega_2 - \omega_1$. $\bar{\Sigma}$ vary with axial position in the channel since ω_1 and ω_2 vary depending on the flux at each position.

The increase in irradiation at (axial) position k, denoted, Dw_k, is obtained from

$$\Delta\omega_K = \phi_K T$$

where ϕ_K is the time-average flux (to be determined) at position k and T is the dwell time. When a fuel bundle is pushed to a new position, the irradiation at the start of the new cycle is equal to the end-of-cycle irradiation at the previous position. Thus, starting from the fresh bundles and knowing the fuel management scheme, ω_1, and ω_2 for all positions in the channel can be determined.

Time-Average Calculations

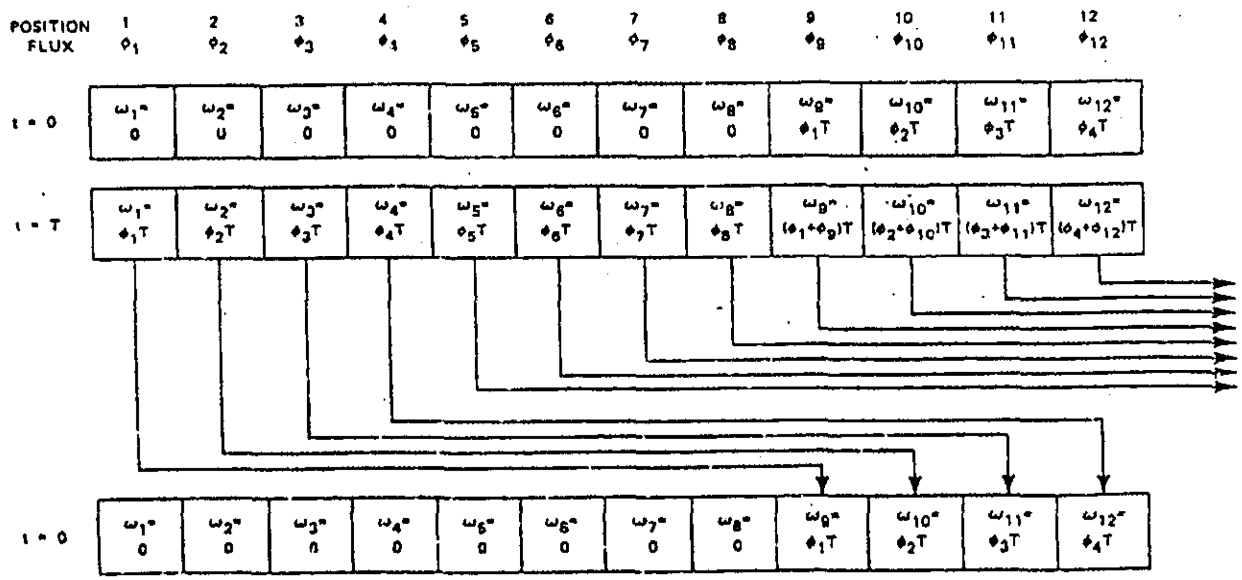
- The dwell time, T, is generally not known but can be related to the average discharge irradiation $\overline{\omega}_{out}$ by

$$T = \phi_K \frac{N\overline{\omega}_{out}}{\sum_K \phi_K}$$

where N is the total number of bundles discharged, and the summation is over all positions occupied by the bundle during its core residence. Figure 8-6 illustrates this argument with an example of an eight-bundle- shift scheme in a twelve-bundle core. Thus,

$$\Delta\omega_K = \phi_K \frac{N\overline{\omega}_{out}}{\sum_K \phi_K}$$

- An iterative procedure is used to seek a self-consistent distribution of $\overline{\Sigma}$ (based on the fuel irradiation) and ϕ_k throughout the core.
- In the usual application of a time-average calculation, the discharge irradiations in each region are varied to obtain a desired excess reactivity and radial form factor.



AVERAGE DISCHARGE IRRADIATION $= \frac{1}{8}\left\{\phi_5 T + \phi_6 T + \phi_7 T + \phi_8 T + (\phi_1 + \phi_9)T + (\phi_2 + \phi_{10})T + (\phi_3 + \phi_{11})T + (\phi_4 + \phi_{12})T\right\}$

$= \frac{T}{8}\left\{\phi_1 + \phi_2 + \phi_3 + \phi_4 + \phi_5 + \phi_6 + \phi_7 + \phi_8 + \phi_9 + \phi_{10} + \phi_{11} + \phi_{12}\right\}$

Figure 8-6: Time-Averaged Eight-Bundle Shift.

Instantaneous Calculations

- At any given moment in the reactor's history, the power distribution is most likely different from the time-average power distribution. In particular, the instantaneous maximum channel and bundle powers are likely to exceed those calculated with a time-average procedure.
- Each instantaneous distribution (snap-shot) is a sample from an infinite number of possible distributions. A series of instantaneous calculations can be treated statistically to provide an estimate of the actual maximum bundle and channel powers, averaged over time.
- The use of instantaneous calculations is illustrated in Figure 4.15, which shows a plot of the maximum channel power versus operating time. To estimate the actual average maximum channel power, several irradiation distributions (corresponding to operating conditions at times t_1, t_2, t_3.......) are selected and the corresponding (instantaneous) power distributions are calculated. The maximum channel powers from these sample cases are then averaged to yield the average maximum channel power, $\overline{P}_{max}$. Moreover, the standard deviation can also be used to estimate the absolute maximum channel power, $\hat{P}_{max}$.

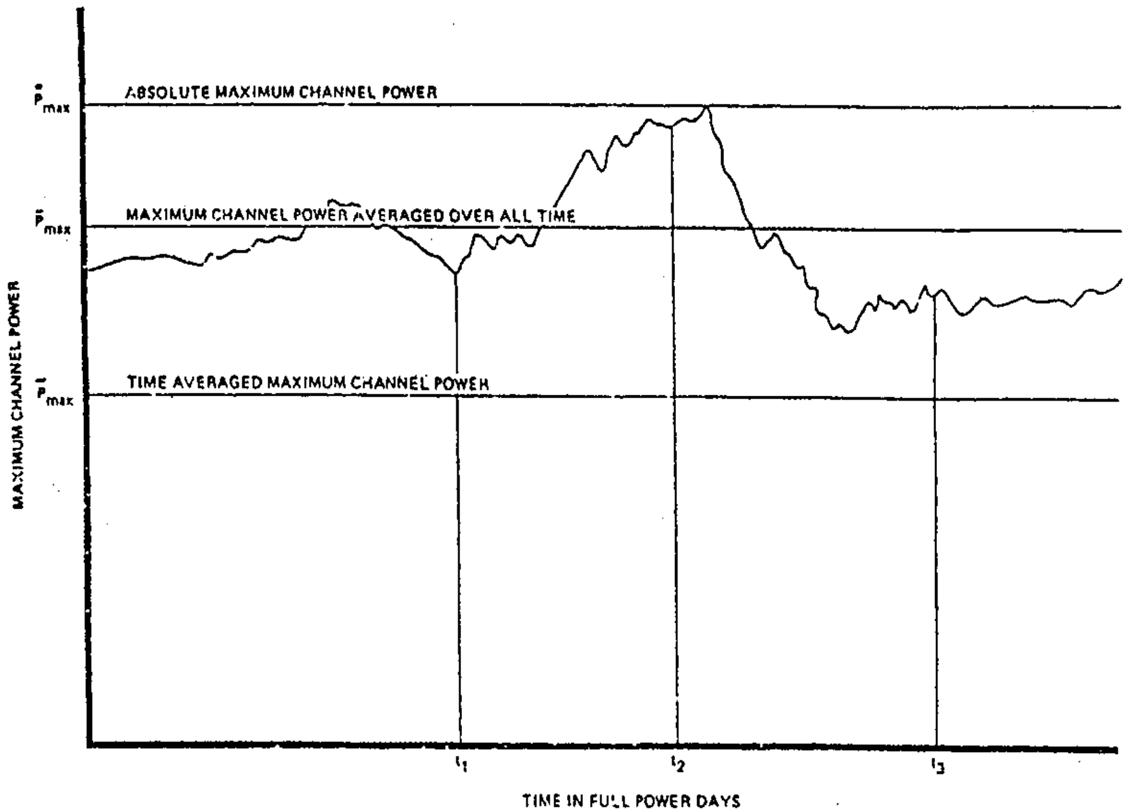


Figure 8-7: Segment of Typical Operation History.

Instantaneous Calculations (continued)

- To obtain an instantaneous irradiation distribution, the irradiation, $\omega(i, j, k)$, of every bundle in the core is expressed as

  $$\omega(i, j, k) = \omega_1(k) + f(i, j).\ (\omega_2(k) - \omega_1(k))$$

  where $\omega_1(k)$ and $\omega_2(k)$ are the irradiations immediately after and before fuelling, respectively, and are obtained from a time-average calculation discussed previously. f(i, j) is the fraction of time that channel (i, j) is through its cycle and is called the channel "age".
- In the absence of a complete operating history, f is selected from a uniform random distribution over the interval (0, 1) and is different for every channel in the core.
- The distribution produced in this way frequently produces maximum bundle and channel powers which are higher than are obtained by simulating core history.
- However, this shortcoming may be eliminated to a large extent by using a more reasonable fuelling pattern than by random fuelling.

Simulations

- The time history of the flux and power distributions is calculated at discrete time steps with the *irradiation distribution incremented from the previous step using the previous flux distribution.*
- During design stages, this type of calculation is used to simulate the initial transient from startup to equilibrium, to investigate the effect of various fuelling rules, and to obtain accurate estimates of maximum powers, discharge burnups, etc.
- During reactor operation, the simulations are performed to obtain bundle power, channel power, and bundle irradiation histories. These are used by the fuel engineer:
  - ⇒ to select channels for refuelling;
  - ⇒ to ensure that channel and bundle powers are kept within specified limits; and
  - ⇒ for burnup evaluation.

MISCELLANEOUS CALCULATIONS

Regional Overpower System and Fuel Management

- In order to protect the reactor against local fuel bundle and channel overpowers that might arise from perturbations in the power distribution or from loss of regulation accidents, CANDU reactors are equipped with a regional overpower protection (ROP) system.
- An "overpower" is a fuel bundle or channel power in excess of specified safety limits. These limits are distinct from and above the normal operating limits on bundle and channel powers.
- Because the local flux distribution is time varying, a detector will measure a flux at any given time which may be higher or lower than the macroscopic average flux in its region. Similarly, channel powers may be higher or lower than their time-average values. The basic problem is that a detector which may be reading a low flux at a particular time is required to protect channels in its vicinity which may be relatively highly powered at that time.
- To solve the problem, the detector outputs are periodically adjusted ("calibrated") so that they give the reference flux multiplied by the "channel power peaking factor" (CPPF). The CPPF is determined by computing the ratio of the instantaneous power to the reference power for each of the high power channels in the core, and selecting the largest ratio.
- The effect of this is that, if the flux at a detector rises above the reference value to its setpoint, the reactor will be shut down before even the highest power channel in the region reaches its overpower limit.
- In CANDU 6 the CPPF is calculated regularly by flux-mapping methods. It is apparent that it is highly desirable to minimize CPPF in order to maximize the margin between the detector readings and the setpoint.

Regional Overpower System and Fuel Management (continued)

- **From the point of view of fuel management, the ROP system presents two problems:**
  - ⇒ **The fuelling strategy must minimize the CPPF in order to allow the maximum operating margin. This implies accurate control of the macroscopic power distribution to ensure that "on average" the actual power distribution is close to the reference.**
  - ⇒ **It also implies minimizing the variations in the fine structure of the power distribution and therefore, keeping to a minimum the perturbation due to fuelling. This means that an axial fuelling scheme in which a small number of fuel bundles is replaced in a channel visit is preferable to one where a large number of bundles is replaced. This, however, is not the only consideration in deciding on the optimum axial fuelling scheme, as will be discussed in the next section.**
  - ⇒ **Concentrated refuelling in the vicinity of one ROP detector will increase its reading, even though this may not increase the CPPF in the core. The high detector reading, if not corrected by a calibration, may lead either to spurious trips or to power deratings, both of which lead to loss of power production.**

Selection of Axial Fuel Management Scheme

- The selection of the bundle shift scheme is usually done by comparing a number of possible schemes and determining the one which minimizes total unit energy cost for the reactor while satisfying the appropriate power limits.
- This comparison is done during the design phase to select the best scheme for reference design and initial fuelling. It is also, at times, repeated during the operating life of a plant to estimate whether different conditions warrant a change.
- Since the CANDU reactors are fuelled on power, a change in the bundle shifting scheme can easily be accomplished with a change in the operating procedure, requiring little lead time and without shutting down the reactor.
- In order to arrive at the axial scheme which minimizes the total unit energy cost, a series of parameters have to be calculated and compared for each scheme. The parameters which are normally required are:

  ⇒ discharge burnup,

  ⇒ maximum channel power and channel power peaking factor,

  ⇒ fuelling machine usage, and

  ⇒ fuel performance and bundle power.

  Many of these parameters are interrelated and therefore they cannot be rigorously considered separately. Nevertheless, we shall make some remarks about each to give an appreciation of their importance.

Fuel Burnup

- To some extent fuel exit burnup is affected by the number of bundles changed at each channel refuelling. While the effect is not great, the burnup tends to be lower for schemes where a greater number of bundles are shifted. Thus an eight-bundle-shift scheme gives a slightly lower burnup than does a four-bundle-shift scheme. Shifting 10 or 12 bundles gives even lower burnup.
- The discharge burnup obtainable from various schemes is usually evaluated initially using a "time-average" model.

Maximum Channel Power and Channel Power Peaking Factor (CPPF)

- Usually the time-average maximum channel power is not significantly affected by the axial fuel management scheme. The variations in channel power with respect to the "nominal" distribution, however, are strongly dependent upon the axial fuel management scheme.
- As described in the previous section, the ROP detectors are frequently calibrated to reflect the maximum ratio of instantaneous to nominal channel power or CPPF.
- In order to maximize the margin to trip it is important that the CPPF be kept as low as possible.
- A fuel-shifting scheme involving a small number of bundles gives smaller variations in the channel power than do shifts involving a larger number of bundles, and therefore gives a smaller CPPF.
- For instance, the CPPF associated with an eight-bundle-shift scheme exceeds unity by an amount about twice that associated with a four-bundle-shift scheme.
- Current CANDU reactors are designed so that the ratio of the limiting channel power to the nominal channel power is higher for the channels in the outer part of the core. Thus, a higher CPPF can be tolerated in the outer region than in the inner. As a consequence, mixed fuel shifting schemes involving, for instance, four-bundle-shift in the inner region and eight-bundle-shift in the outer core region are often used.

Fuelling Machine Usage

- In order to minimize the load and the maintenance costs on the fuelling machine, the number of fuelling operations should be kept as small as possible. From this point of view, the more bundles loaded per cycle, the fewer visits the fuelling machine has to make. Fuel shifting schemes involving large number of bundles are therefore desirable.
- Also, there is an upper limit on the capability of the fuel handling system so that it may not be possible to fuel the entire core with the fuelling scheme involving a small number of bundles per shift, for example, a four-bundle-shift As discussed previously, it is possible to fuel outer-region channels with an eight-bundle-shift scheme and inner region channels with a four-bundle-shift scheme.

Fuel Performance

- Another factor considered in selecting the axial fuelling scheme is the fuel performance, specifically, the probability of fuel defects.
- If irradiated fuel bundles are moved along the channel from a low power position to a high power position, the sudden increase in power (power ramp) may cause the fuel cladding to rupture.
- Such a fuel failure allows radioactive fission products to enter the PHT system and produce high radiation dose rates near the equipment.

Data for Fuel Performance Assessment and Accident Analysis

- A CANDU 6 reactor core contains nearly a quarter of a million fuel elements (37 elements per bundle). Each element during its life in the core has a different power and burnup history. This is because the power of the element changes for reasons such as:
  - ⇒ changes in the concentration of fissionable isotopes,
  - ⇒ movements of the fuel in the channel during refuelling,
  - ⇒ perturbations in the flux due to maneuvering of reactivity devices, fuelling of neighbouring channels, or xenon transients, and
  - ⇒ changes in total reactor power due to normal power maneuvering (i.e., load following) or abnormal conditions (i.e., equipment malfunctions).
- Clearly, analysis of every single element to assess its behaviour for fuel design or for accident analysis is impractical. Recourse is then made to upper-bound techniques and conservative assumptions.
- For the CANDU reactor, this technique consists of calculating a bundle-power-history envelope. This is a curve of expected bundle power versus burnup which encompasses or "envelopes" all possible individual bundle histories and includes all the changes in fuel power due to the effects listed above.
- If the analysis is performed on a hypothetical bundle whose history follows the envelope, it will be conservative for all individual bundles whose histories fall below it.

Fuel Reshuffling in the First Cycle

- The first time a channel is refuelled, the bundles discharged from the last two positions (#11 and #12) in the channel have very low burnup. If these bundles are reshuffled back into the core to acquire additional burnup, fuel costs for the first cycle will be reduced.
- The "Swing-8" fuelling scheme involves taking out 10 bundles while inserting 8 fresh bundles. The first two bundles out 11 and 12, are then re-inserted into their original positions, as shown in Figure 8.8.

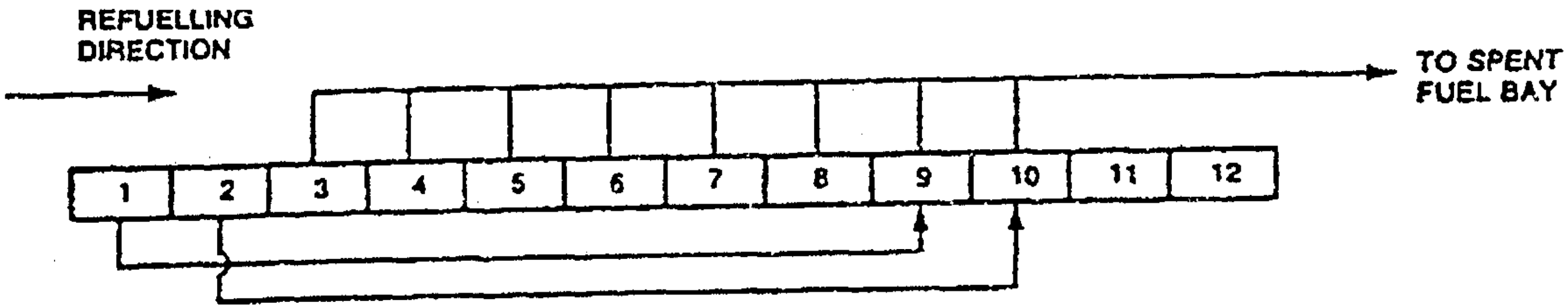


Figure 8-8: Swing-Eight Refuelling Scheme.

- A simulation of the "Swing-8" fuelling scheme was carried out using the FMPD computer code for the CANDU 6 reactor. A summary of the results along with the values corresponding to the standard-8 fuelling scheme is given below:

Case	Burnup of First 4560 Bundles Discharged (MW.h/kgU)	Difference from Reference (%)	Average FM Visit Rate (Channels/Day from Onset of Fuelling)	Difference from Reference (%)
Reference	121.4	-	2.48	-
Swing-8	134.0	10.4	2.38	-4.0

Fuel Reshuffling in the First Cycle (continued)

- **Figures 4.17 - 4.19 show the average discharge burnup per 10-FPD interval, cumulative discharge burnup, and fuelling machine visit rate per 10-FPD interval, respectively, for both schemes. These results show that the "Swing-8"" fuelling scheme results in a significant burnup improvement.**

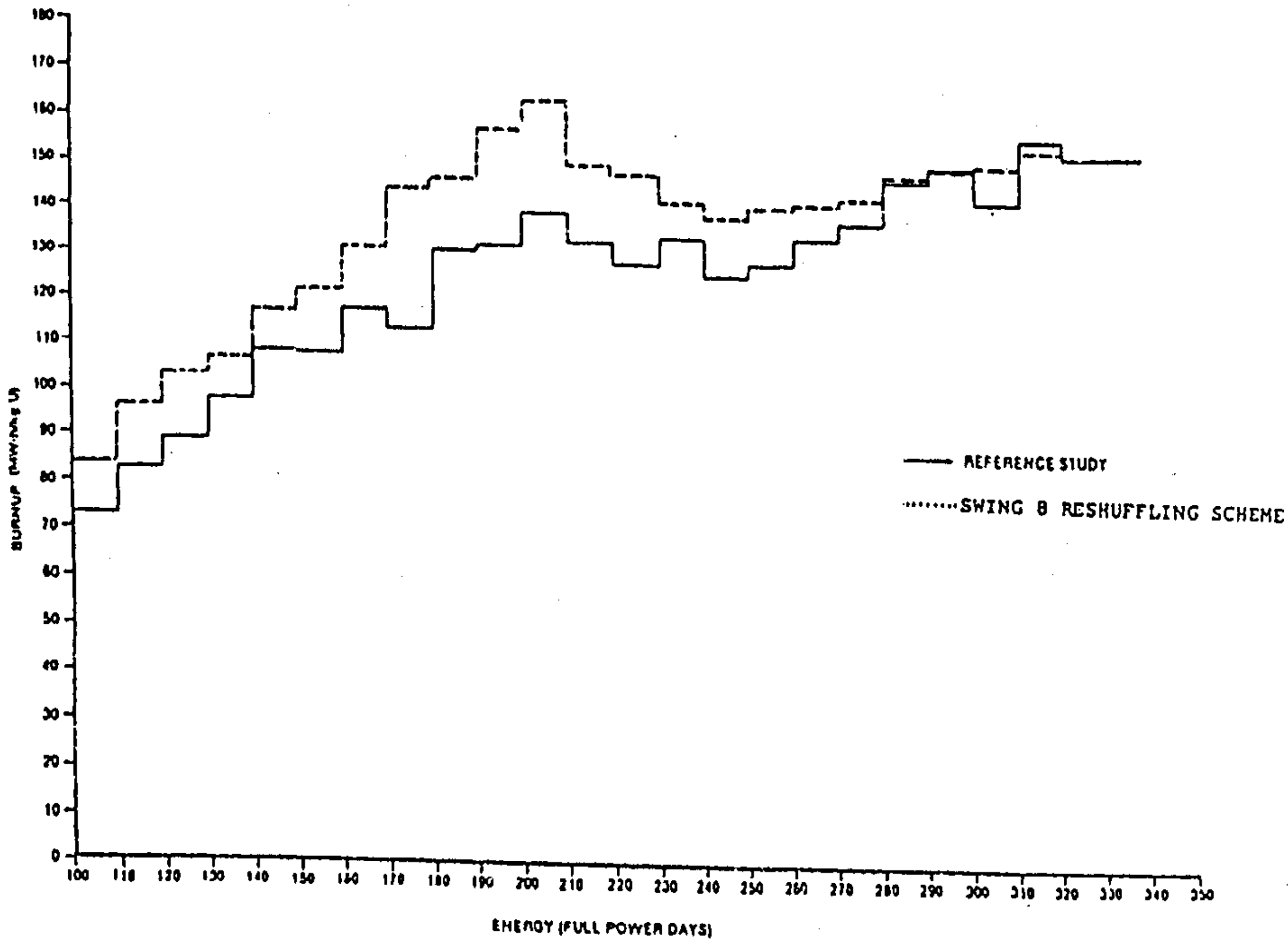


Figure 8-9: Average Discharge Burnup per 10 FPD Interval.

Fuel Reshuffling in the First Cycle (continued)

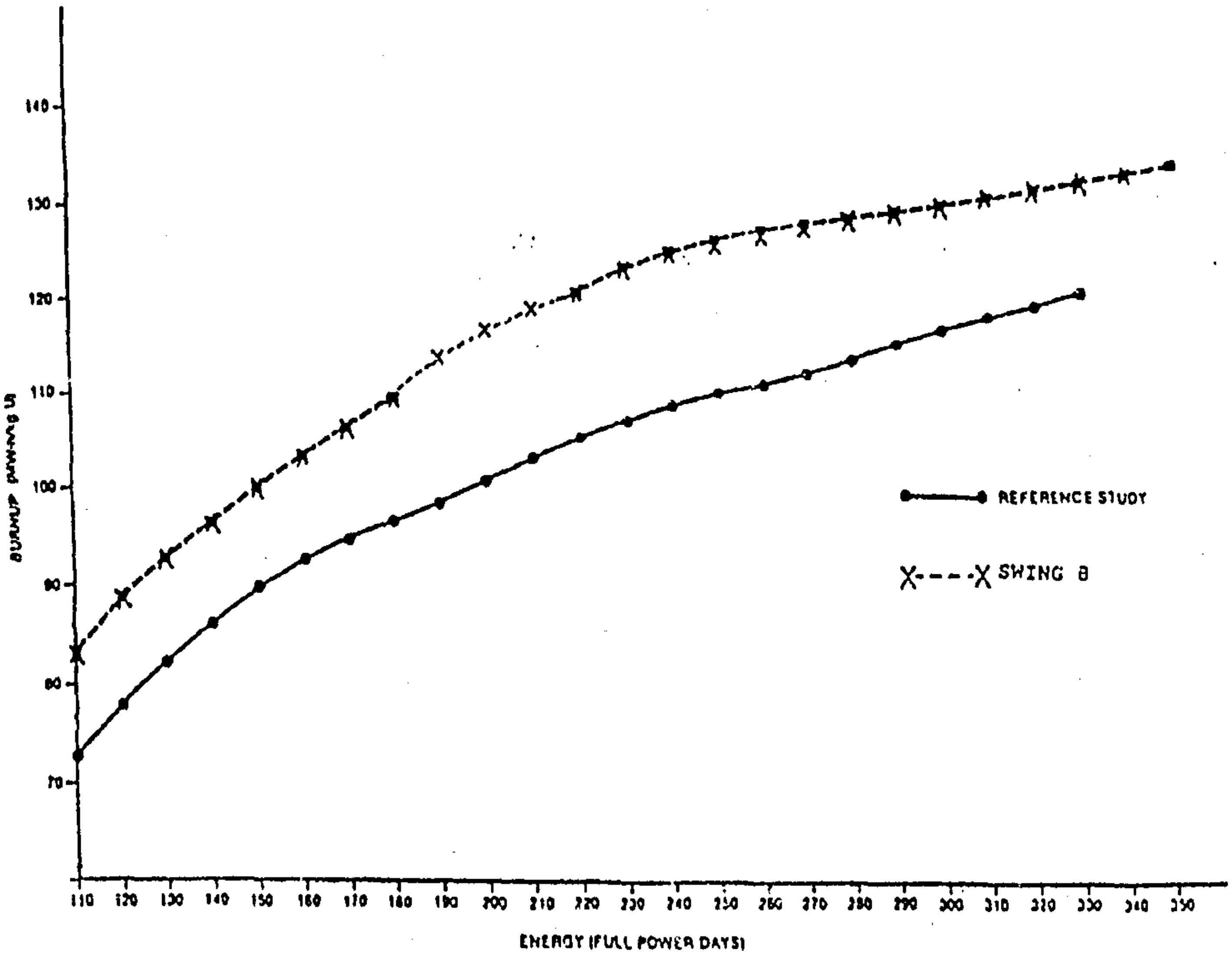


Figure 8-10: Cumulative Discharge Burnup.

Fuel Reshuffling in the First Cycle (continued)

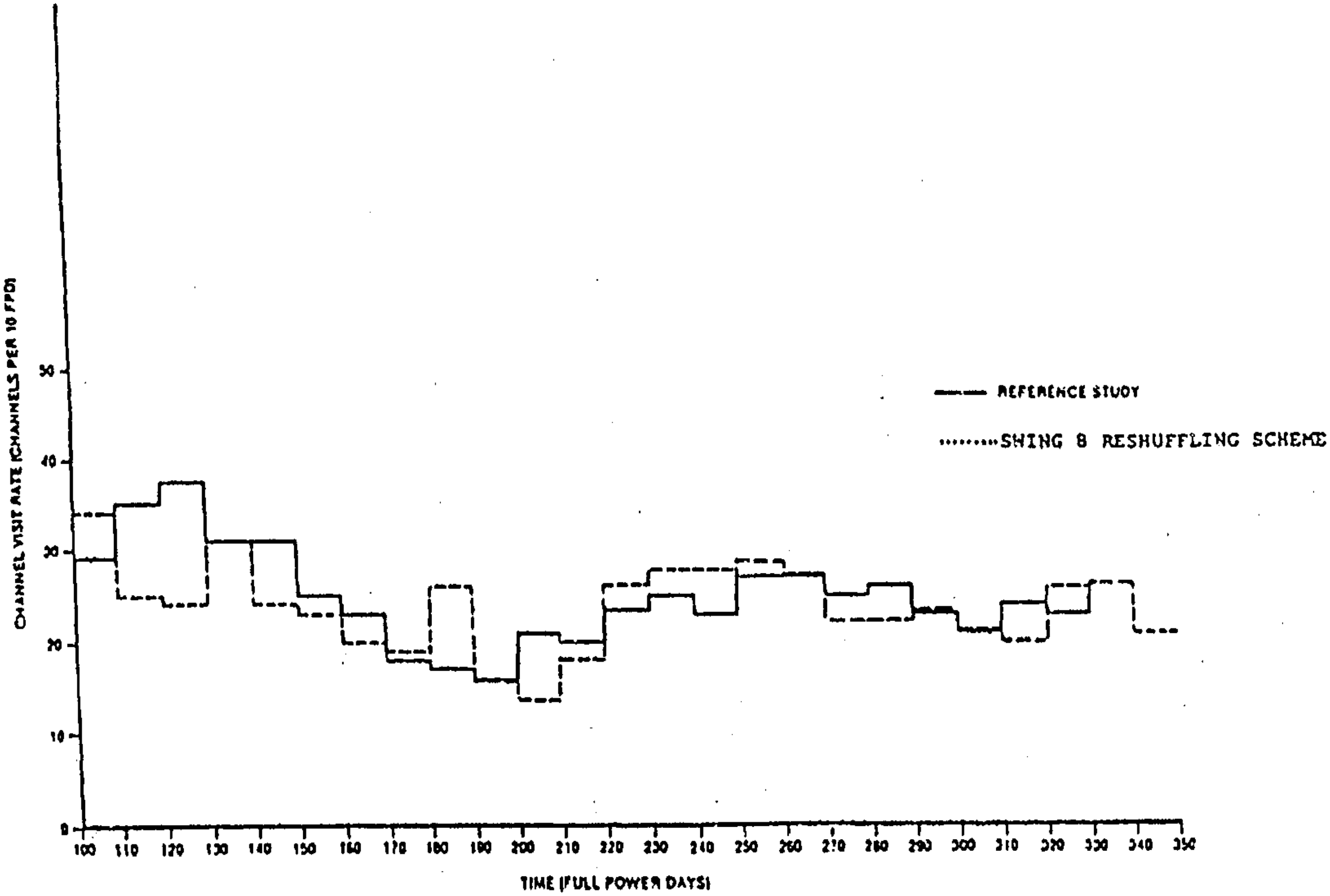


Figure 8-11: Fuelling Machine Visit rate per 10 FPD Interval.

Fuelling Machine Unavailability

- If refuelling were to stop, core reactivity would decrease (by about 0.4 mk/day in the CANDU 6 core).
- To maintain criticality, the regulating system would first tend to drain the liquid zone-control compartments to the lower limit of their control range.
- The operator would also ensure that any moderator poison which might exist at the time would be removed. These measures would normally permit continued operation at full power for several days.
- 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.
- However, as the adjuster rods are withdrawn the reactor power must be gradually reduced because of changes in the power distribution associated with adjuster rod withdrawal.
- In the unlikely event that the fuelling machine remains unavailable for several weeks, requiring most of the adjuster rods to be withdrawn, a significant change in the fuel burnup distribution, relative to the nominal equilibrium condition, would occur.
- When the fuelling machines become available, a greater than normal fuelling rate would probably persist until sufficient reactivity is provided to permit re-insertion of the adjuster rods and hence restoration of 100% power.
- The selection of channels for refuelling would be based on the burnup distribution existing when refuelling is resumed.