Chapter 4 of

Reference 2

IN-CORE FUEL MANAGEMENT

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4. IN-CORE FUEL MANAGEMENT

4.1 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 that in reactors which must be refuelled during shutdowns. Since power production is not interrupted for refuelling, it is not necessary to tailor the refuelling schedule to the utility's system load requirements. Excess reactivity requirements are at a minimum: only a few milli-k for control, and that needed for xenon override purposes need be provided. This leads to excellent neutron economy and low fuelling costs.

Several refuelling operations are normally carried out daily, so that fuelling is essentially continuous. By adjusting the fuelling rate in the various core regions, the power distribution in these regions can be effectively controlled over a time scale of the order of weeks.

The fuel is in the form of short bundles contained in a pressure tube or "channel". To refuel a channel, a pair of fuelling machines latch onto each end of the channel. New fuel bundles are inserted at one end, old fuel is pushed along the channel, and spent fuel is discharged into the other machine. Typically, four or eight fresh bundles are added at each fuelling. Figure 4.1 illustrates the 8-bundle-shift scheme, where the eight bundles near the outlet end of the channel are discharged, and the four bundles previously at the inlet end are moved 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.

4.2 Objectives

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:

a) 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.

b) The core power distribution must be controlled to satisfy safety and operational limits on fuel and channel powers.

c) The fuel burnup is to be maximized within the operational constraints, to minimize the fuelling cost.

d) Fuel defects are to be avoided. This minimizes replacement fuel costs and radiological occupational hazards.

e) The fuel-handling capability must be optimized. This minimizes capital, operating and maintenance costs.

4.3 Periods During Operating Life

From the point of view of fuel management, the operating life of a CANDU reactor can be separated into three periods.

The first period is from first criticality until onset of fuelling. It is of limited duration, usually about 100 to 150 full power days (FPD). The reactor is initially loaded with all fresh fuel (except for some depleted bundles as explained in Section 4.3.1). Consequently, there is considerable excess reactivity, which is compensated by adding boron poison to the moderator. Fuel-management calculations are required to assess the effect of the initial fuel loading on the subsequent power operation.

When the excess reactivity in the core falls to a small value, fuelling begins in order to maintain the reactor critical. During this transitional or "pre-equilibrium" period, the reactor gradually approaches the final or "equilibrium" state.

The equilibrium condition in a CANDU reactor is reached after approximately 400 to 500 FPD. It is characterized by a relatively unchanging core configuration in which the macroscopic or global power and burnup distributions do not vary significantly with time. The burnup of the discharged fuel, and the fuelling rate of new fuel, become essentially constant.

The equilibrium period covers about 95 percent of the reactor life. It is by far the most important period in determining the total unit energy cost. Most fuel management studies are therefore performed for this core configuration.

4.3.1 Initial Fuel Load and Transient to Onset of Fuelling

At equilibrium, the CANDU reactor power distribution is flattened by a combination of adjuster rods and differential burnup. When starting with all fresh fuel, however, the central region power would be unacceptably high unless some additional means of flattening in the absence of differential burnup is provided. This is achieved typically by placing two depleted fuel bundles in each channel in the central region of the core.

Depleted fuel refers to fuel having a lower U-235 content than natural fuel (which contains 0.72 atom percent of U-235 in the uranium metal component). Figure 4.2 shows the reactivity variation with burnup for natural fuel and for depleted fuel having a U-235 content of 0.52 atom percent. The reactivity rises initially because of plutonium buildup as irradiation proceeds. Thus, it is necessary to simulate operation past the plutonium peak to ascertain the actual best loading. The optimum depleted-fuel loading is obtained by simulating reactor operation from startup to onset of fuelling, for various initial loadings (i.e. amount of depletion and positions of depleted-fuel bundles).

In the CANDU 6, the initial fuel optimization process led to specifying two bundles in each of the central 80 fuel channels, as shown in Figure 4.3. The bundles were located in positions 8 and 9 (the bundle positions in the channels are numbered from 1 to 12 in the direction of fuelling). The optimum U-235 content was found to be 0.52 atom percent. With this initial fuel loading the variation of excess reactivity with time is shown in Figure 4.4. Note that the excess reactivity initially increases from about 16 mk to 23 mk at the plutonium peak. Figures 4.5, 4.6 and 4.7 show representative power distributions in the horizontal radial direction at zero irradiation, at 40 FPD, and at 100 FPD respectively.

The main feature to be noted is that "dishing" of the power distribution, which is rather pronounced at 0 FPD, flattens out with increasing fuel burnup. The maximum bundle power correspondingly decreases as burnup increases.

4.3.2 *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.

At this stage, refuelling of outer region channels begins. In this region, channel burnup decreases with increasing radius (i.e. decreasing power). Therefore, the 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.

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. For example, if for a few days only the outermost channels are being refuelled, a very high rate (almost 6 channels per day for the CANDU 6) would be required to keep up with the reactivity loss, since these channels are worth somewhat less than a central channel. It is not possible for the fuelling machines to maintain this rate, so that outermost channel fuelling has to be intermingled with high-worth, inner-region channels, or postponed to some convenient time. Fortunately, this region does not have to be visited very often - about 4 or 5 times a month on the average.

Figure 4.8 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. The corresponding maximum channel and bundle power variations obtained in the simulation are shown in Figures 4.9 and 4.10.

4.3.3 Equilibrium Fuel Management

Although fuelling rates quickly approach equilibrium values, an equilibrium burnup distribution is attained after about 500 FPD. Because of this, 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. Thereafter, 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.

4.3.3.1 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. However, 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 4.11. This distribution is calculated using averaged fuel parameters at each bundle location in the core. The power distribution for a typical reactor with channel-to-channel burnup variations shows channel power "ripple" effects of around 10% about the time-averaged power. Recently fuelled channels tend to have the highest powers and channels near maximum burnup tend to have the lowest powers.

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. Thus, 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, however, 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.

4.3.3.2 Control of Azimuthal Power Distribution

In addition to controlling the radial power distribution, it is desirable to maintain the power distribution fairly uniform azimuthally. In principle, this could be fairly easily accomplished by always fuelling exactly symmetrically so that each quadrant of the core is identical. In practice this is often not possible. For example, a defective fuel bundle occurring anywhere in the core would be removed soon after it was detected, possibly rendering the core asymmetric. In addition, the core has structural components (guide tubes, etc.) which are not necessarily symmetrically arranged. 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 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 4.11. 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.

4.3.3.3 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. However, 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. Thus, 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, shown in Figure 4.1, is the reference fuel-management scheme for the CANDU 6. It is called the standard 8-bundle-shift fuelling scheme.

4.3.4 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:*

a) highest burnup to minimize fuelling costs,

b) power distribution to be controlled so that axial, radial and azimuthal symmetry is maintained and the distribution remains close to the reference power shape,

c) maximum separation between fuelled channels to avoid hot spots, and

d) high reactivity gain.

4.4 Fuel Management Calculations

4.4.1 The RFSP Code

RFSP is a computer program used to perform fuel management calculations for CANDU reactors. The program solves the two-group three-dimensional diffusion equations by a finite difference iterative technique using cell-centre fluxes. It is capable of generating nominal bundle and channel power distributions and simulating reactor operations, including refuelling and burnup steps.

Some of the features of the code are:

a) It allows variable mesh spacings. That is, the grid for the flux calculations can be selected by the user to fit the requirements of the problem without being limited by the positions of the fuel bundles in the core.

b) It can use, at any boundary, extrapolated boundary conditions (where the flux extrapolates to zero at a specified distance from the boundary) or symmetric boundary conditions (where the boundary acts as a "mirror").

c) It is of modular design. That is, each element which has a distinct function is a separate entity with well defined input and output. This makes the code flexible and easy to modify. Similarly, the data are organized in blocks according to function and type.

Three-dimensional core models similar to the one illustrated in Figures 4.13(a) and 4.13(b) are used in RFSP. Depending on the requirement of the problem, symmetry can be used to reduce the cost of a calculation.

Reactivity devices and structural materials are represented by incremental cross-sections which are added to the fuel cross-section of the affected lattice cells. These incremental "supercell" cross-sections are calculated separately by suitable programs. Typical models have from 5,000 to 40,000 mesh points depending on the requirements of the problem.

4.4.2 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.

4.4.2.1 Homogeneous Calculations

This is the simplest procedure and is based on the continuous bi-directional 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.

4.4.2.2 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 Σ 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 $\Delta\omega = \omega_2 - \omega_1$. $\bar{\Sigma}$ will 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 $\Delta\omega_k$, 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.

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

$$T = \frac{N\ \overline{\omega}_{out}}{\sum_k \phi_k}$$

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 4.14 illustrates this argument with an example of an eight-bundle- shift scheme in a twelve-bundle core. Thus,

$$\Delta\omega_k = \phi_k \frac{N\ \omega_{out}}{\sum_k \phi_k}$$

Note that the fluxes on the right hand side are also the time-average fluxes (to be determined). An iterative procedure must therefore be 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.

Two other types of calculations are also performed, one to provide the realistic average maximum bundle and channel powers, and the other to simulate reactor operating history.

4.4.2.3 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, P_{max}.

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. The main reason is that the random selection of channel ages may place several channels of the same age together whereas a station fuelling engineer avoids fuelling adjacent channels at the same time, especially in the high power region. However, this shortcoming may be eliminated to a large extent by using a more reasonable fuelling pattern than by random fuelling.

4.4.2.4 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:

a) to select channels for refuelling;

b) to ensure that channel and bundle powers are kept within specified limits; and

c) for burnup evaluation.

4.5 Miscellaneous Calculations

4.5.1 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 (see Section 2.8).

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.

From the point of view of fuel management, the ROP system presents two problems:

a) 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 we shall discuss in Section 4.5.2.

b) 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.

4.5.2 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:

a) discharge burnup,

b) maximum channel power and channel power peaking factor,

c) fuelling machine usage, and

d) 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.

4.5.2.1 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.

4.5.2.2 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 we have seen in Section 4.5.1, 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 (e.g., Ontario Hydro Bruce A and B reactors).

4.5.2.3 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.

4.5.2.4 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.

4.5.3 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:

a) changes in the concentration of fissionable isotopes,

b) movements of the fuel in the channel during refuelling,

c) perturbations in the flux due to manoeuvring of reactivity devices, fuelling of neighbouring channels, or xenon transients, and

d) changes in total reactor power due to normal power manoeuvring (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 "envelops" all possible individual bundle histories and includes all the changes in fuel power due to the effects listed above. Clearly, 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.

4.6 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 4.16.

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 in Table 4.1. 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.

4.7 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.

4.8 Cobalt-60 Production

Cobalt-60 is a radioactive isotope of cobalt. It emits gamma radiation and is used world-wide in radiation therapy and radiographic equipment.

Cobalt-60 production in the CANDU reactors is achieved by using adjuster rods made of cobalt.

Adjuster rods are normally positioned inside the reactor core and fulfil the following basic functions:

a) they provide, on withdrawal, positive reactivity to override the growth of xenon poison immediately after a power reduction or a shutdown, or to compensate for core reactivity decay during operation without refuelling.

b) they provide the desired flux and power flattening by appropriate distribution of absorption strength in the various rods.

The neutron absorption required in the adjuster design has been provided in the CANDU reactors by using either cobalt or stainless steel. The Pickering 'A' reactors operated with cobalt adjusters for over a decade. Of the four CANDU 6 reactors, Point Lepreau and Wolsong are equipped with stainless steel adjusters, whereas Cordoba has cobalt adjusters, and G-2 operated for some time with cobalt adjusters.

Cobalt adjusters consist of cobalt "bundles" placed in Zircaloy tubes. These bundles are ~8" long and ~$2^1/_2$" in diameter. Each bundle has one to six "pencils" equidistantly located on a pitch circle of ~2" diameter. Each pencil in turn is a Zircaloy tube containing cobalt slugs or pellets. The adjusters are irradiated in the reactor for a period of about $1^1/_2$ years before replacement.

Typical Cobalt-60 production in a CANDU reactor is ~ 5.5 MCi per year, with a specific activity of 80 Ci/g after one year of operation at 80% capacity factor.

4.9 Fuel Burnup Warranties

There are three distinct types of fuel burnup warranties which have been offered and negotiated for the CANDU 6 reactors. In each case, the warranted value is related to a set of well defined reactor operating conditions. A procedure is written, and mutually agreed upon with the client, according to which the warranty demonstration test is to be performed and various corrections are to be calculated to account for differences in actual operating conditions and the conditions stated in the warranty. The procedure specifies the measurements to be performed during the warranty demonstration test period including recording of various operating conditions.

Following is a brief description of the three types of fuel burnup warranty.

4.9.1 Specific Fuel Consumption Warranty

In this type, the warranted value is the amount of fuel consumed per unit of thermal energy produced after equilibrium fuel conditions have been established. The duration of the warranty demonstration test is 150 FPD. During this period, the amount of steam produced at the steam generators is measured along with the number of fuel bundles added to (or discharged from) the reactor core. A record of various operating conditions is carefully maintained. The measured specific fuel consumption is corrected to account for differences in actual operating conditions and the conditions specified in the warranty. The corrected specific consumption is compared with the warranted value to demonstrate compliance.

4.9.2 Initial Fuel Load Warranty

In this type, the warranted value is the thermal energy produced by the first 4560 fuel bundles discharged (equal to the number of fuel bundles in the initial load). Since the energy produced by these bundles cannot be measured directly, this type of warranty requires RFSP computer simulations to calculate the energy produced by each individual bundle. A careful record of operating conditions is again maintained and the information is used either directly in the computer simulations or suitable corrections are applied to the results obtained in the simulations. Compliance with the warranty is demonstrated by comparing the corrected value with the warranted value.

4.9.3 Nuclear Characteristics Warranty

The warranted value in this warranty is the boron concentration required to keep the reactor just critical at first criticality. The nuclear characteristics of any nuclear reactor determine the excess reactivity of the core when loaded with unirradiated fuel. In CANDU reactors, this excess reactivity can be determined by measuring the boron concentration required in the moderator at first criticality. The excess reactivity from that point on depends primarily on the power history and fuel management program. In CANDU reactors, where on-line refuelling is the primary means of reactivity control, the excess reactivity is kept near zero after refuelling starts by refuelling at an appropriate rate. Following a transitional period, the refuelling reaches an equilibrium state where the refuelling rate is constant provided the characteristics of the non-fuel core components are unchanged. The refuelling rate is then dependent on the nuclear characteristics of the core only. There is, therefore, a direct relationship between the initial boron concentration in the moderator and the achieved equilibrium fuelling rate and hence equilibrium fuel burnup in CANDU reactors.

An obvious advantage of this type of warranty is that it can be discharged immediately after the reactor is started up and detailed measurements over an extended period are not required.

Table 4.1
Summary of Results

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

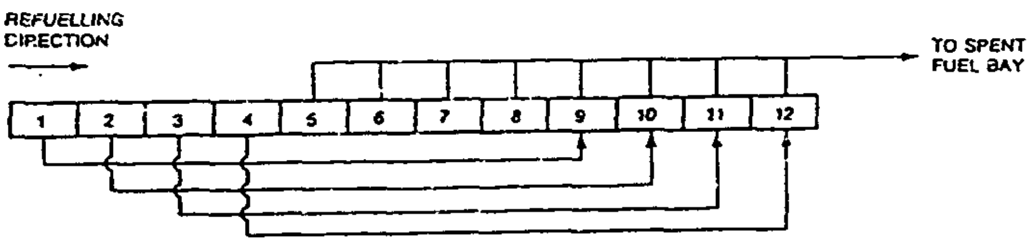

Figure 4.1 Standard 8-Bundle-Shift Refuelling Scheme

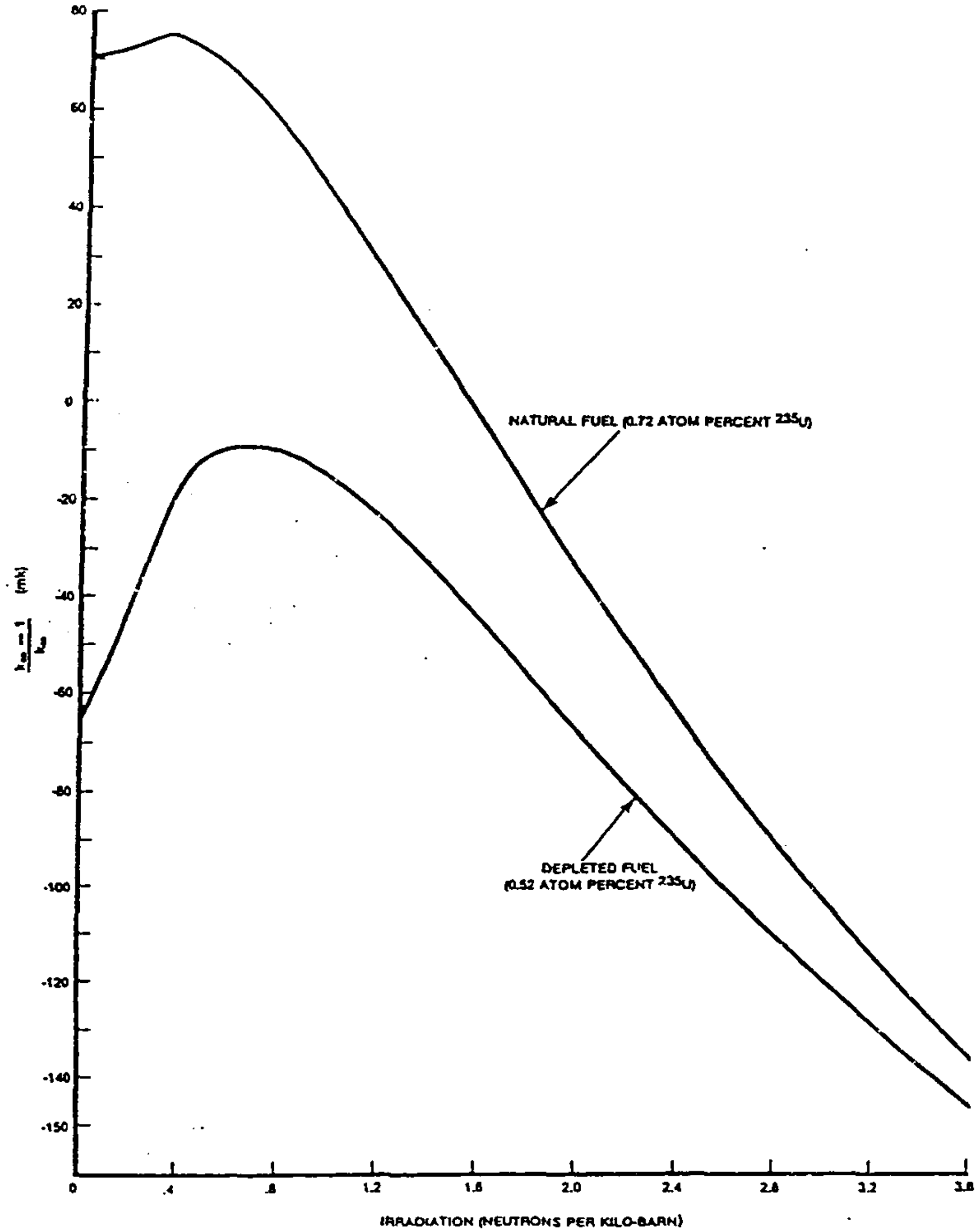

Figure 4.2 Reactivity versus Irradiation of Natural and Depleted 37-Element Fuel

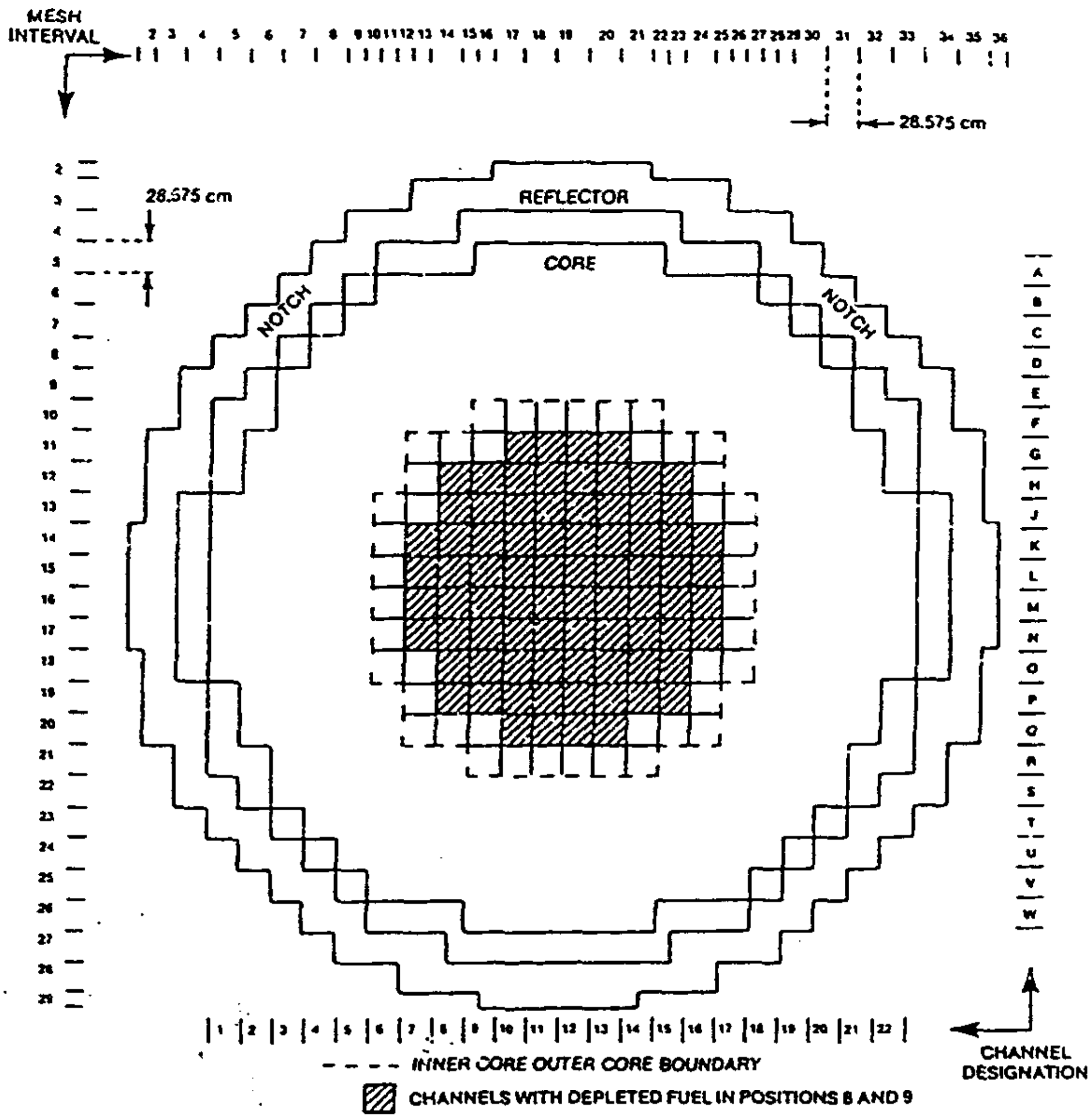

Figure 4.3 600 MW Reactor Model Face View Showing Initial Loading of Depleted Fuel

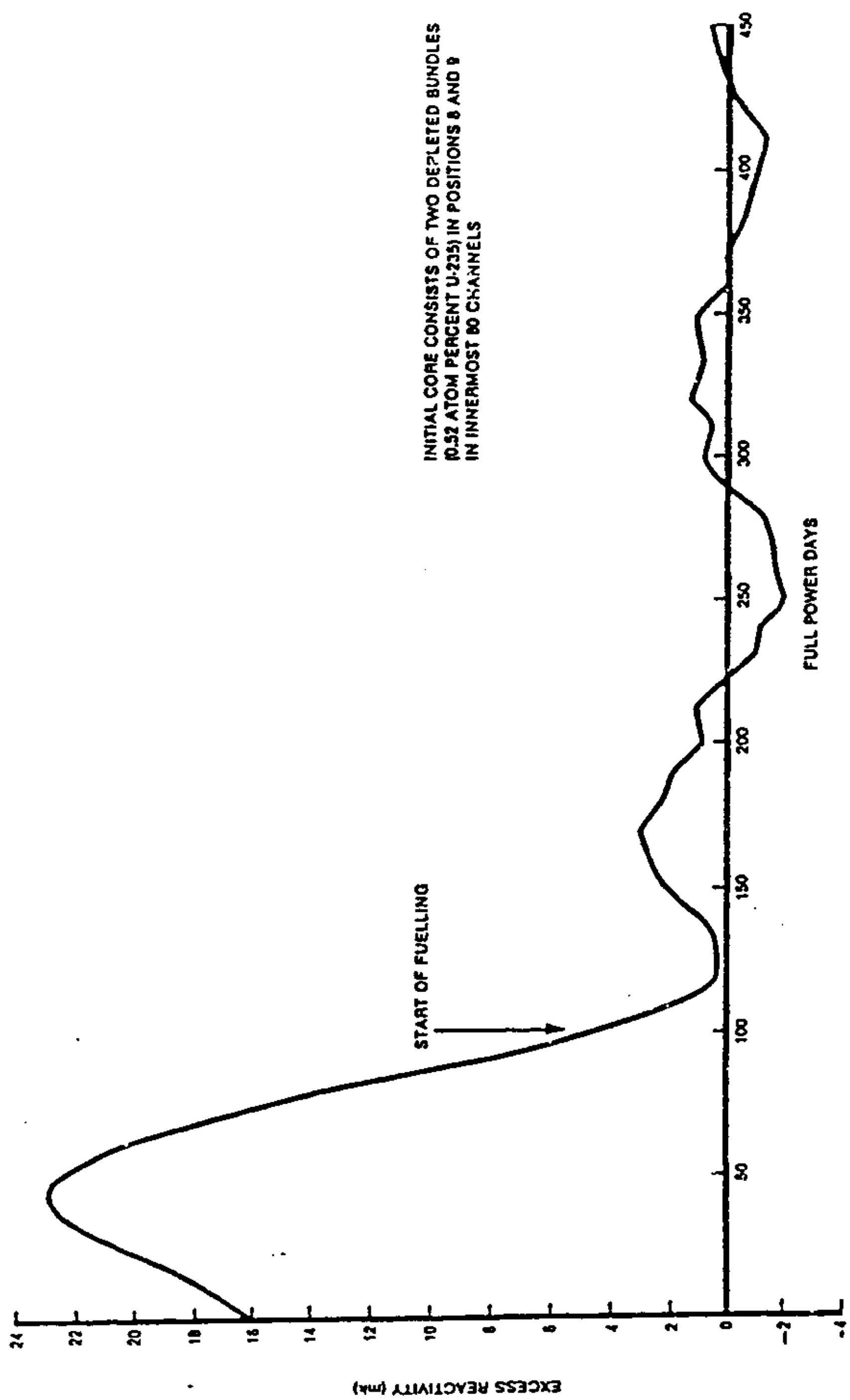

Figure 4.4 Variation of Excess Reactivity During Initial Burnup Period (FMDP Simulations)

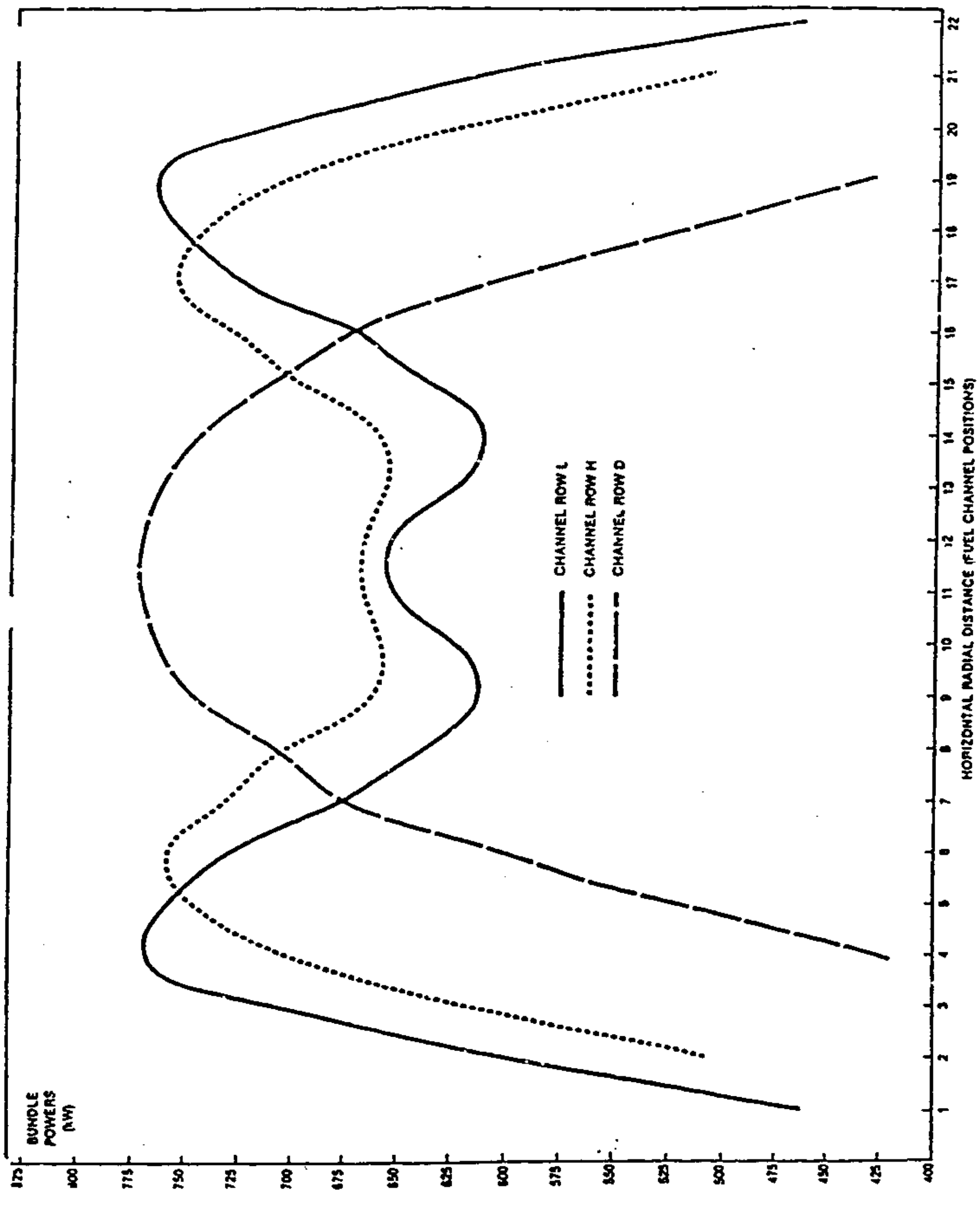

Figure 4.5 Horizontal Radial Bundle Power Distribution at 0 FPD

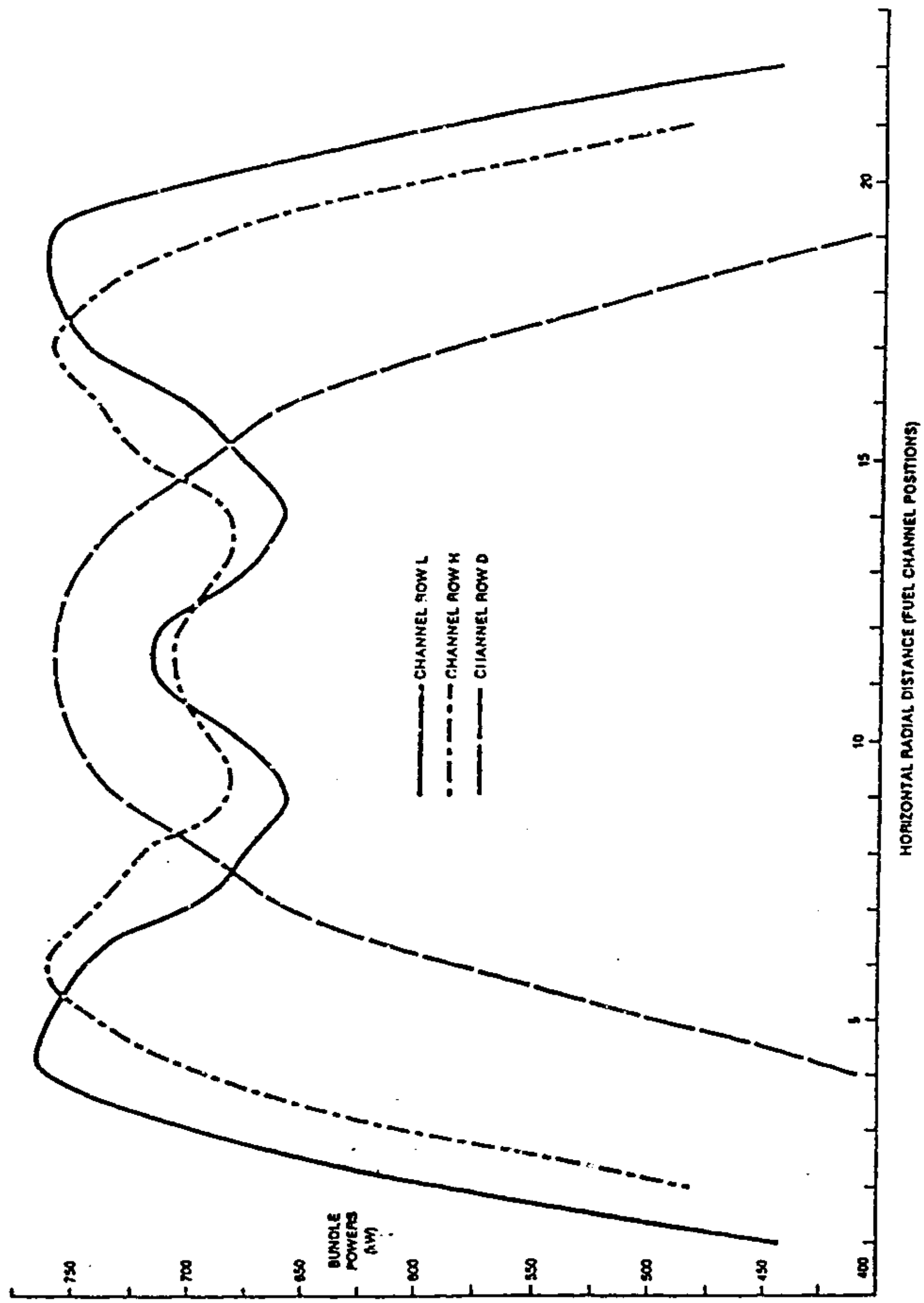

Figure 4.6 Horizontal Radial Bundle Power Distribution at 40 FPD

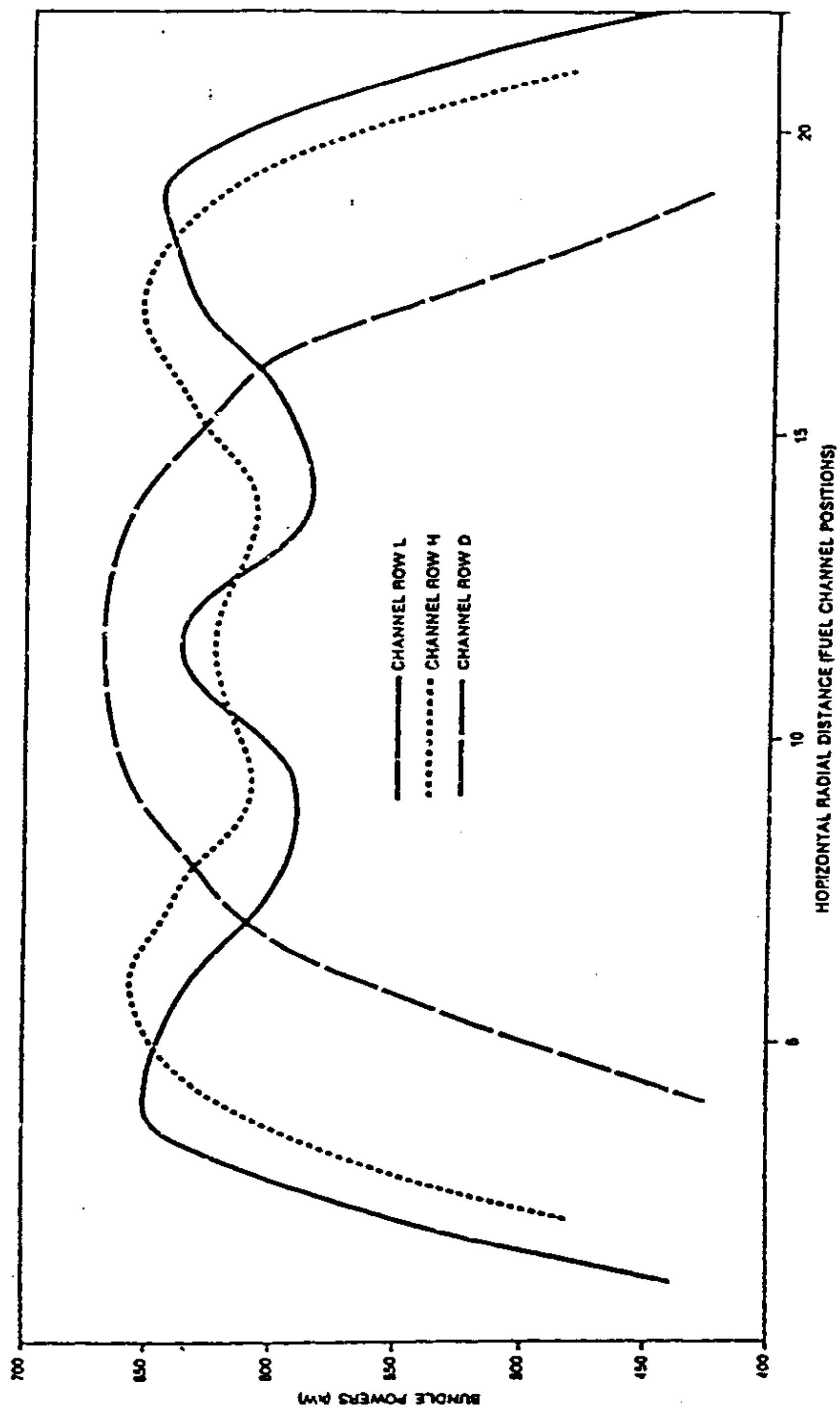

Figure 4.7 Horizontal Radial Bundle Power Distribution at 100 FPD

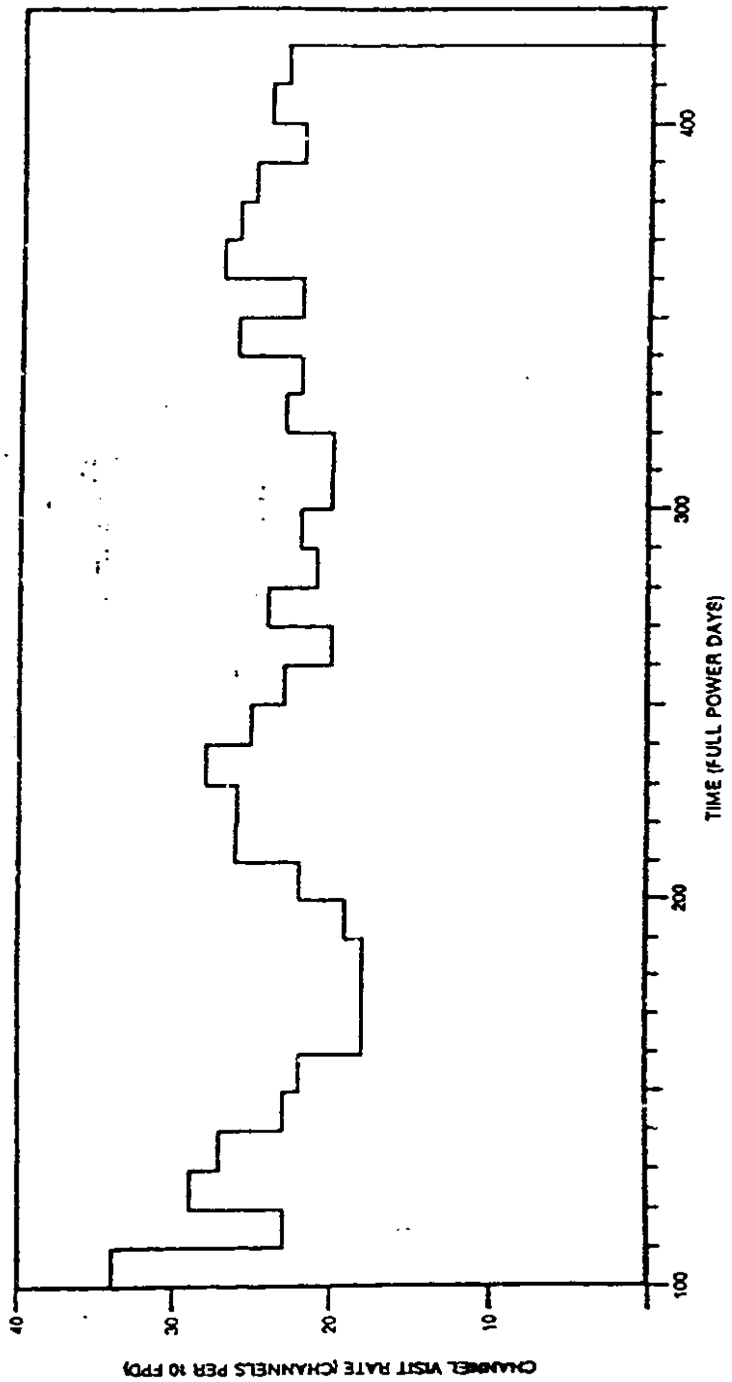

Figure 4.8 Fuelling Machine Visit Rate per 10 FPD Interval

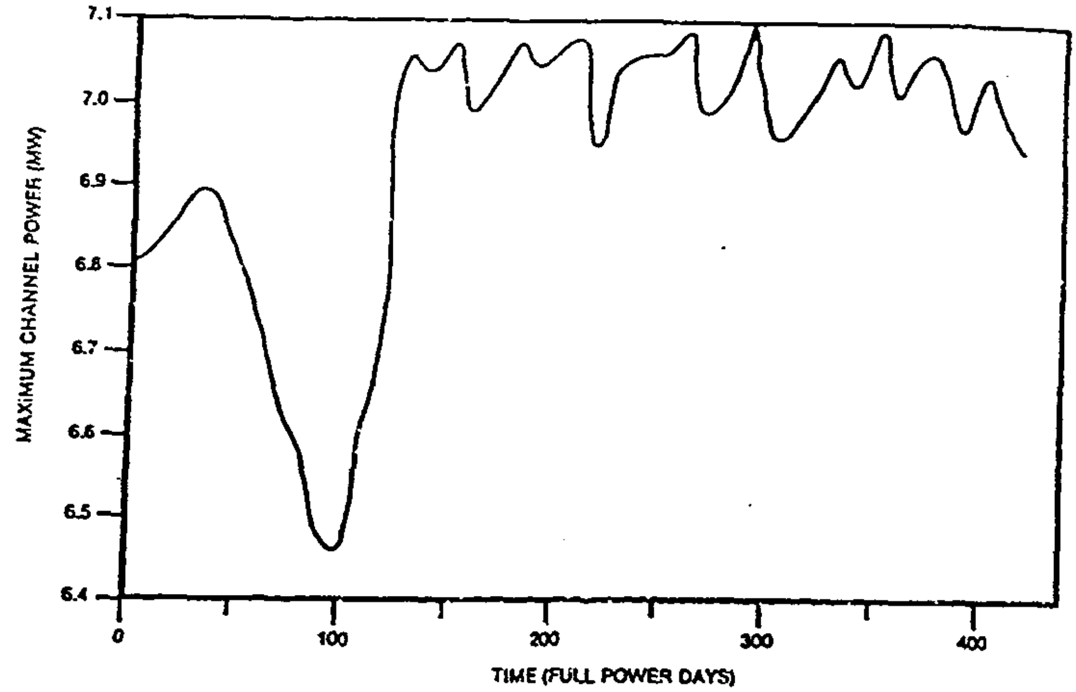

Figure 4.9 Maximum Channel Power

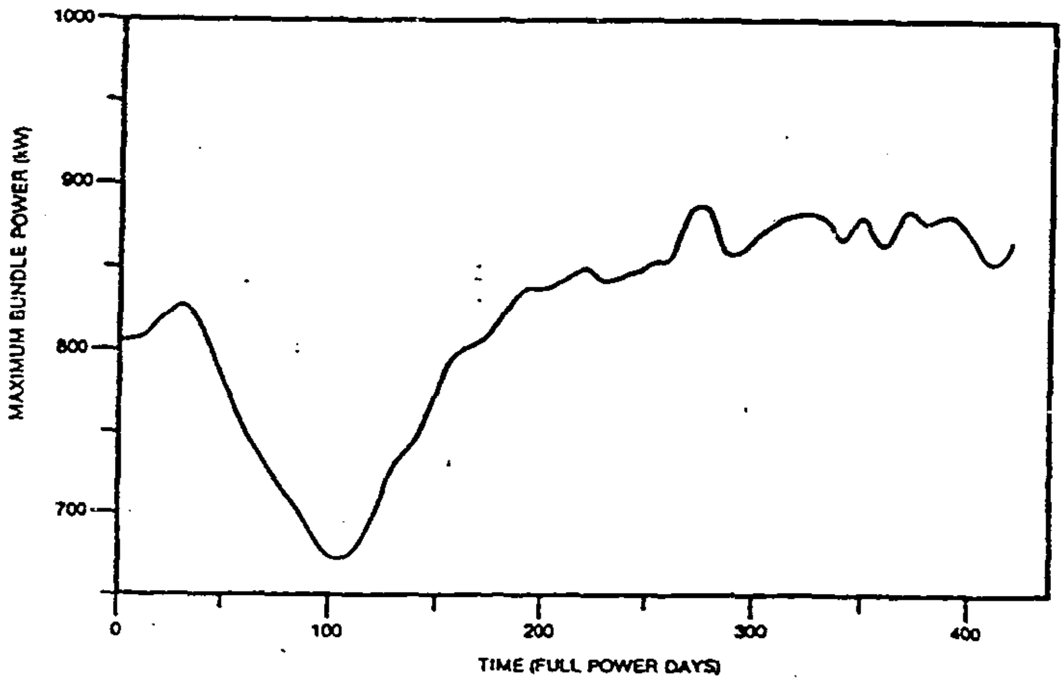

Figure 4.10 Maximum Bundle Power

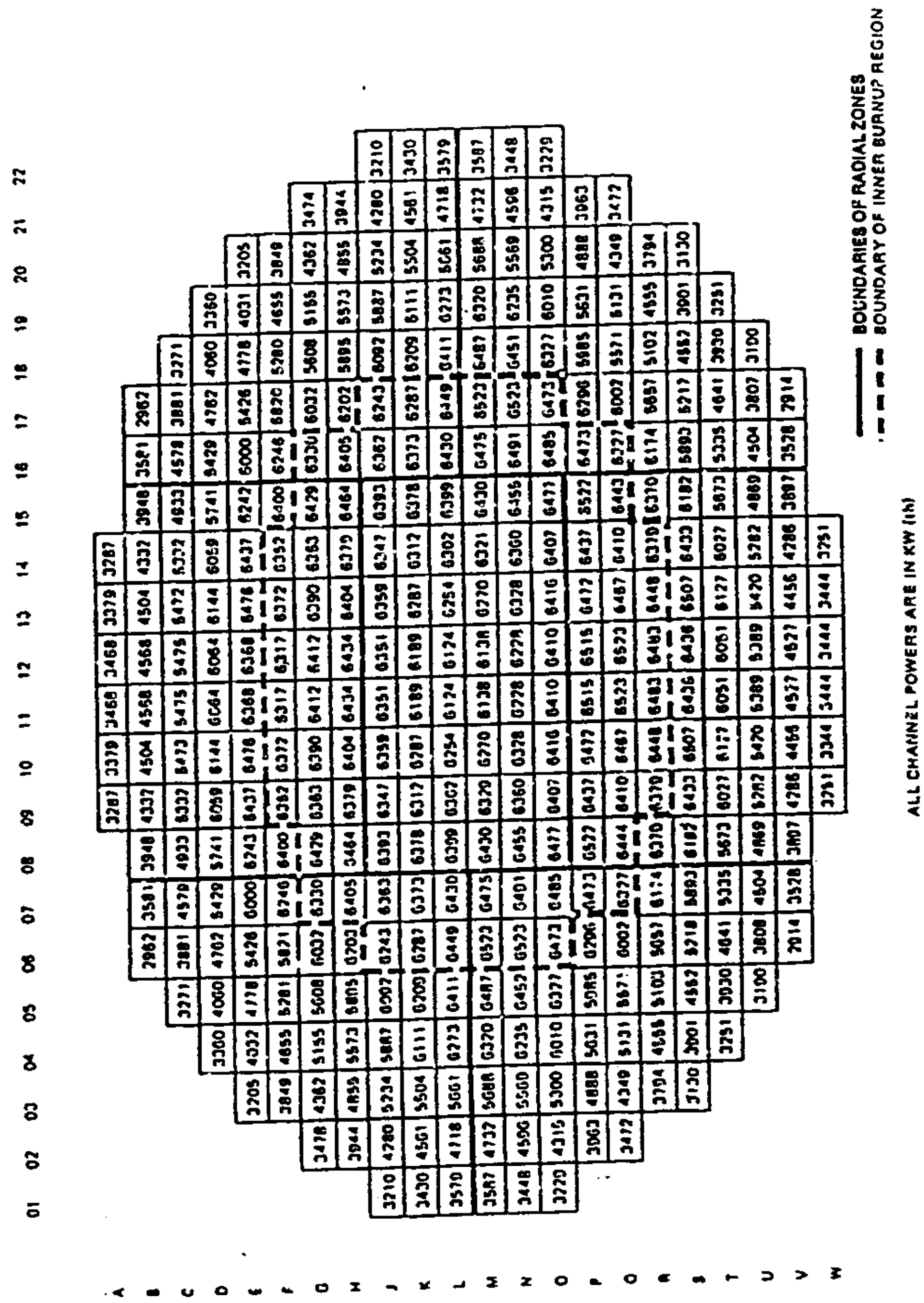

Figure 4.11 Time Average Channel Powers

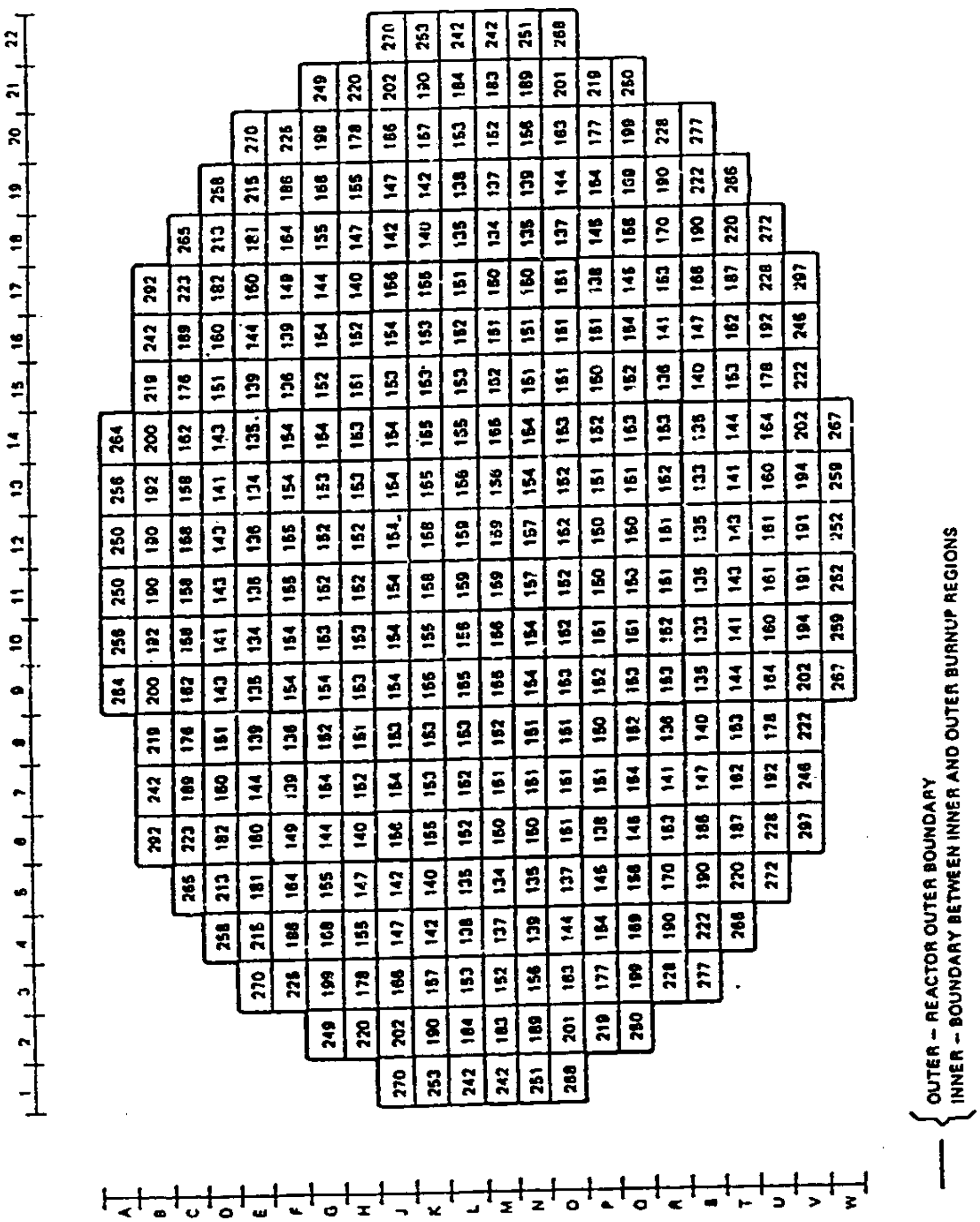

Figure 4.12 Average Channel Dwell Times in Full Power Days (based on time-average calculation)

MESH SPACINGS

X DIRECTION:

MESH NUMBER(S)	DIMENSION
1,37	0 cm
2,36	11.375 cm
3-8,14 17-21,24 30-35	28.575 cm
9-13,15,16 22,23 25-29	14.2875 cm

Y DIRECTION:

MESH NUMBER(S)	DIMENSION
1,30	0 cm
2,29	11.375 cm
3-28	28.575 cm

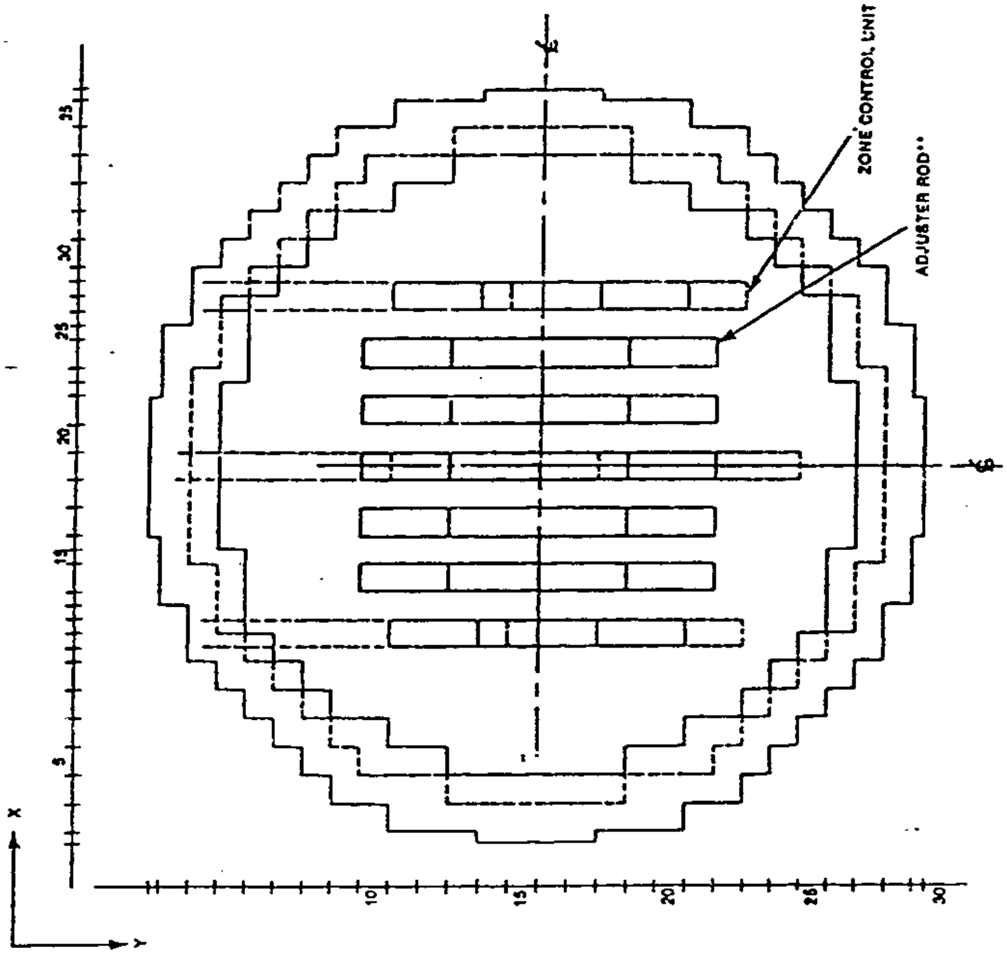

Figure 4.13(a) CANDU 6 Full Core Model (x-y Direction)

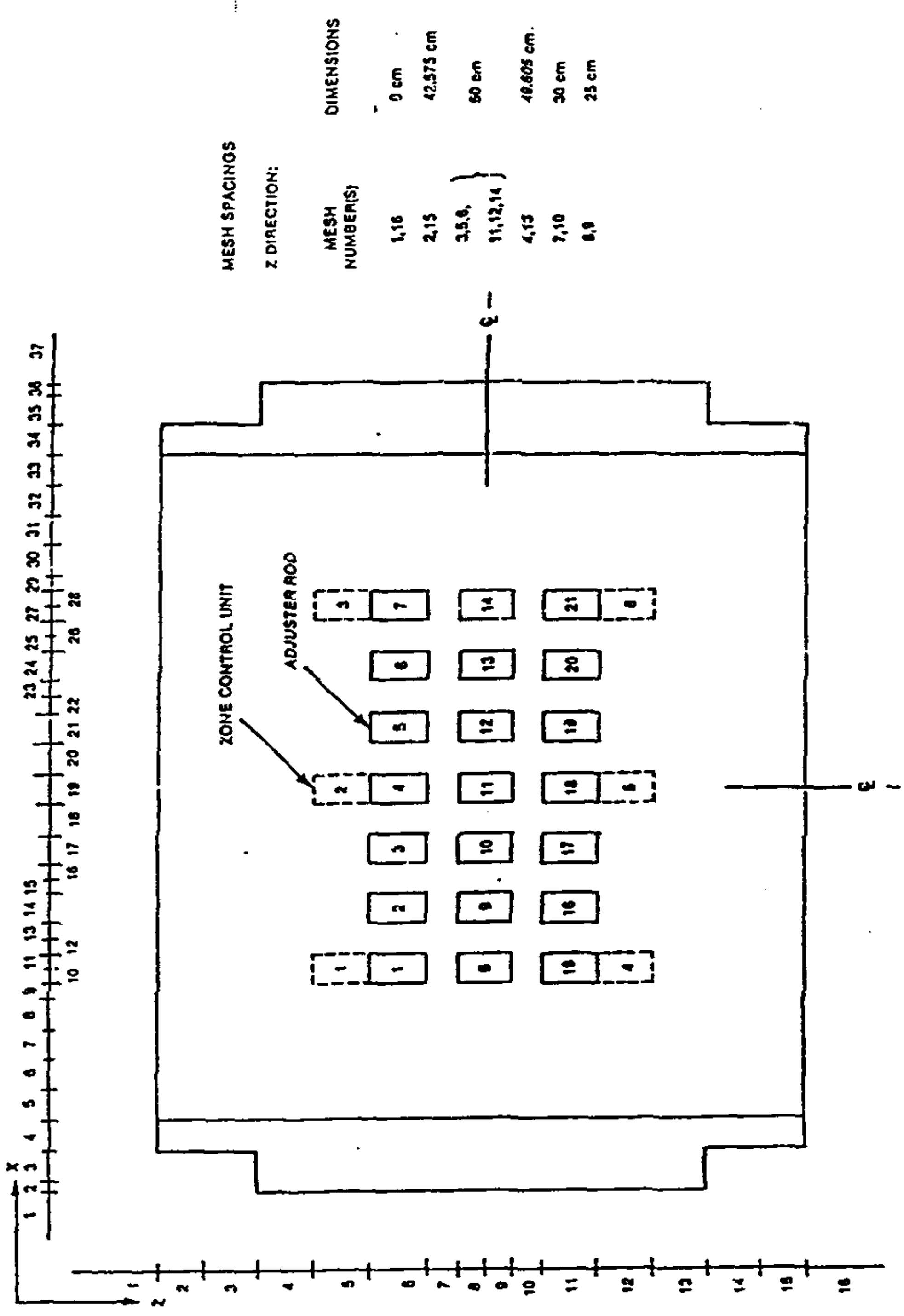

Figure 4.13(b). CANDU 6 Full Core Model (x-z Direction)

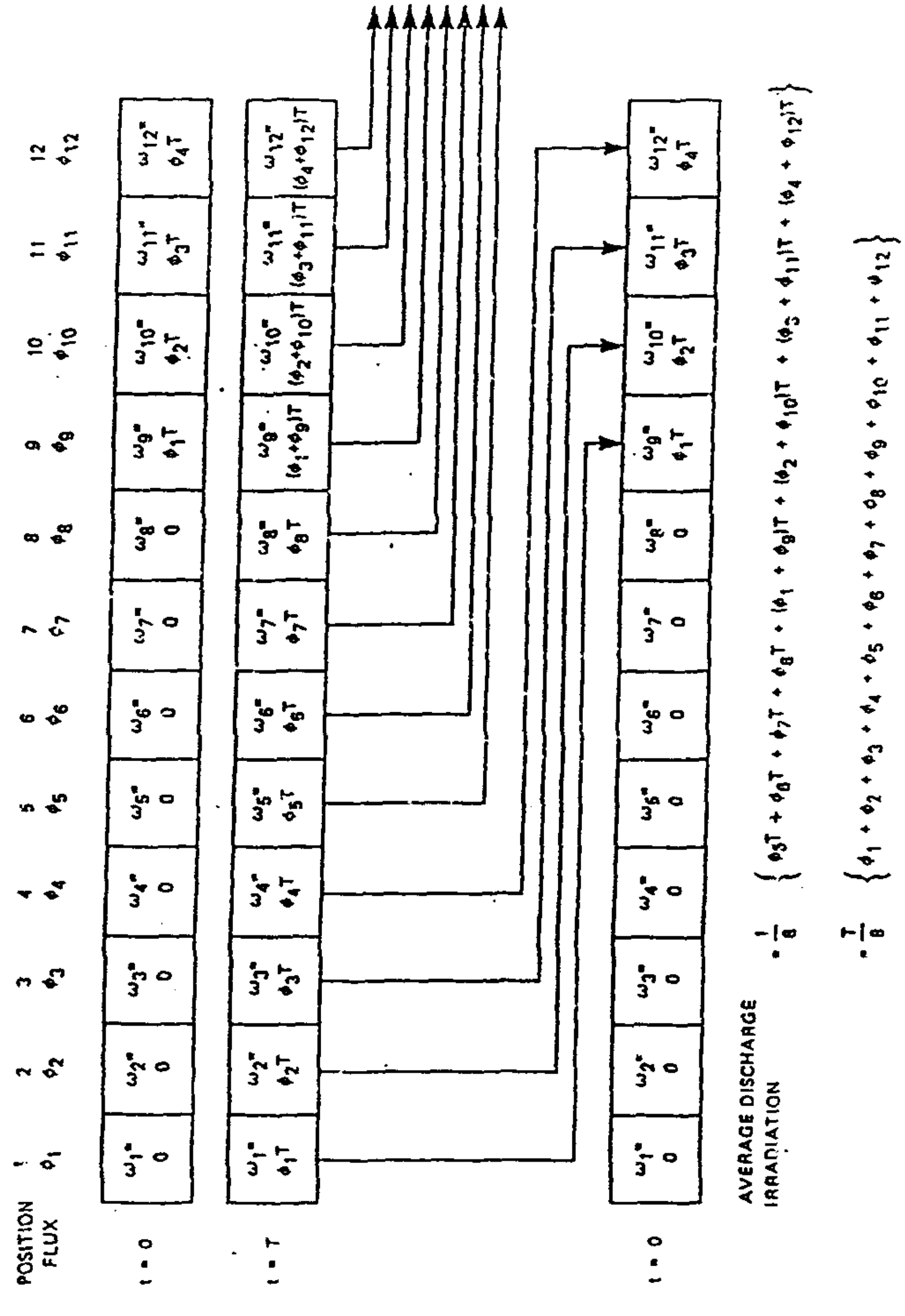

Figure 4.14 Time-Averaged Eight-Bundle Shift

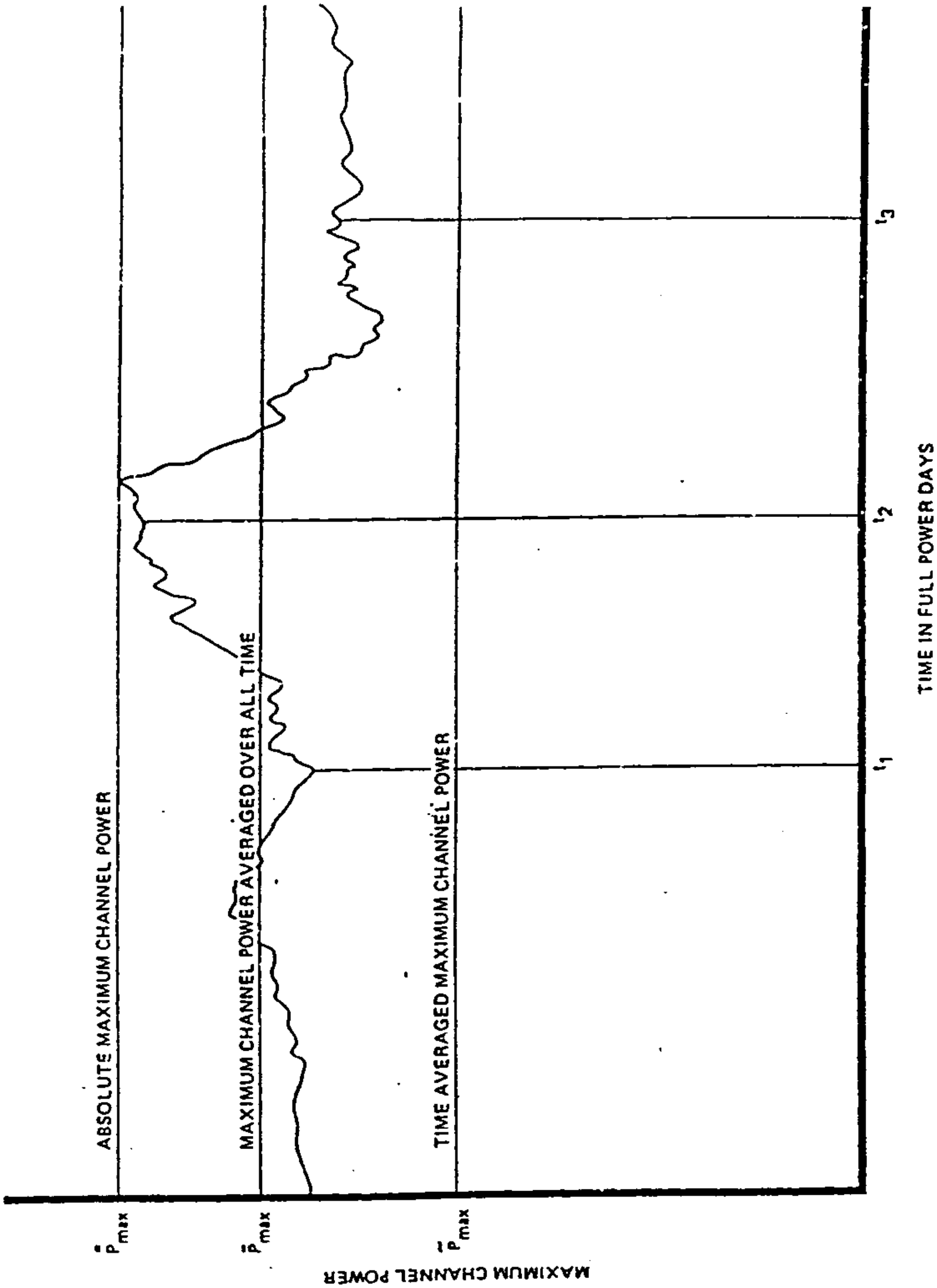

Figure 4.15 Segment of Typical Operation History

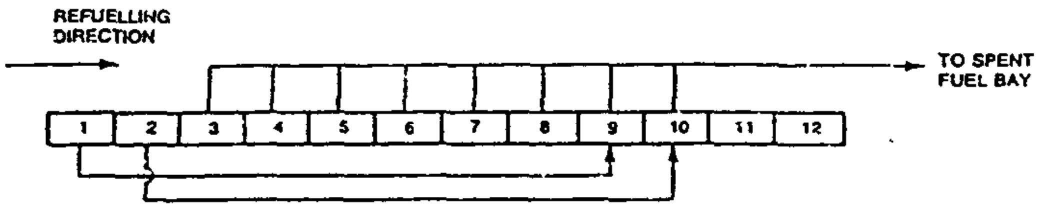

Figure 4.16 Swing-Eight Refuelling Scheme

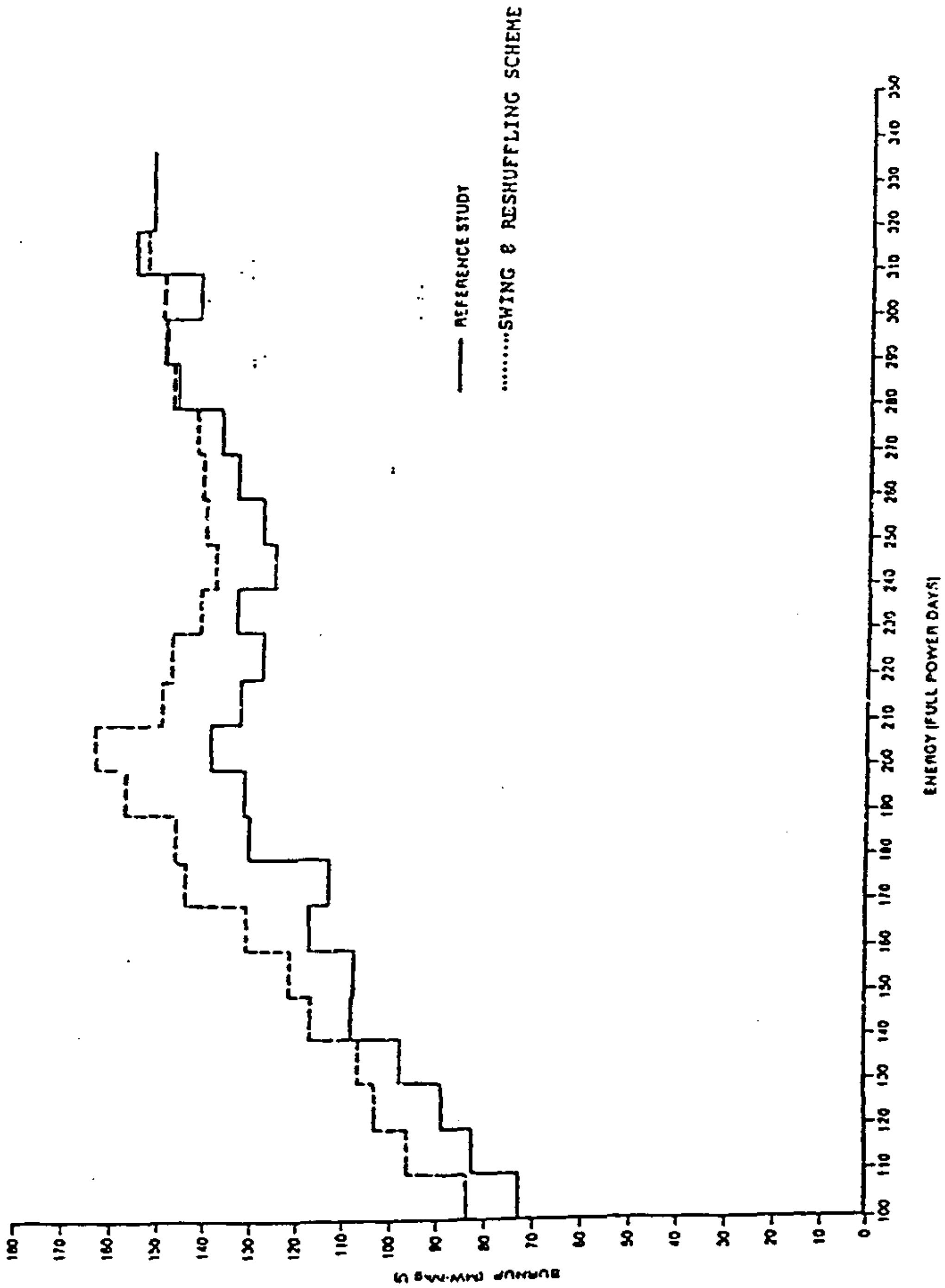

Figure 4.17 Average Discharge Burnup per 10 FPD Interval

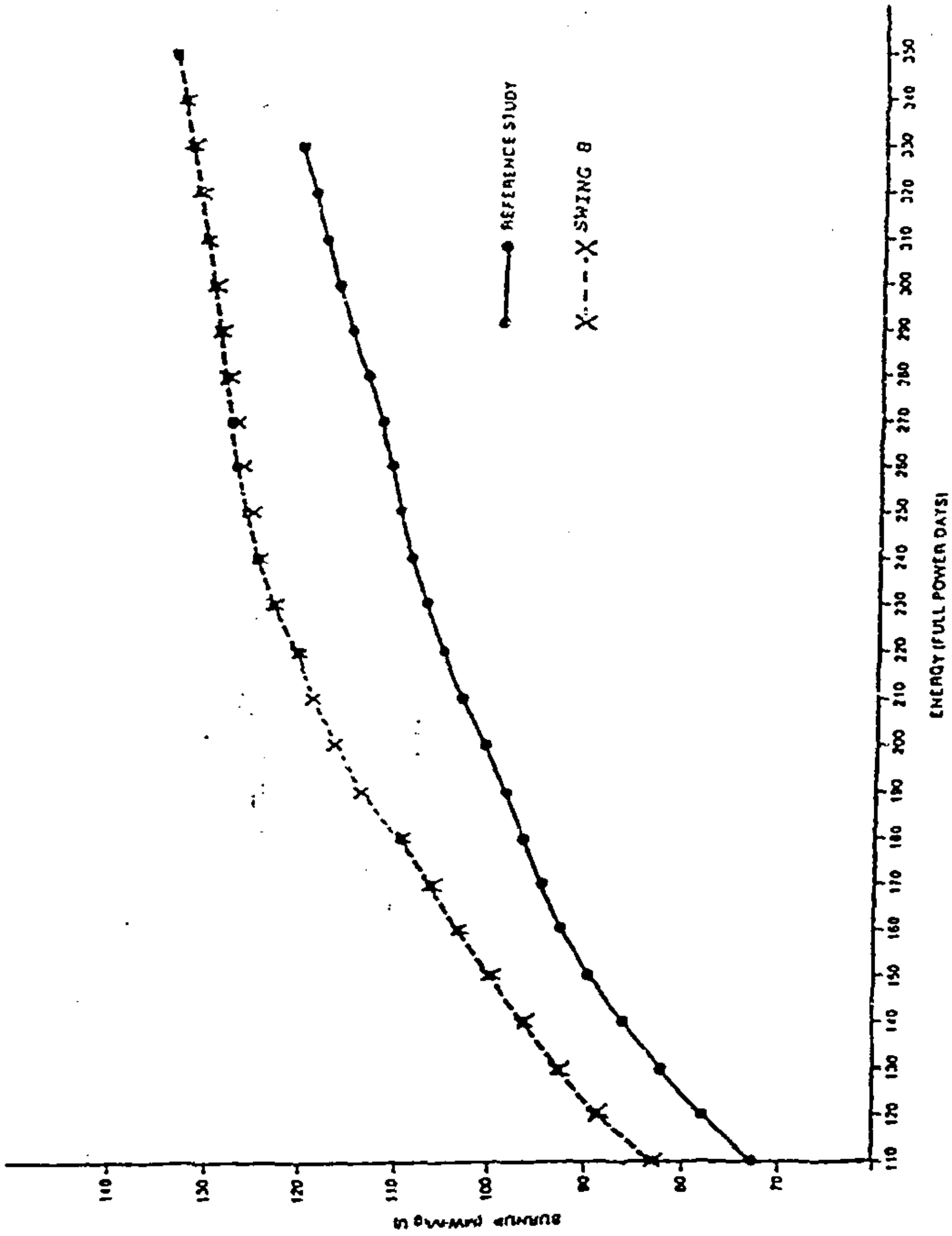

Figure 4.18 Cumulative Discharge Burnup

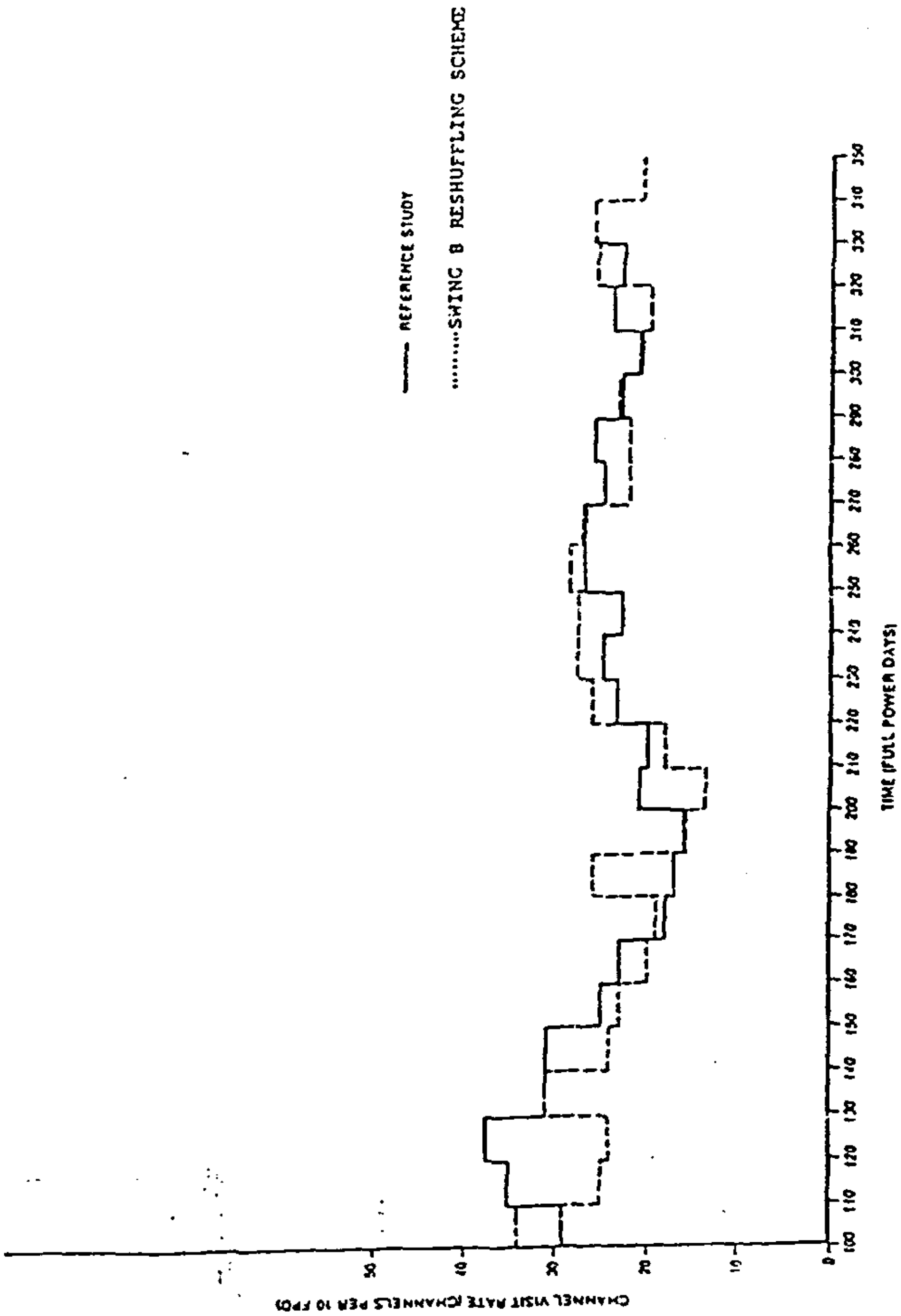

Figure 4.19 Fuelling Machine Visit Rate per 10 FPD Interval