Chapters 5 & 6 of

Reference 4

FUEL MANAGEMENT & REACTOR OPERATION

REVIEW OF OPERATING EXPERIENCE

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5.0 Fuel Management and Reactor Operation

5.1 Introduction

The last two sections are concerned with fuel management during reactor operation. We shall review the procedures used by Ontario Hydro to plan and implement the fuel scheduling, discuss some special problems that arise during reactor operation and present data to demonstrate our ability to meet the objectives of efficient fuel management. These sections are of particular interest for the reactor physicist who is involved with the daily operation of a CANDU reactor, or who provides advice to the operating staff when unusual or unforseen situations develop.

5.2 Organization of Ontario Hydro With Respect to Fuel Management

Ontario Hydro is the electric utility serving the Canadian province of Ontario. Currently it has an installed electrical capacity of approximately 25000 MW of which over 5000 MW are in Nuclear Generating Stations (NGS), all using CANDU-PHW reactors. The nuclear stations operated by Ontario Hydro are listed in Table V.1, along with the ones currently under construction. Within Ontario Hydro, the Nuclear Generation Division has the responsibilty for operating the stations, and for planning and implementing the fuel scheduling. A staff group, located away from the generating stations, defines the limitations within which the fuel should operate, provides expertise in the event of unusual or unexpected occurrences, and analysis of long term problems. The work includes support and co-ordination of research and development activities to anticipate the cause of malfunctions or provide improved performance for the fuel. It also includes feedback of operating data to the designers of new generating stations.

The operating and technical personnel at the stations are concerned with the daily operation of the reactor and with the solution of problems which do not require the use of specialized tools (i.e., large computers) or methods. This type of organization, which has been built over a considerable period of time, is appropriate for utilities with a large nuclear capacity in their generating mix, and may not be typical of other utilities operating CANDU reactors.

5.3 Procedures for Fuel Scheduling in Ontario Hydro

The planning and implementation of the fuel management is a co-operative effort between head office and station operating staff, with a key function being provided by the "monthly" SORO simulation. Their roles are discussed in the following.

5.3.1 The Role of Head Office Staff

The activity of Head Office staff with regard to fuel management usually begins well before the reactor is commissioned. Studies are done, in collaboration with the reactor designers, to compare various fuel bundle shifting schemes and select the most suitable for reactor operation. Calculations are performed to determine the initial fuel loading and to simulate the initial core transient and the approach to equilibrium.

Results of these studies are used, in conjunction with the data provided by the designers, to plan the fuel procurement and fabrication. Very often the effects of varying fuelling rules are studied by simulating a period of operation at equilibrium. The results are usually reviewed and discussed with the operating staff and may be used as part of their training.

During reactor commissioning and initial low power operation, special tests are performed to verify or improve the accuracy of the data and computer methods which will be used later in fuel management. These tests typically include measurements of reactivity worth of control and shutdown devices, flux distributions, etc.

Once the reactor begins power operation, the Head Office personnel follow the fuel management by running the SORO program, usually on a monthly basis, to simulate the actual station operation. Support to operating staff is also provided in the event that unusual problems lead to special difficulties in planning the fuel scheduling. Typical examples are the occurrence of fuel defects or the temporary unavailability of the fuel handling equipment. We shall discuss these problems later in this section.

Complementary to this function of direct support is the collection and analysis of operating data. Activities in this area include:

(a) Fuel performance analyses. The output from the monthly SORO simulation provides the input to a program which records the operating history of each bundle which has gone through the reactor. These data are analyzed to determine the mechanisms leading to fuel defects and to provide feedback to designers on criteria for more efficient operation of the reactor.

(b) Analyses of the reactor regulating and protective systems to optimize their performance and assure that the reliability targets are met.

(c) Calculation of cobalt activity in the adjuster rods. The Pickering NGS A units are equipped with adjuster rods made of cobalt. These are periodically removed from the core when they reach a certain activity since the Co-60 produced has a commercial value.

5.3.2 The Role of the Fuel Engineer

Each operating station in Ontario Hydro has a "fuel engineer". This is a professional or a group of professionals who have the responsibility for planning the fuel scheduling on a daily basis and dealing with all operating problems related to reactor physics. Once the bundle shifting scheme has been selected through design studies, the main function of the fuel engineer is to provide the operators with a list of channels to be fuelled in the following period of operation. In order to determine this list at any given time, the fuel engineer must first establish the status of the core and of other systems such as ROP, reactor regulating system, etc. which are affected by fuelling.

To determine the status of the core the fuel engineer has available the latest SORO simulation and readings from the reactor's instrumentation. The SORO output contains all the information needed to plan the fuel scheduling on the basis of the general guidelines discussed in the previous lecture. This output includes the detailed channel and bundle power distributions, the irradiation of each bundle or channel in the core and a list of channels in descending order of burnup for each zone. The SORO simulation, however, is normally performed on a monthly basis and therefore the information provided may be partially or completely out-of-date.

While in general the irradiation distribution or the channel burnup provided by SORO are still approximately valid, the local bundle and channel power distribution may have changed significantly since the simulation was performed.

The power distribution, however, can be inferred from the available reactor instrumentation readings. The instrumentation varies from station to station. Some stations such as Bruce NGS A have a flux mapping system which provides an on-line three-dimensional map of the flux distribution using the signals from a set of in-core detectors and a modal flux synthesis method [17]. Other stations, such as Pickering NGS A, have coolant temperature instrumentation at the outlet end of each fuel channel and at the inlet reactor headers. In general, a first indication of the power distribution can be obtained from the distribution of the water level in the zone controllers. A persistent low level in one zone may indicate that the zone is underpowered and needs fuelling. A better indication of the power distribution can be derived from flux mapping or temperature rise across each channel.

Once the status of the core is established, the fuel engineer can select the channels to be fuelled using the channel burnup list from SORO and the general guidelines discussed previously. Particular care is usually taken to account for the effect that fuelling may have on the ROP and control system in-core detectors. Special SORO predictive simulations can be performed or the fuel engineer can rely on the experience obtained in similar situations.

Usually, enough channels are selected at one time to allow fuelling at the desired rate for one to two weeks at full power operation. The list of channels selected, however is re-evaluated and, if necessary, revised on a daily basis to reflect the current status of the core. The frequency of predictive SORO simulation usually varies with the age of the reactor and the experience of the fuel engineer. For the initial period of operation at Bruce NGS A, predictive simulations were performed twice weekly on average. This frequency has now decreased considerably.

5.3.3 The SORO Monthly Simulation

Apart from the various predictive simulations which may be required, a SORO simulation is performed once a month to provide data on the operating history of the reactor for the previous month of operation.

The simulation is performed following the steps described in Section 2.3.3. Some of the input data, however, are obtained directly from the station's records. These data include the sequence of channels fuelled during the month, the position of the zone controllers averaged over a period of 4 or 5 days, the reactor power history and data to identify the fuel bundles which have been loaded or discharged from the reactor during the period.

In the simulation, a flux calculation is performed at intervals of 4 to 5 full power days. The channels fuelled during each interval are simulated as being fuelled in a batch at the beginning of the interval. This tends to overestimate slightly the actual maximum bundle and channel power, and core reactivity. A number of tests performed have indicated that the error is negligible for practical purposes. This is in contrast to FMDP which simulates fuelling within the interval.

The output from SORO includes, as we have seen, the power and irradiation for each bundle at each time step and several other data which are used for fuel accounting (i.e. bundle serial numbers) and long term analyses.

5.3.4 Accuracy of SORO and SORO Simulation

Given the importance of the SORO simulation in planning and following the fuel scheduling, the code has been extensively validated against operating data.

Figure 5.1 presents a comparison of channel power as calculated by SORO, and as measured by instrumented channels for the Bruce NGS A reactors. The mean diffference is -1.8% with a standard deviation of 3%. The agreement is within the error of the instrumentation. Another way of verifying the SORO simulation is to compare the discharge burnup of selected bundles with that obtained by measuring, through chemical separation and mass spectrometry, the U-235/U-238 ratio and deriving the burnup from a lattice code. The results for various elements of two Bruce NGS A fuel bundles are shown in Figure 5.2. The difference is less than 3%.

A third method of validating SORO is to compare the measured activity of the cobalt adjuster rods removed from the core with that predicted using the flux distributions calculated by SORO. A typical comparison for a set of adjuster rods is given in Table V.2. The mean and standard deviation are 1.1% and 5% respectively.

5.3.5 Accuracy of FMDP and FMDP Simulation

Both FMDP and SORO obtain their cross sections (fuel tables) from the POWDERPUFS program. The FMDP program allows modelling of the reactor with variable mesh spacing so that any desired degree of accuracy can be obtained, whereas SORO uses a fixed one lattice pitch square by one bundle length mesh spacing. (There are other minor approximations made in SORO which are not made in FMDP, which will not concern us here.) In principle, one can input a SORO model into FMDP, and reproduce the SORO flux distribution. In this case, the verification of SORO discussed above is also a verification of FMDP.

In practice, one usually takes advantage of the FMDP features, and consequently FMDP models are usually more detailed than SORO models. Incremental cross sections of devices (eg. adjuster rods) in SORO are frequently obtained by matching flux distributions and reactivity against the corresponding FMDP distribution.

FMDP has been independently verified against flux measurement taken during Bruce GS A commissioning. Figure 5.3 shows measured and simulated flux distributions for Bruce GS A initial core. Figure 5.4 shows the discrepancies between simulated and measured fluxes. (Note that Figure 5.1 shows channel powers, where 5.4 shows fluxes, so they are not directly comparable.)

The burnup and CPPF prdictions from FMDP time averaged and instantaneous calculations have been compared with Bruce NGS A operating data. The predicted burnup agreed with the fuel added within one percent. The predicted CPPF was 1.10 which agreed with observed values of from 1.08 to 1.11.

5.4 Special Operating Problems

The normal fuel scheduling is, at times, disrupted by unusual events. These are often related to fuel failures or malfunction of the fuel handling equipment. The flexibility inherent in the on-power fuelling feature of the CANDU system permits the fuelling strategy to be adapted promptly to the changing operating conditions with minimum loss of production. Typical situations which affect the fuel management are discussed in the following.

5.4.1 Occurrence of Fuel Defects

The performance of the CANDU fuel has been outstanding as we will see later when reviewing operating experience. Some fuel defects, however, did occur in the Douglas Point and Pickering reactors in the early part of their operating life. Most fuel failures originated when there were large increases of power in fuel bundles which had accumulated appreciable burnup. The principal defect mechanism was stress corrosion cracking of the Zircalloy fuel sheath induced by fission products, mainly iodine. The fuel burnup governs the iodine inventory and the power increase determines the UO_2 temperature and hence the release of iodine to the Zircalloy surface.

CANDU reactors are normally equipped with a Failed Fuel Detection system which allows the defected fuel bundles to be located quickly. Failed bundles are removed from the core by fuelling.

In most cases, the occurrence of defects is followed by a re-examination of the fuel management schemes in order to eliminate the potential for further fuel failures. This re-examination may lead to a change in the fuel shifting scheme. As we have seen in 3.4.1.4, some fuel shifting schemes may lead to large increases in bundle power in excess of an empirically determined "defect line" as illustrated in Figure 3.4.

Excessive and concentrated fuelling in one region of the core may also lead to high bundle powers and fuel failures. In this case the removal of the defective bundles must be accompanied by reactor power derating and a fuelling strategy which reduces the power in the region where the failures have occurred. Bundles with a U-235 content lower than that of natural fuel (depleted bundles) may be used to replace the defective bundles and reduce the region's power.

5.4.2 Reactivity Shim Operation

Since the reactivity control margin in the zone controllers is very small, whenever the fuel handling equipment becomes unavailable additional positive reactivity must be provided to keep the reactor operating. For most CANDU reactors reactivity shim compensation is accomplished by withdrawing adjuster rods from the core in a pre-specified sequence. Removal of adjuster rods leads to a distortion in the normal flux distribution. In most cases some derating is required to keep the maximum bundle and channel power within target limits. The derating depends on the number of adjuster rods withdrawn from the core and hence on the duration of fuel handling system outage. Table V.3 gives the reactor power level vs number of adjuster rods withdrawn for a typical CANDU. Typically, the reactivity worth of a single adjuster rod is approximately 1×10^{-3} $\Delta k/k$ on average while the reactivity loss due to fuel burnup is in order of 0.3 to 0.4×10^{-3} k/k per full power day so that in the great majority of cases only the first few adjuster rods need to be withdrawn from the reactor core. If, however, the inability to fuel persists for a significant time, a special fuel management strategy must be followed, once fuelling capabilty is re-established, in order to speed up the recovery to full power operation and return to a normal flux distribution.

The fuelling strategy followed varies from case to case. Normally priority is given to improving rapidly the overall core reactivity rather than the flux distribution. In the recovery period the channels to be fuelled are selected primarily on the basis of high reactivity gain.

5.4.3 Moderator Poison Management

In the CANDU reactors long term reactivity control is achieved by maintaining an appropriate fuelling rate. Moderator poison is not normally required for the equilibrium core. Adding poison to the moderator leads to a burnup penalty and to increased fuelling machine usage. On the other hand with poison present, if fuelling becomes unavailable, the reactor can be operated at full power by decreasing gradually the moderator boron concentration rather than removing adjuster rods.

Some CANDU reactors are equipped with booster rods instead of adjuster rods. These are rods of highly enriched uranium which are normally parked outside the core, and are inserted when additional reactivity is required. If booster rods are used for reactivity shim, besides the cost of the lost generating capability associated with the flux distortion, there is an additional cost associated with the burnup of booster fuel.

The optimum moderator poison is then determined by the economic balance between burnup penalty on one hand and reactor derating and booster fuel burnup on the other, and by the expected frequency and duration of the fuelling machine outages. Some moderator poison can also be used in anticipation of a period of peak electrical demand from the power grid to assure continuous full power operation.

The Pickering NGS A reactors are not normally operated with poison in the moderator, while the Bruce NGS A reactors, which are equipped with booster rods, run normally with enough poison in the moderator to allow full power operation for 8-10 days without fuelling.

5.4.4 Example of Reactivity Shim Transient

To illustrate some of the problems which can be encountered in the operation of a power reactor and to demonstrate the flexibility of the CANDU fuel management in meeting unforeseen situations, we will now review a transient that occurred in Pickering Unit 1 in the fall of 1974.

A series of events related to problems with the reactor coolant temperature instrumentation and to some non-optimum fuelling led to bundle powers in excess of the target limits and to a significant side to side tilt in the power distribution.

The high bundle power was discovered through the SORO monthly simulation and the reactor was immediately derated by a few percent in accordance with operating practices. This problem was further complicated by a failure of the fuelling machine a few days later. There then ensued a period of 84 days during which no fuelling took place. A complete history of the event is shown in Figure 5.5. Adjuster rods were withdrawn from the core in a pre-determined sequence and the reactor derated in successive steps. The normal reactor power limits for operation with adjuster rods withdrawn could not be used because of the flux distortions. New limits were derived using a time-dependent neutron diffusion code to follow the xenon transients and the burnup distribution from the SORO runs. The reactor was operated with up to 16 adjuster rods withdrawn from the core. The rods were withdrawn in pairs to minimize the flux distortion.

During this period many predictive SORO simulations were done to study recovery fuelling patterns. Since fuelling could not be done to correct the original flux distortion, the location of the maximum bundle power shifted in the core depending upon the number of adjuster rods withdrawn. Each time more rods were withdrawn, a new fuelling pattern was examined.

Once fuelling capability was re-established the ideal fuelling pattern would have been one which immediately improved the flux distribution. This could have been achieved by either fuelling in the high power region of the core with depleted fuel or by fuelling a large number of channels well away from this region. Neither of these schemes, however, would have improved the reactivity of the core rapidly. The decision was then made to fuel channels with high reactivity gain. This led to all the adjuster rods being reinserted after 122 channels were fuelled. However, reactor power was still restricted to 96% of full power because of bundle power in excess of the target limit.

Table V.1

<u>CANDU Nuclear Stations</u>

	Station	Owner	Electrical Output MW(e) net	First Electricity
(1)	NPD	Ontario Hydro/AECL	22	1962
(2)	Douglas Point	AECL	208	1967
(3)	Pickering GS A	Ontario Hydro	4 x 508 = 2032	1971-1973
(4)	Gentilly-1	AECL	250	1971
(5)	KANUPP	Pakistan	125	1971
(6)	RAPP	India	2 x 200 = 400	1972-80
(7)	Bruce GS A	Ontario Hydro	4 x 732 = 2928	1976-1979
(8)	Bruce GS B	Ontario Hydro	4 x 732 = 2928	1983-1987
(9)	Gentilly-2	Hydro Quebec	638	1982
(10)	Cordoba	CNEA, Argentina	600	1981
(11)	Point Lepreau	NBEPC, New Brunswick	635	1981
(12)	Pickering GS B	Ontario Hydro	4 x 516 = 2064	1982-1983
(13)	Wolsung 1	Korea Electric Co.	629	1982
(14)	Darlington GS A	Ontario Hydro	4 x 881 = 3224	1988-1990
			Total = 16683	

Table V.2

Co-60 Calculated Activity Versus Measurements

d	Calc. Activity At Measurement	Measured Activity (Ci)	$\frac{\text{Calc.-Meas}}{\text{Meas.}} \times 100\%$
A3	224,781	222,962	+ 0.8%
A8	223,657	231,392	- 3.3%
A14	161,792	158,132	+ 2.3%
A6	383,096	392,310	- 2.3%
A7	380,549	387,492	- 1.8%
A8	393,322	349,216	+12.6%
A10	376,078	378,422	- 0.6%
A17	284,423	280,486	+ 1.4%

mean and standard deviation is (1.1 ± 5.0)%. Another set gave 6 ± 3.5)%.

Table V.3

Adjuster Rods Withdrawn for Reactivity Shim Operation

Pickering GS A Reactors

No. of Adjuster Rods Withdrawn	Reactor Power Level (% of Full Power)
2	100
4	100
6	100
8	98
10	90
12	90
14	86
16	83

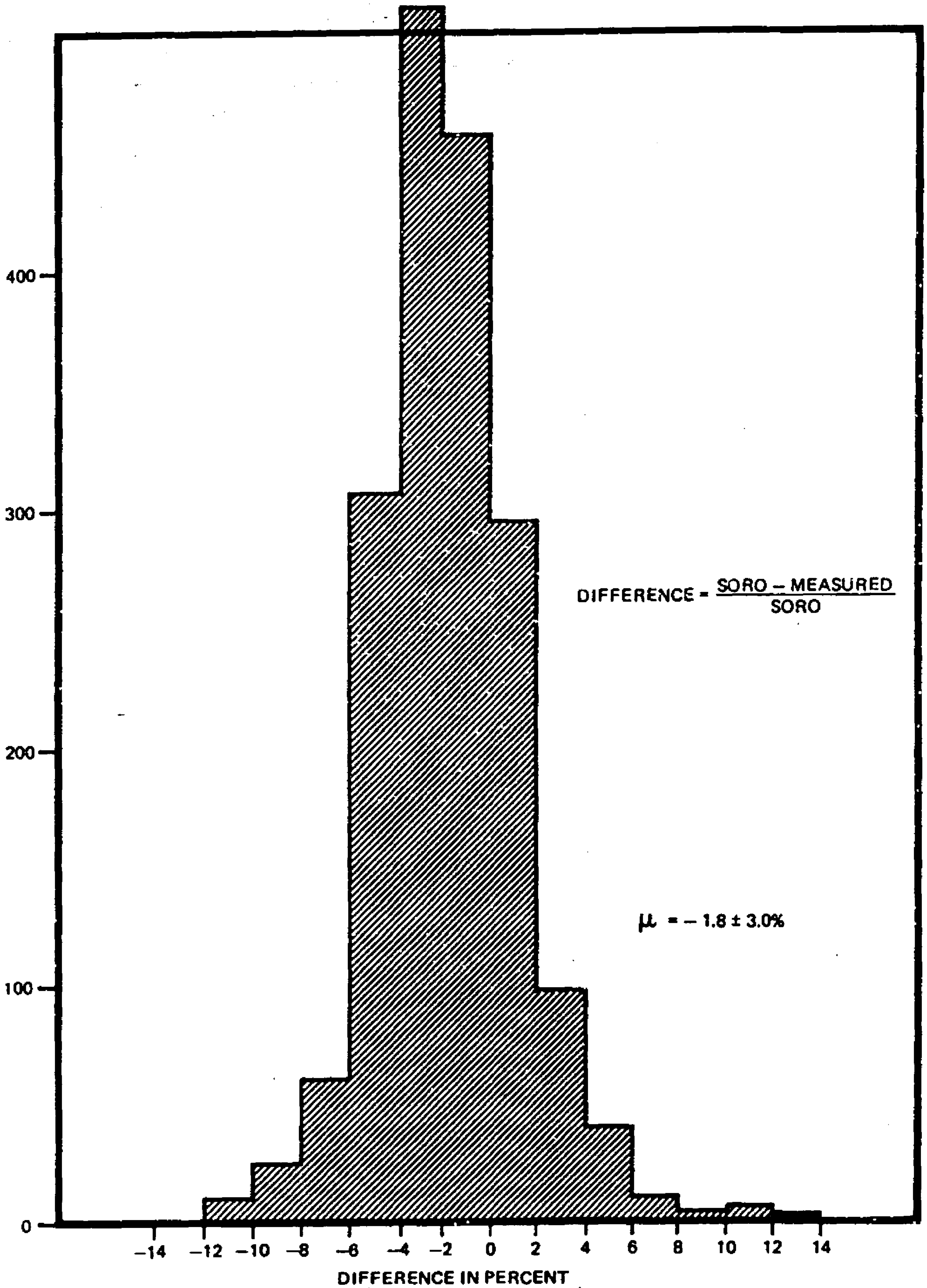
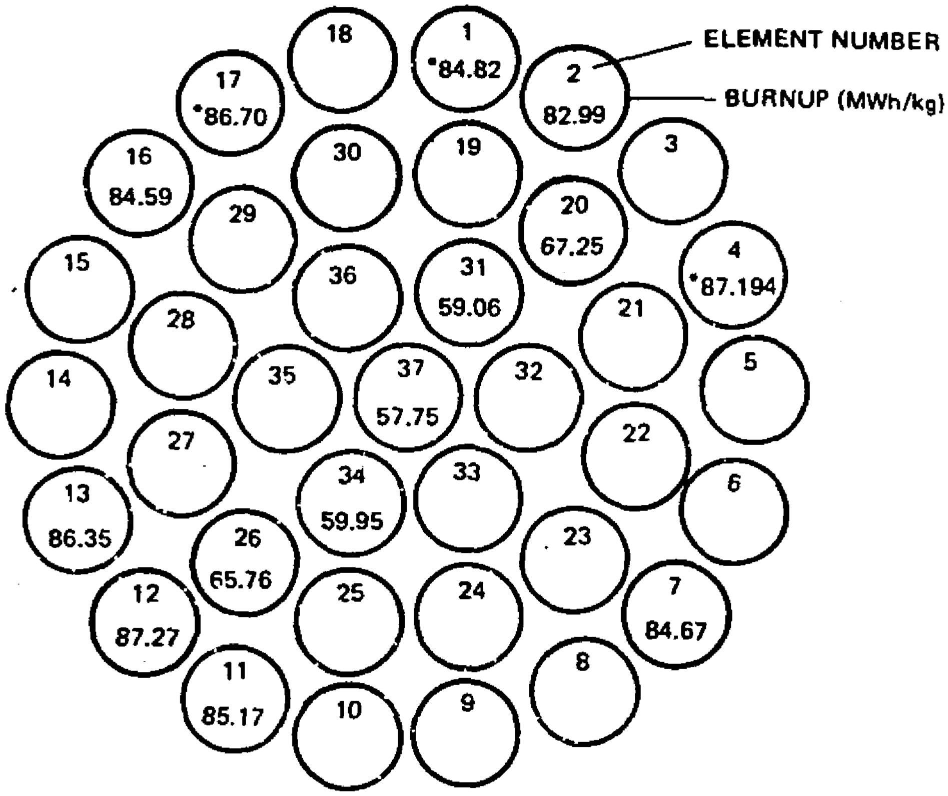


FIGURE 5.I
FREQUENCY DISTRIBUTION OF CHANNEL DIFFERENCES (SORO AND MEASURED) FOR BRUCE A

BURNUP ANALYSIS OF BUNDLES F09048C AND F11153C



*THREE OUTER ELEMENTS OF F11153C; ALL OTHER BURNUP VALUES ARE FOR F09048C

		F09048C	F11153C
AVERAGE ELEMENT BURNUP (MW.h/kg) [BASED ON LATREP TABLES]	OUTER ELEMENT	85.17	86.24
	INTERMEDIATE ELEMENTS	66.51	–
	INNER ELEMENT	59.51	–
	CENTRE ELEMENT	57.75	–
WEIGHTED AVERAGE BUNDLE BURNUP BASED ON LATREP (MW.h/kg)		74.22	76.32
SORO PREDICTED AVERAGE BUNDLE BURNUP (MW.h/kg)		76.2	78.2
% DIFFERENCE †		+2.5%	+2.5%

† % DIFFERENCE = $\frac{\text{SORO PREDICTED BURNUP} - \text{LATREP DERIVED BURNUP}}{\text{LATREP DERIVED BURNUP}} \times 100\%$

FIGURE 5.2
COMPARISON OF PREDICTED AND MEASURED
BURNUP FOR SELECTED ELEMENTS

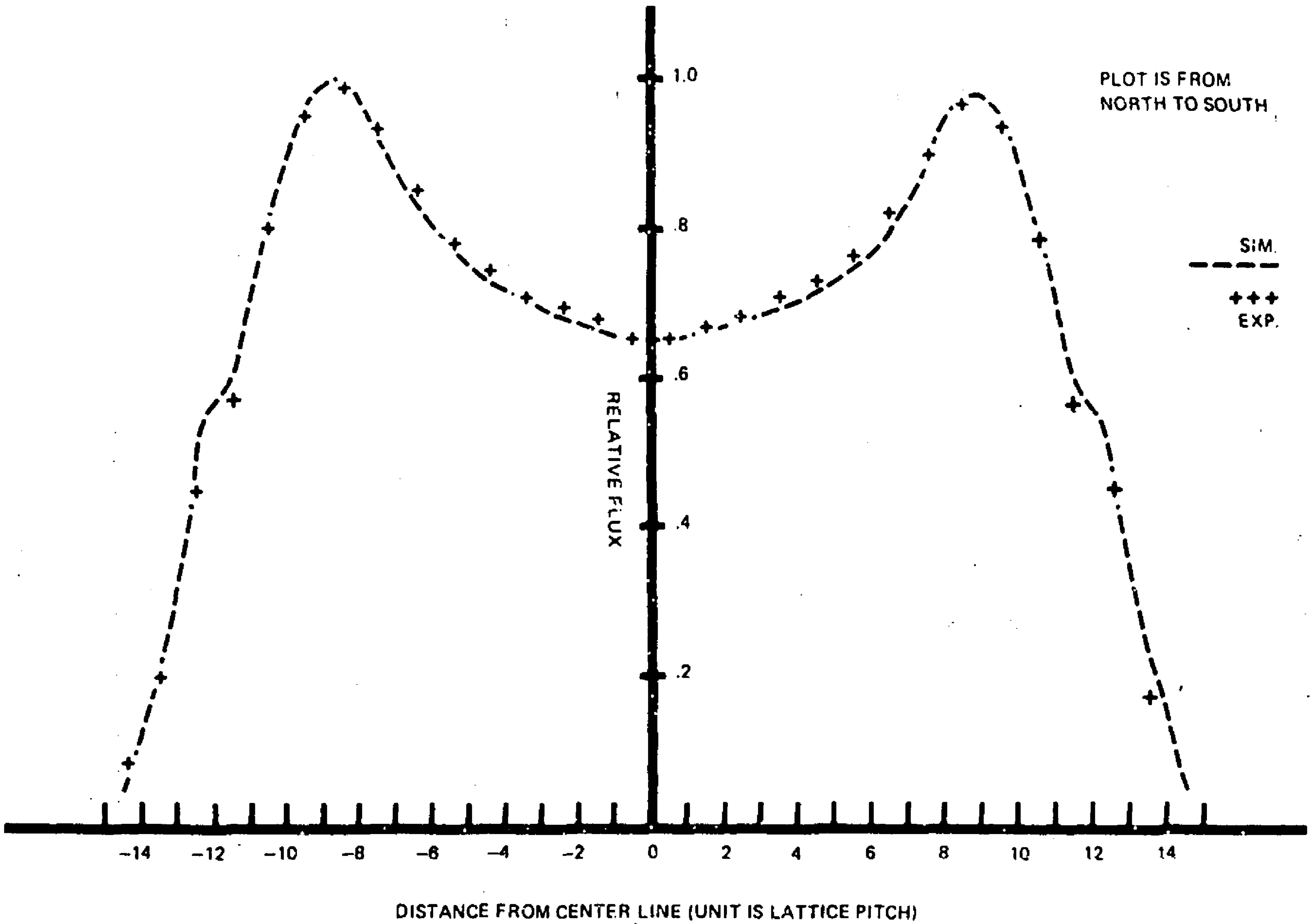


FIGURE 5.3
COMPARISON BETWEEN TRAVELLING FISSION CHAMBER DATA AND SIMULATION IN BRUCE A

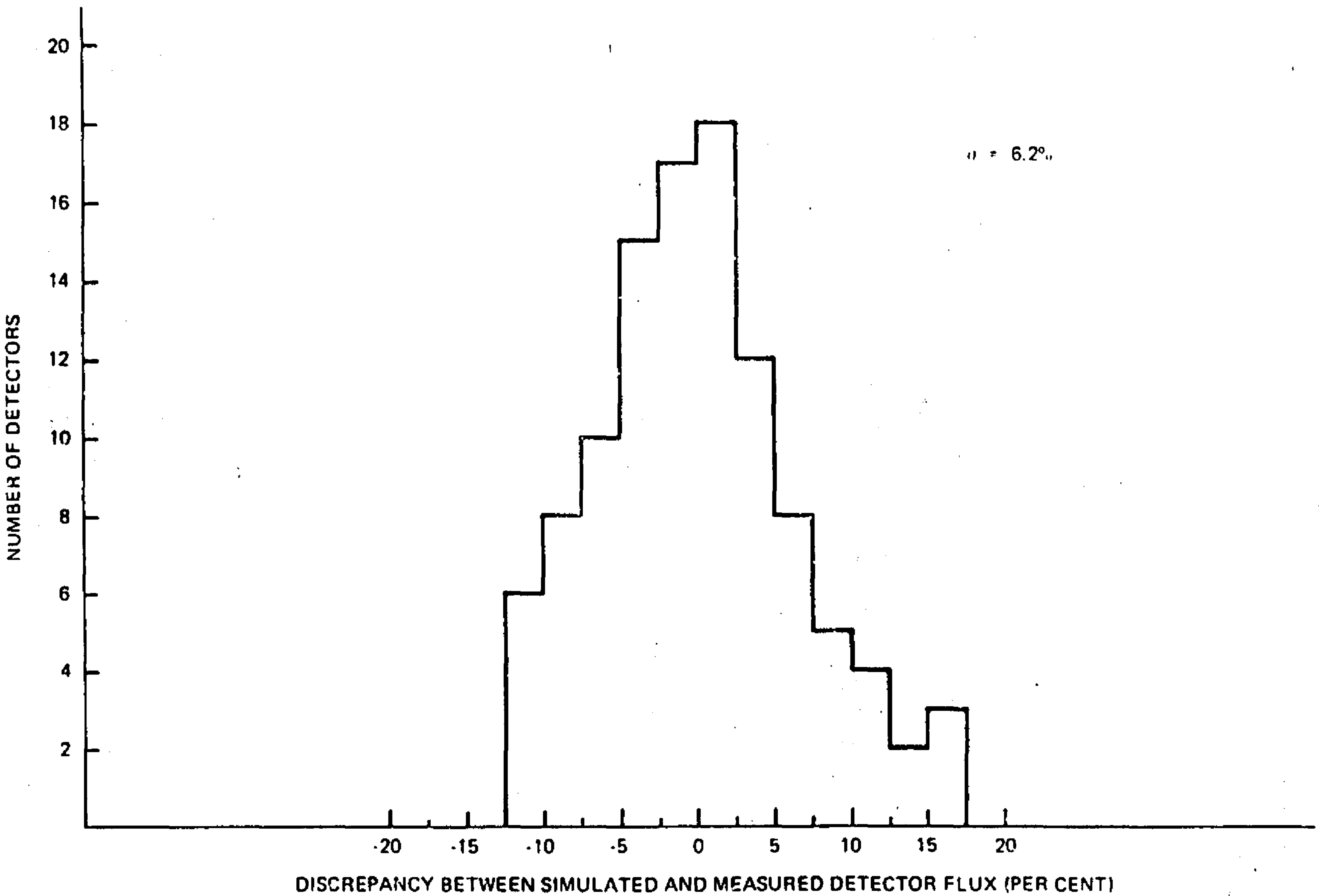


FIGURE 5.4
ZERO POWER FRESH CORE – COMPARISON BETWEEN SELF POWERED DETECTOR DATA AND SIMULATION

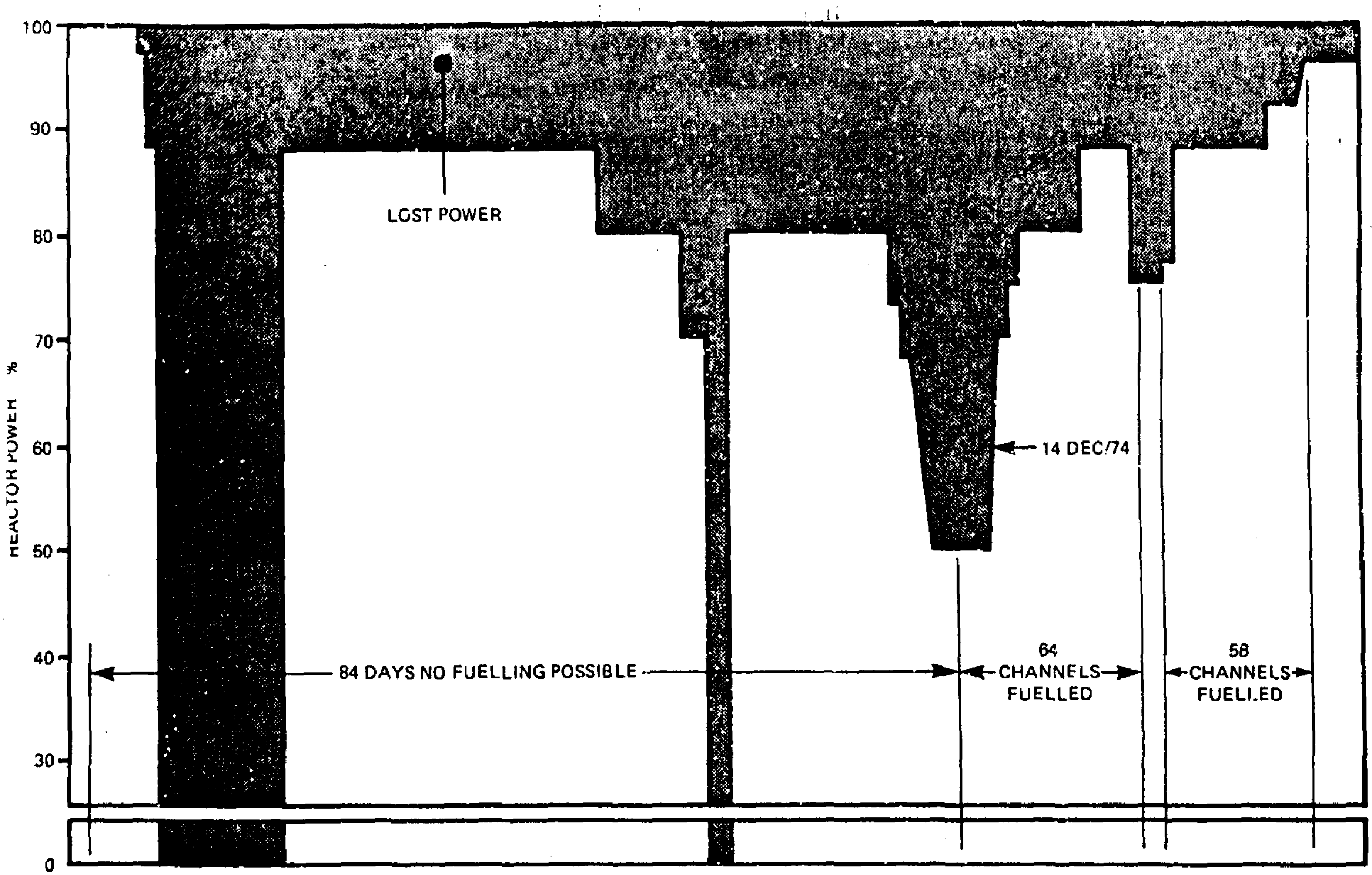


FIGURE 5.5
PICKERING G.S. UNIT 1 DERATING HISTORY
18 SEPT./74 to 14 JAN./75

6.0 REVIEW OF OPERATING EXPERIENCE

6.1 Introduction

The excellent performance of the Pickering reactors is a measure of the successful operation of CANDU reactors. These reactors have achieved a high capacity factor and very low fuelling cost. Approximately 30 reactor-years of commercial experience have now been accumulated with the four Pickering reactors.

The average capacity factor of all units since their in-service date is very close to 80 percent. In 1978 the total unit energy cost at Pickering was 10.1 m$/kWh. This compares favourably with the fuelling cost alone of 13.7 m$/kWh for the most efficient coal-fired station in the Ontario Hydro system. Meeting the objectives of efficient fuel management both during design and operation has made a significant contribution to this achievement.

To illustrate how this performance is achieved with the methods and procedures for fuel management discussed in the previous sections, we shall now review the operating experience at the Pickering and Bruce Nuclear Generating Stations. In doing this we shall consider one typical unit from each station and highlight the lessons learned and problems of general interest encountered.

6.2 Fuel Management at Pickering

6.2.1 Initial Operation

Pickering Unit 1 went critical on February 25, 1971. The Pickering core was designed to have a radially uniform discharge burnup. Adjuster rods provide radial and axial flux flattening. The first fuel charge consisted entirely of natural UO_2 bundles. Because the adjusters provided sufficient flattening, no "depleted" fuel bundles were required. Fuelling began at approximately 5 TWh (~130 FPD) when the excess reactivity in the core was reduced to approximately $5 \times 10^{-3}\ \Delta k/k$. A uniform 8 bundle shift scheme was selected as being the most suitable on the basis of the following economic factors:

(a) fuel make-up cost, that is the cost of fuel bundles inserted in the core per unit energy output;

(b) fuelling machine operating and maintenance cost; and

(c) costs associated with fuel defects.

At that time the only known cause of fuel failure associated with fuelling was large increases in fuel rating of highly irradiated bundles after fuel shifting. No special consideration was given to minimizing the CPPF. The Pickering reactors use out-of-core instrumentation rather than in-core detectors for overpower protection. Out-of-core instrumentation is not very sensitive to local flux perturbations. In addition, the Pickering reactors have pre-specified limits on the coolant temperature rise across each channel. If these limits are approached, because of an overpower, the reactor power is reduced.

By late 1971, a large increase in the iodine-131 concentration in the heat transport system indicated the presence of fuel failures. The resulting investigation revealed two reasons for the fuel defects:

(a) excessive variations in bundle power due to adjuster rod maneuvering; and

(b) high incremental bundle powers due to the eight bundle shifting scheme.

The first problem was eliminated by re-analyzing the adjuster rod sequencing and associated reactor power levels, with an imposed arbitrary limit of 15% on bundle power variations. The new adjuster rod withdrawal sequence considerably reduced bundle power variations.

The second cause of fuel defects was due to two effects:

(a) large permanent increase in fuel rating when bundles in position 1 are moved to position 9 by an 8 bundle shift, and

(b) a short exposure (about 15 minutes) of bundles in position 1 and 2 to high powers at the centre of the channel during the fuel movement.

To remedy the problem two steps were taken. Fuel management simulations were carried out to compare the economics of 8, 10 and 12 bundle shifting in light of the increased cost associated with fuel defects. The 10 bundle shift scheme was found to give a small burnup penalty when compared to the 8 bundle shifting scheme, while eliminating permanent increases in bundle power due to fuel re-arrangement within the channel. This scheme was, therefore, adopted for all the high power channels in the core.

The exposure of some bundles to high fluxes in the centre of the channel during fuel movement was shortened to about 5 minutes by a change in the sequence of operation of the fuelling machine. These steps were very effective. Of the approximately 48,000 bundles fuelled to the end of 1974, 101 had developed defects. Of these, 88 are attributed to the above effects. Excluding these the defect rate is 0.027 percent.

Some of the lessons learned in the area of fuel scheduling from this period of operation of the Pickering reactors can be summarized as follows:

(a) It is valuable to be able to simulate reactor operation accurately and in a timely manner. The availability of individual bundle power histories from the simulations enabled a prompt identification of the defective bundle location and provided the data to understand the underlying causes of fuel defects.

(b) It is valuable to be able to compare different bundle shifting schemes on short notice, taking into account changing operating requirements or situations unforseen during the design phase.

(c) The flexibility of the CANDU fuel scheduling allowed the station to adapt to new schemes and incorporate changing operating requirements without having to shut down the reactors.

(d) It was important to develop a fuel design more tolerant of the variations in power which can be expected from movement of the reactivity mechanisms or from the fuel shifting scheme itself.

6.2.2 Subsequent Experience

In 1972, tests indicated that the deposition of a thin graphite layer on the inner surface of the fuel sheath would make the fuel more tolerant to power variations. This fuel, designated CANLUB, became the standard design and bundles of this type were used to fuel the reactors starting in 1974. The experience gained with this fuel design allowed the relaxation of the 15% limit on short term power variation. The fuel shifting scheme, however, was not changed. Since then the fuel management at Pickering has been very successful when measured against the objectives described in the introduction of the first section.

6.2.2.1 Maximum Bundle Power History

Figure 6.1 shows the maximum bundle power as a function of integrated reactor energy for Pickering Unit 1. The shaded band is a ±10% variation about the nominal reference bundle power of 640 kW, the upper end of the band being the target power limit of 705 kW. The original objective of the fuel scheduling was to maintain the maximum bundle power close to the nominal 640 kW value. The data show that, in general, this was achieved.

In particular, if we examine the period after 1974 (40 TWh) with the unit having reached maturity, the variation in maximum bundle power is very small. A slow trend towards a lower target maximum bundle power is also evident from about 50 TWh. In the last 4 years the maximum bundle power has been varying around an average value of approximately 600 kW with variations of the order of 6% or less.

6.2.2.2 Maximum Channel Power History

The history of the maximum channel power is given in Figure 6.2. The reference design value of 5.5 MW has been maintained, with a few exceptions, to within ±10%. As with the maximum bundle power, the band of variation around the nominal value decreased as the unit reached maturity.

6.2.2.3 Burnup and Fuel Consumed

Figure 6.3 shows the core excess reactivity as a function of reactor integrated power. After the initial reactivity transient due to fresh fuel had decayed, the excess reactivity in the core was maintained close to zero. Moderator poison as a means of "storing" reactivity has been used very rarely at Pickering. Figure 6.4 shows the average monthly discharge burnup as obtained by the SORO simulation. Figure 6.5 shows the fuel added versus reactor heat. Also plotted is the line of "ideal fuel added" assuming a burnup of 175 MWh/kg. The data indicate that the burnup is in the range 170-175 MWh/kg.

Unit 3 and 4 have Zr 2.5% Nb pressure tube rather than zircalloy. This material allows thinner pressure tubes to be used with an attendant burnup gain of approximately 15 MWh/kg.

6.2.2.4 Fuel Defect Performance

The performance of the fuel at Pickering after the initial problems were solved has been extremely good. As can be seen from Table VI.1, the total number of defective bundles, including suspected ones, was 112 up to the end of June 1978. This gave a defect rate for the 4 units of 0.12%.

6.3 Fuel Management at Bruce

The Bruce units were the first CANDU reactors to incorporate a regional overpower (ROP) system for overpower protection. Early fuel management studies indicated that controlling and minimizing the CPPF was imperative to maintain an adequate operating margin at the ROP in-core detectors. As we discussed in the first section, the ROP detectors are calibrated on a frequent basis to reflect the CPPF existing in the core. Large variations in the CPPF would increase the frequency of time consuming calibrations and the probability of spurious activation of the shutdown systems.

The fuelling schemes used at Pickering (8 or 10 bundle shift) would produce unacceptably high CPPF in Bruce A. On the other hand schemes involving a small number of bundles, 2 or 4, tend to increase the fuelling machine usage and cause relatively high increases in bundle power during shifting, leading to higher probability of fuel defects. From a number of studies performed during the final design phase, it was concluded that the most suitable scheme was a mixed 4 and 8 bundle shifting. As indicated in Figure 6.6 the channels in the inner part of the core are fuelled with a four bundle shift, while the outer channels are fuelled with an eight bundle shift.

The studies showed that this scheme has the following characteristics:

(a) It yields a discharge burnup comparable to that obtainable from a uniform 2 or 4 bundle shifting and slightly higher than that of an 8 or 10 bundle shifting scheme.

(b) The (CPPF-1) is approximately half that of an 8 or 10 bundle shift.

(c) The probability of fuel defects due to fuelling was acceptably low. CANLUB fuel, which is more tolerant to power variations, is the reference design.

A uniform 4 bundle shift would have been preferable from the point of view of minimizing CPPF. This scheme, however, would have increased excessively the fuelling machine usage. Fuel management at Bruce has been generally successful as we shall see later by reviewing the operating data. Some operational difficulties associated with fuelling have been encountered, however, with the reactor regulating system and the ROP system. A brief discussion is outlined below.

6.3.1 Reactor Regulating System

As we have seen in the first section, the reactor regulating system employs in-core, self-powered detectors to provide an estimate of the power in 14 zones (regions) of the core which are controlled by the 14 light water zone controllers. The flux detectors are continuously calibrated to estimates of the thermal power in each zone. The calibration factors are derived from 3 or 4 fully instrumented channels (inlet and outlet flow, inlet temperature and temperature rise measurements) located in each zone.

A typical response of the zone controllers to a fuelling operation is shown in Figures 6.7 and 6.8. Zones 3 and 10, which are close to the channel being fuelled, change in level by approximately 20%. The remaining controllers show little change. The figure shows a comparison of actual data with a simulation using the SMOKIN code [18]. This code is often used in conjunction with SORO to predict the control system configuration after fuelling. Ideally, the fuel scheduling provides the means of controlling the power distribution and, hence, of maintaining an approximately uniform level distribution in the controllers. At Bruce, however, individual controllers have displayed a tendency to drift to extreme level over a period of fuelling. This anomalous drift has adversely affected, at times, the ability to maintain the desired fuel scheduling. Analysis has shown that the drift is directly related to local burnup dependent flux variations which are not completely calibrated out of the in-core flux detector signals.

A fuelling operation causes a redistribution of the flux and power distribution in the core. The perturbation consists of both a global tilt component and localized flux peaking component. Since the number of controllers is limited, only the global tilts can be effectively controlled. Localized flux peaks due to the fine structure in the irradiation distribution cannot be controlled. If these are not calibrated out of the detector signals, an inappropriate control action might be taken which can cause the controllers to drift to extreme values.

The problem is presently being handled by performing periodic manual adjustments of the pre-calibrated detector signals and spatial power distribution setpoints. Efforts are currently underway to modify the spatial control algorithm to make it less sensitive to these local flux variations.

Another difficulty encountered is related to over-response of individual zone controller level changes when one of the fully instrumented channels is fuelled. Since an average of a few measured channel powers in a zone is used to provide an estimate of the average power in the zone, the local power peaking in a freshly fuelled channel may result in an apparent higher zone average power. The zone controller is called upon to reduce the estimated power to the desired setpoint and does so by filling to a higher level then is required.

Some test data collected at Bruce are shown in the upper part of Figure 6.9. It can be seen that the change in level in the controllers is strongly influenced by the distance between the channel being fuelled and the closest fully instrumented channel.

The lower part of Figure 6.9 shows the response of the zone controllers when the zonal power is estimated from the temperature rise across each channel in the zone and the instrumented channels. The response is fairly independent of the distance up to about 3 lattice pitches.

This type of calibration, which is also used at Pickering, is only a temporary solution to the problem. The Bruce reactors are currently operated at full electrical output which corresponds to approximately 88% of full thermal power. Once the additional power is required to provide steam for a heavy water plant on the site, some channels will be boiling at the outlet end. The power estimate from temperature measurements will, therefore, be unreliable. A more permanent solution is being sought through modification of spatial control algorithm as mentioned above.

These problems have indicated the need for a representation of the control system response in fuel management programs, like SORO, which are often used to predict the fuelling pattern during operation.

A model of the control system based on the SMOKIN program is now being incorporated into the SORO program.

6.3.2 The Regional Overpower System

The occasional difficulties in maintaining a reasonable distribution of zone controller levels have also caused additional problems in maintaining an adequate margin at the ROP detectors. Since the desired fuelling pattern could not always be maintained, relatively high CPPF's were occasionally encountered.

Moreover, as mentioned previously, particular care had to be taken in fuelling channels close to ROP detectors. The observed changes in detector reading following fuelling close to a detector is in the range 1.5 to 6 percent. Of this change, up to 2 percent has, in some cases, been attributed to control system action. In general, those changes in detector signals exceed the changes in channel powers, thereby resulting in an effective reduction of the operating margin.

The net result of fuelling on the ROP system detectors and regulating system response has been to place an abnormal burden on operating personnel to ensure that fuelling does not lead to spurious overpower trips of the reactor. This has resulted in small temporary deratings and loss of production due to inadequate operating margin in the ROP system.

Some improvements are expected to be obtained through proposed modifications of the spatial control algorithm. The benefits will be derived through an improved ability to maintain a better distribution of the level in the zone controllers and an attendant improvement in the control of the CPPF.

6.3.3 Maximum Bundle Power History

Maximum bundle power as a function of integrated energy for Bruce Unit 1 is presented in Figure 6.10.

It can be seen that after the onset of fuelling the maximum bundle power increased fairly rapidly to a value of approximately 800 kW $\pm$10%. The variations in Bruce are somehow larger than Pickering due to the fact that the reactor has not yet reached maturity and also to the fact that no special attempt was made to strictly control the bundle power. The operational margin on maximum bundle power is larger in Bruce that it is in Pickering.

6.3.4 Maximum Channel Power History

Because of the relatively narrow margin on the ROP system and the need to minimize the CPPF, good control was kept on the maximum channel power. As can be seen from Figure 6.11, the target value of 6.0 MW has been maintained, with a few exceptions, within a very small band.

6.3.5 Burnup and Fuel Consumed

Figure 6.12 shows the fuel usage, burnup, and core excess reactivity as function of reactor integrated power. The upper portion of the figure shows the core excess reactivity. After the initial reactivity transient due to fresh fuel had decayed, the excess reactivity in the core was maintained close to 5 x 10^{-3} k/k. This excess reactivity is held in soluble boron in the moderator to provide additional "shim" reactivity when fuelling machines are unavailable. The Bruce reactor does not have adjuster rods for shim purposes. Power shaping is provided principlely by burnup flattening.

The lower portion of the figure shows the average monthly discharge burnup as obtained by the SORO simulation, and the fuel added versus reactor heat curve. Also, plotted is the line of "ideal fuel added", for a burnup of 195 MWh/kg. With boron in the moderator, the actual fuel added data indicate a burnup of about 175 MWh/kg.

6.3.6 Fuel Defect Performance

Table VI.1 shows the defect rates for both Pickering and Bruce. Overall defect rate was .11%, comparable to Pickering. Bruce uses 37 element CANLUB fuel. The station has not yet reached maturity. Most of the 9 confirmed defects were due to manufacturing defects in the fuel bundles and are not related to fuelling.

6.3.7 Channel Power Peaking Factor

Figure 6.13 shows the channel power peaking factor as calculated by SORO.

6.4 Conclusion

In this report a broad overview of the analytical methods and operating procedures used in CANDU-PHW fuel management has been given. Following a brief description of some of the reactor systems which are more closely associated with fuelling, the methods which are employed to determine "reference" and "instantaneous" power distributions for the equilibrium core have been discussed. The salient features of the fuel management computer codes most commonly used, and the parameters which have to be calculated as part of the analysis of the equilibrium core have been reviewed. The general guidelines for selecting the sequence of channels to be fuelled while the reactor is in the approach to equilibrium and equilibrium phases was discussed.

Operating procedures used by Ontario Hydro to plan and implement the fuel management in operating reactors were described. Some special operating problems were discussed in this context. A review of operating experience for the Pickering NGS A and Bruce NGS A was presented. This review indicated that the objectives of fuel management set out in Section 1.1.2 are achieved in actual reactor operation. Meeting these objectives with the methods of calculation and operating procedures discussed contributed strongly to the achievement of high capacity factors and low fuelling costs for the CANDU-PHW reactors.

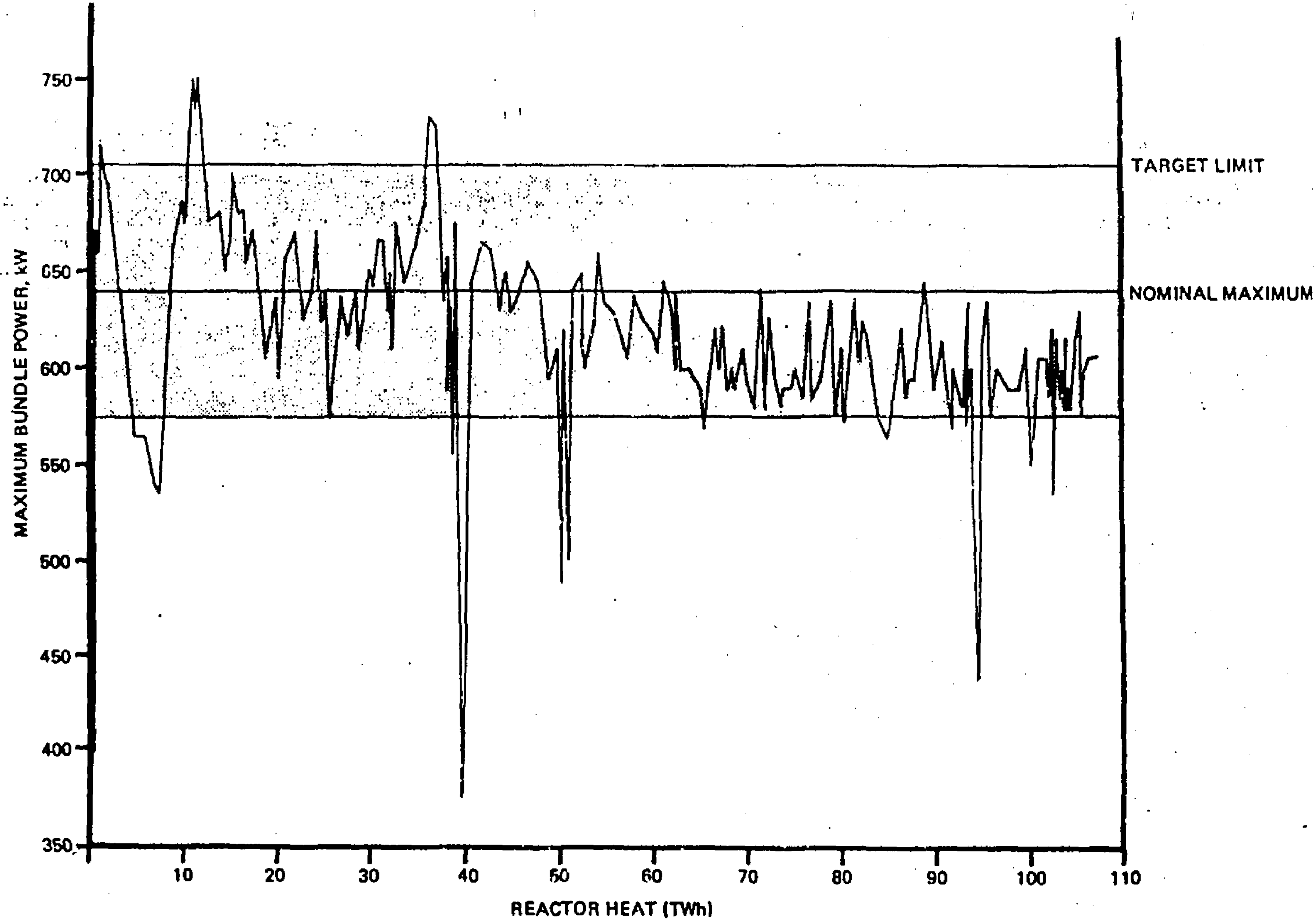


FIGURE 6.1
PICKERING UNIT 1, MAXIMUM BUNDLE POWER

Table VI.1

Fuel Defect Statistics
(To End of June, 1978)

	NPD	Douglas Point	Pickering Unit 1	Pickering Unit 2	Pickering Unit 3	Pickering Unit 4	Pickering Total	Bruce Unit 1	Bruce Unit 2	Bruce Unit 3	Bruce Unit 4	Bruce Tota
irst Core Bundles	1 188	3 632[a]	4 680	4 680	4 680	4 680	18 720	6 240	6 240	6 240	--	18 72
eplacement	2 852	12 085	23 800	22 442	16 992	14 292	77 526	4 836	5 042	1 264		11 14
otal Bundles rradiated	4 040	15 717	28 480	27 122	21 672	18 972	96 246	11 076	11 282	7 504		29 86
efect Bundles visually confirmed	8	58	77	0	6	1	84	4	5	0		[illegible]
efect Bundles[b] suspected	0	33	24	1	0	3	28	8	16	0		2
otal Defective undles (confirmed nd suspected)	8	91	101	1	6	4	112	12	21	0		33
efect Rate % accumulative)	0.198	0.579	0.355	0.004	0.028	0.021	0.116	0.108	0.186	0.000		0.111
efect Rate % (1976)	0.000	0.194	0.000	0.000	0.000	0.000	0.000	--	--	--	-	--
efect Rate % (1977)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.035	0.136	0.000		0.06
efect Rate % (1978)	0.000	0.000	0.030	0.000	0.000	0.000	0.008	0.101	0.100	0.000		0.07

otes for Fuel Defect Statistics

a) Forty cobalt bundles are not included.
b) A minimum of one defective bundle is assumed to have been discharged from Positions 5 to 10 of channels from which defective fuel was suspected on discharge based on radioactivity measurements (e.g., bay water, bay fields, air, release through the stack) or due to defect location measurements (DN of feeder scan) prior to channel being discharged.

c) Defect Rate $= \frac{\text{total defective bundles}}{\text{total bundles irradiated}} \times 100$

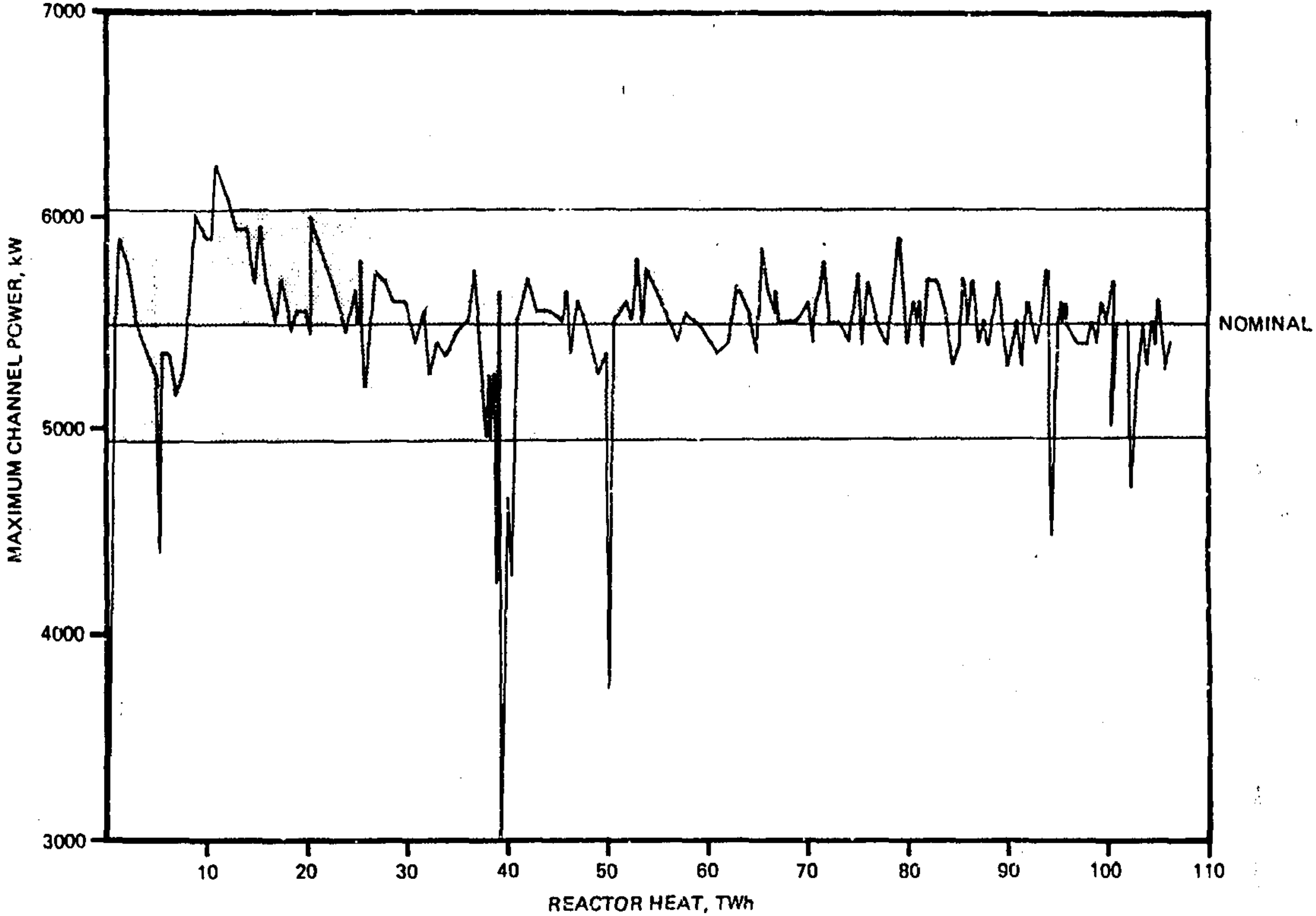


FIGURE 6.2
PICKERING UNIT 1, MAXIMUM CHANNEL POWER

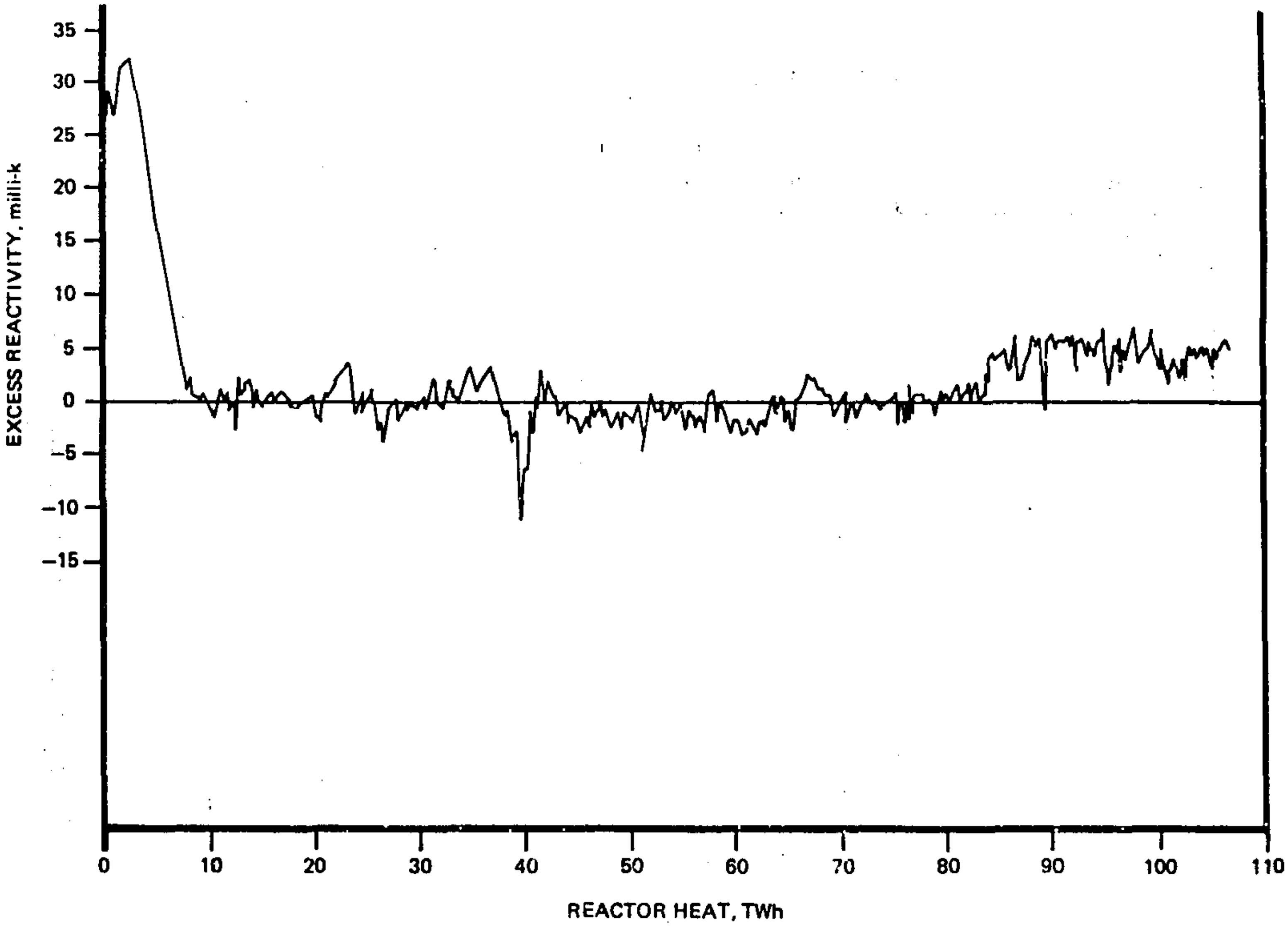


FIGURE 6.3
PICKERING UNIT 1, CORE EXCESS REACTIVITY

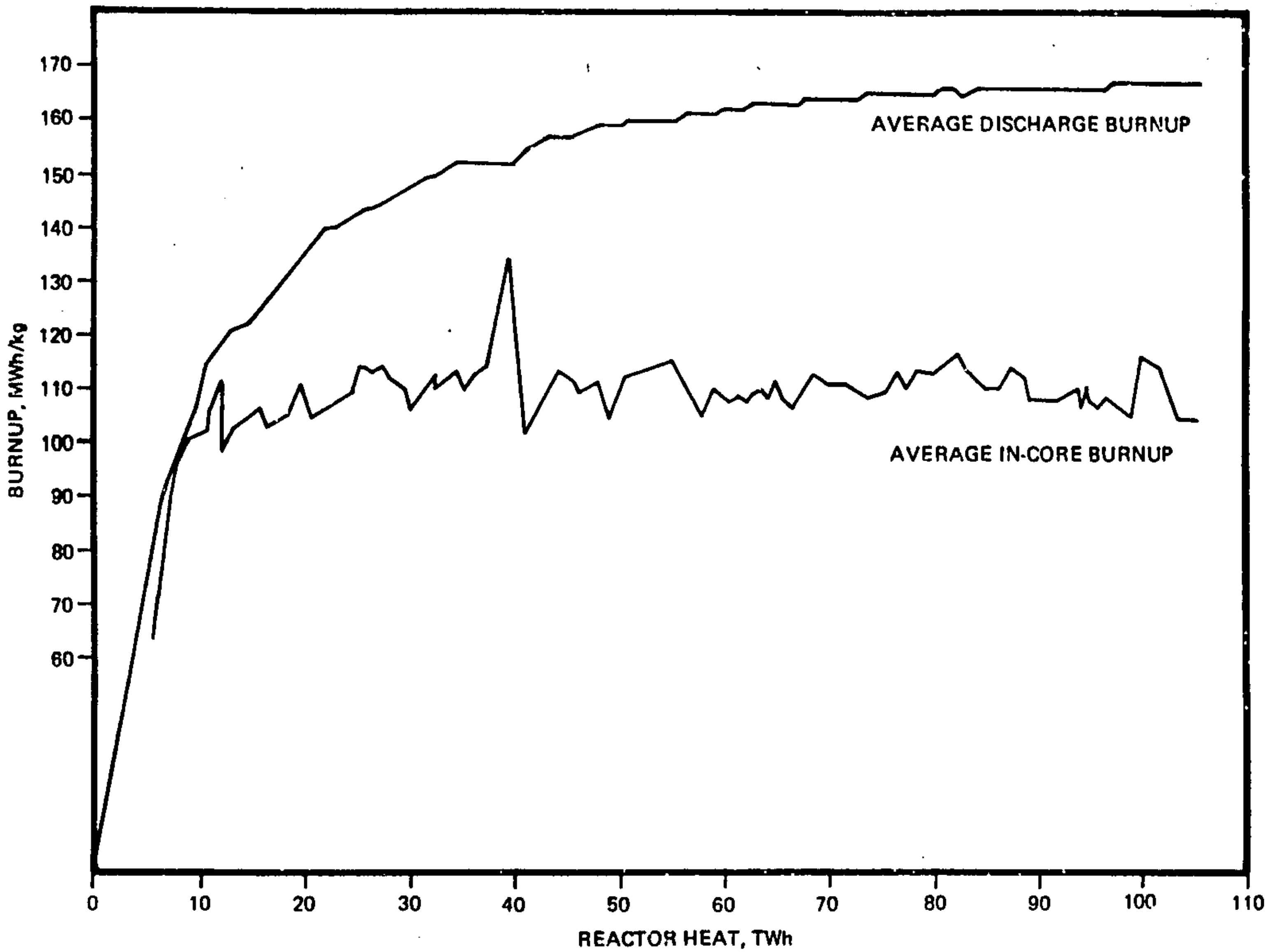


FIGURE 6.4
PICKERING UNIT 1, BURNUP

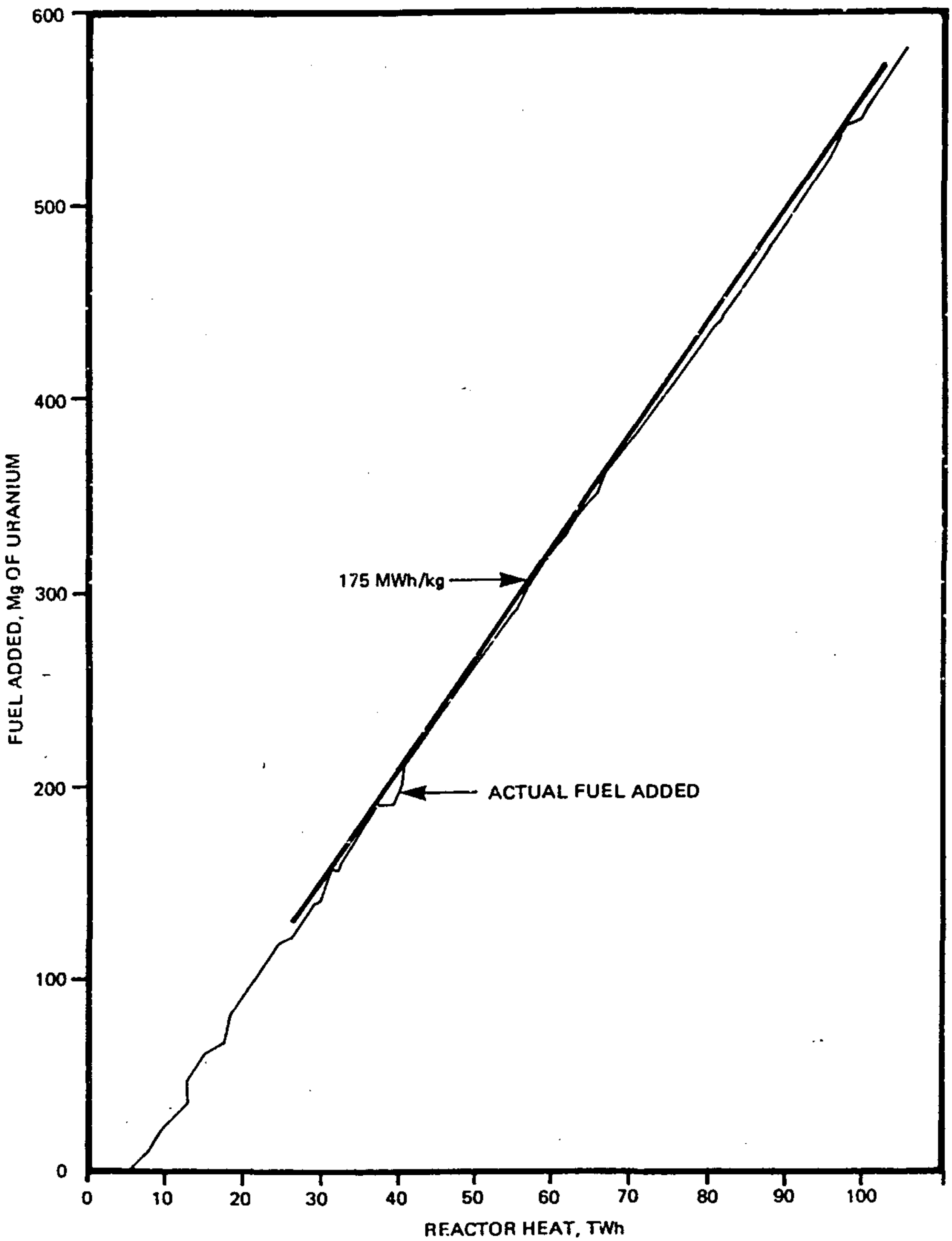


FIGURE 6.5
PICKERING UNIT 1, FUEL USAGE

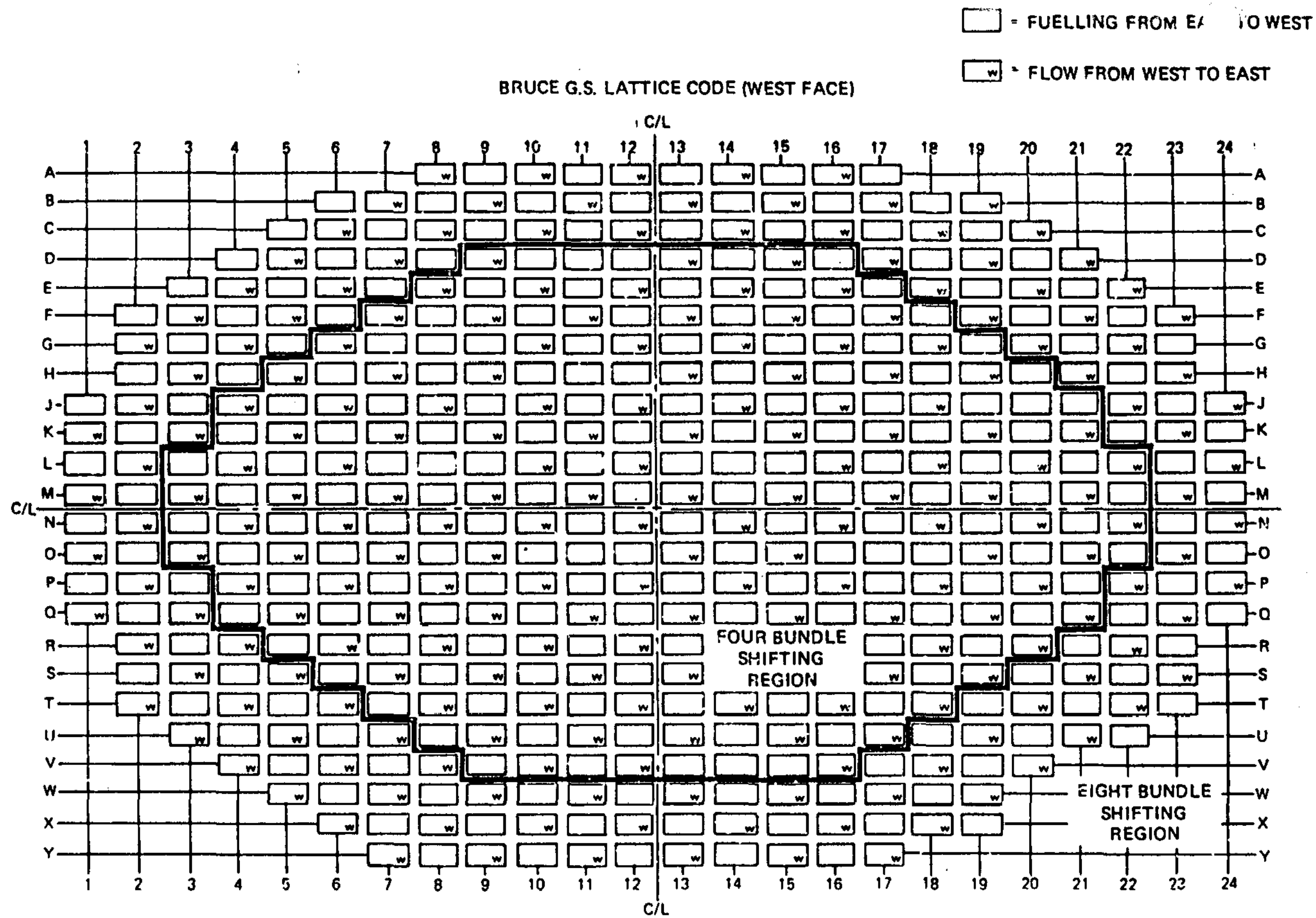


FIGURE 6.6
BRUCE A FUEL SHIFTING REGIONS

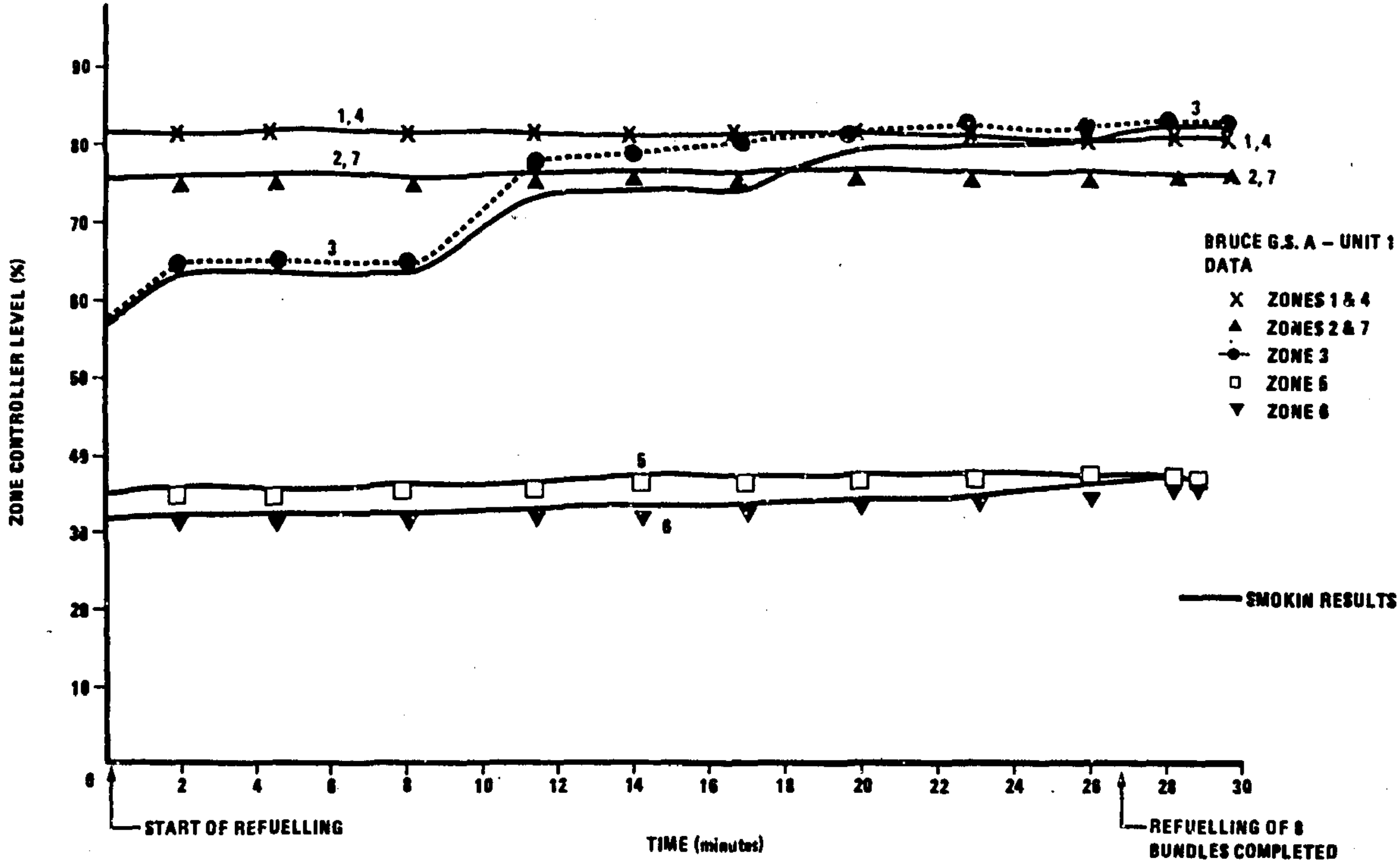


FIGURE 6.7
ZONE CONTROLLER LEVEL TRANSIENT FOR SINGLE CHANNEL REFUELLING (ZONES 1 TO 7)

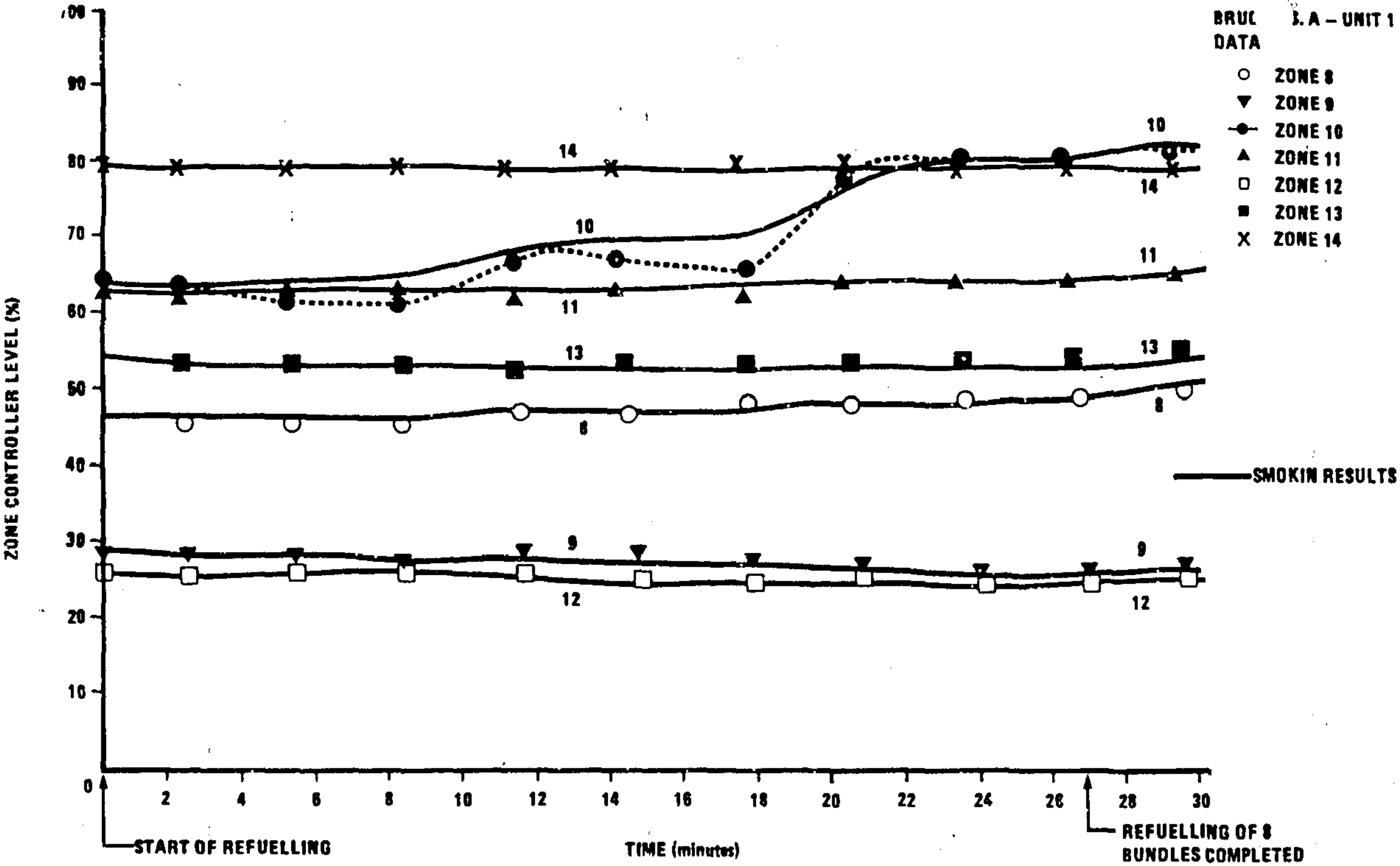


FIGURE 6.8
ZONE CONTROLLER LEVEL TRANSIENT FOR
SINGLE CHANNEL REFUELLING (ZONES 8 TO 14)

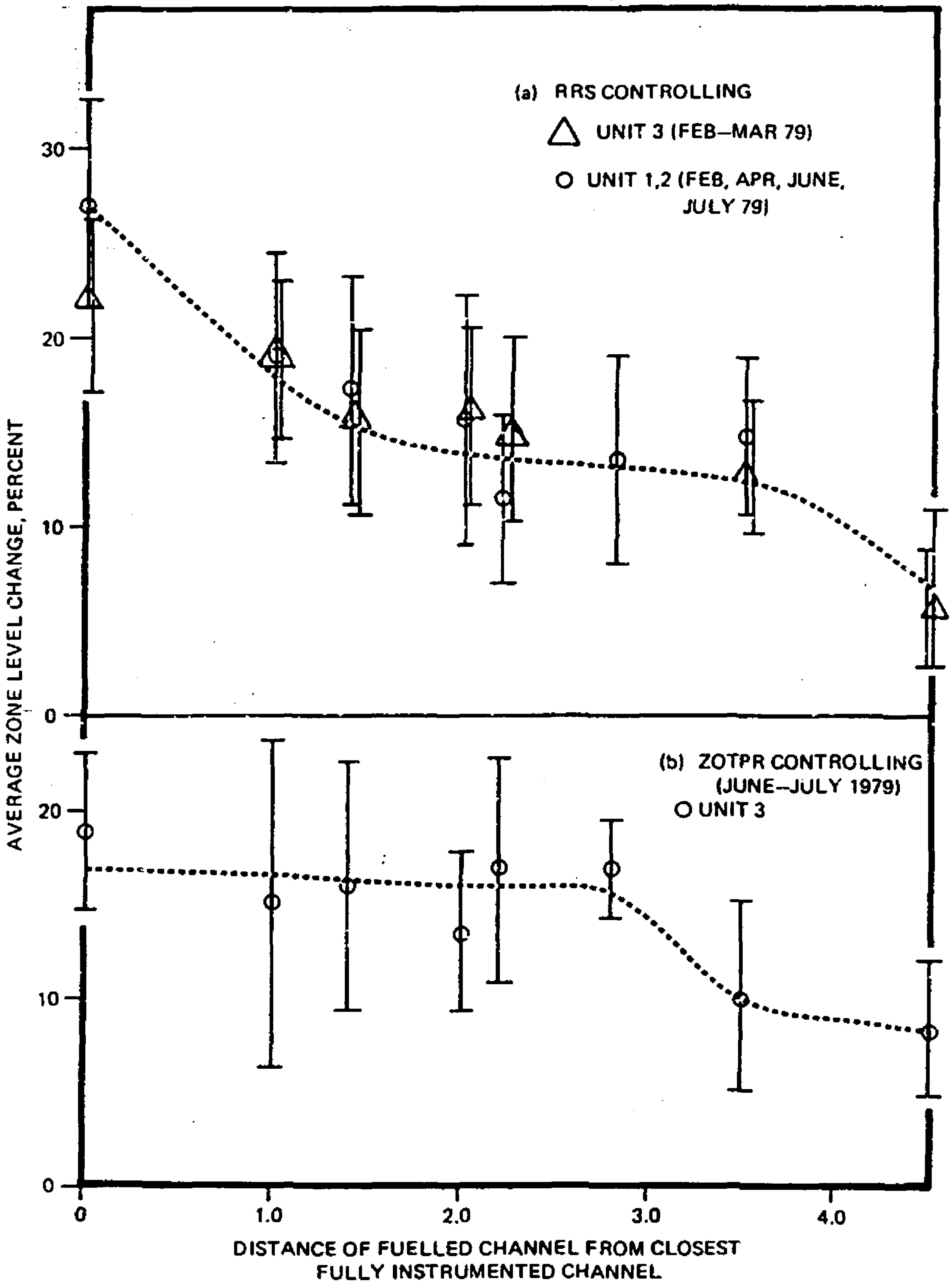


FIGURE 6.9
BRUCE NGS–3
AVG ZONE LEVEL CHANGE (FUELLED ZONE)

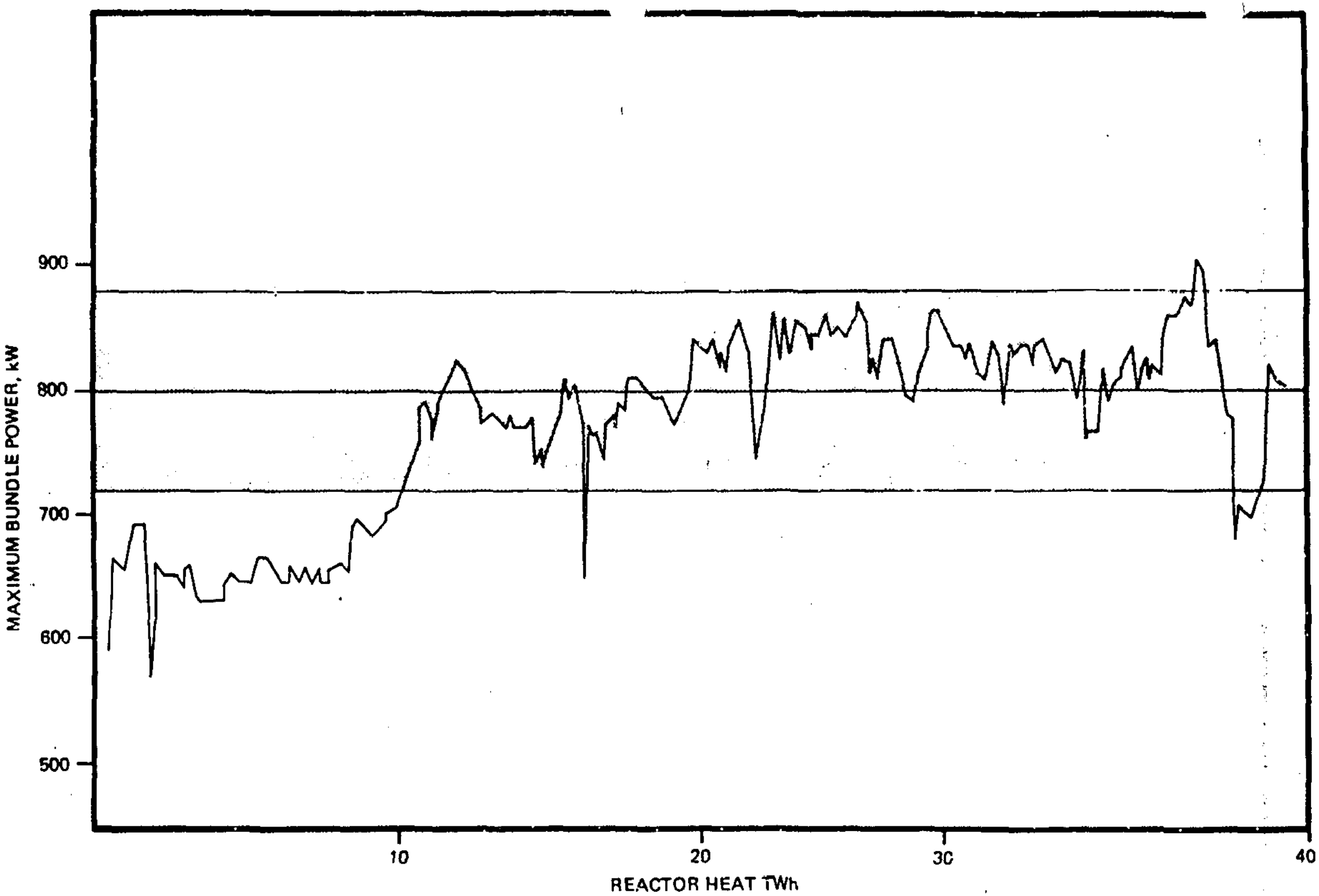


FIGURE 6.10
BRUCE UNIT 1,
MAXIMUM BUNDLE POWER

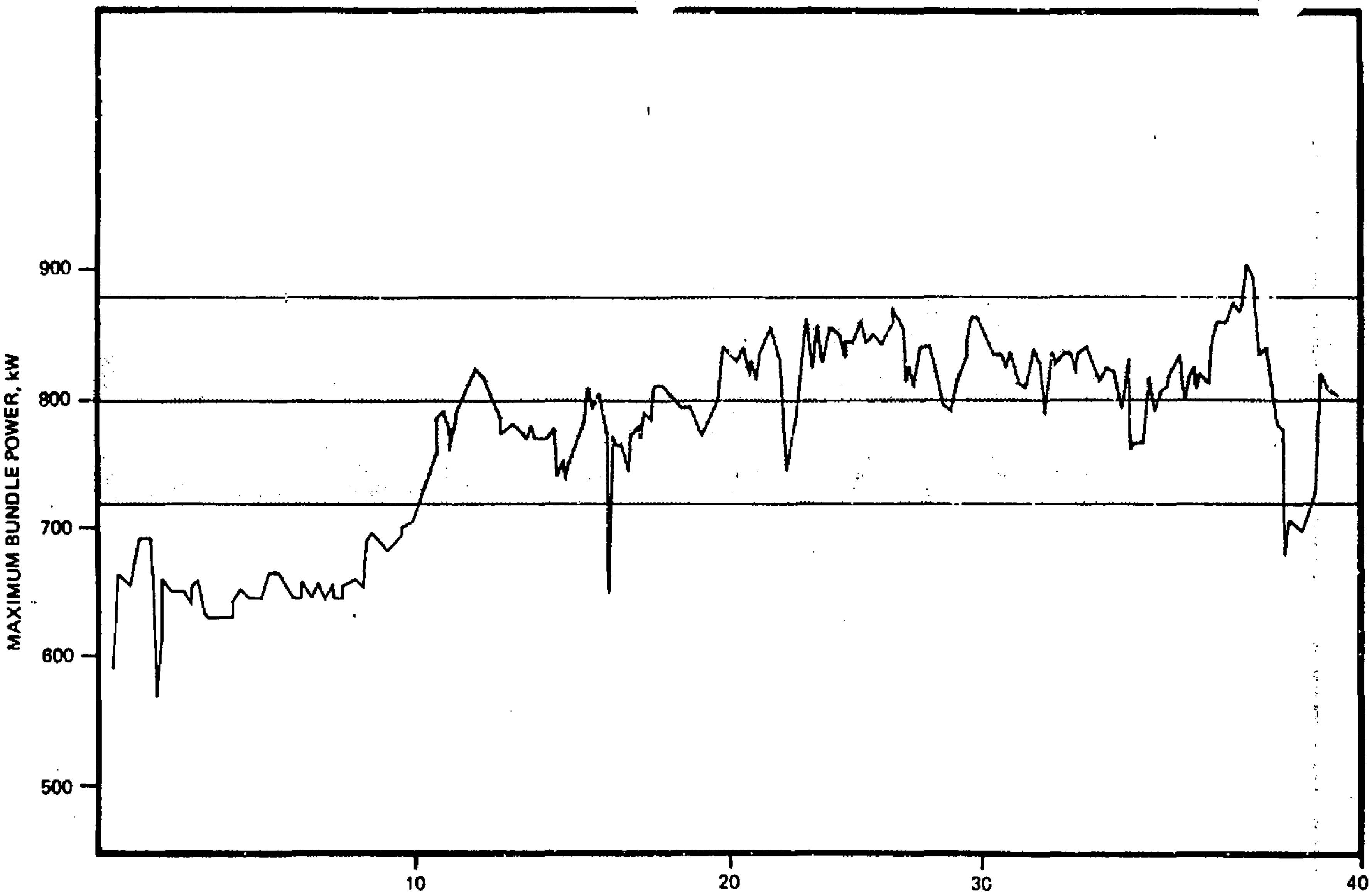


FIGURE 6.10
BRUCE UNIT 1,
MAXIMUM BUNDLE POWER

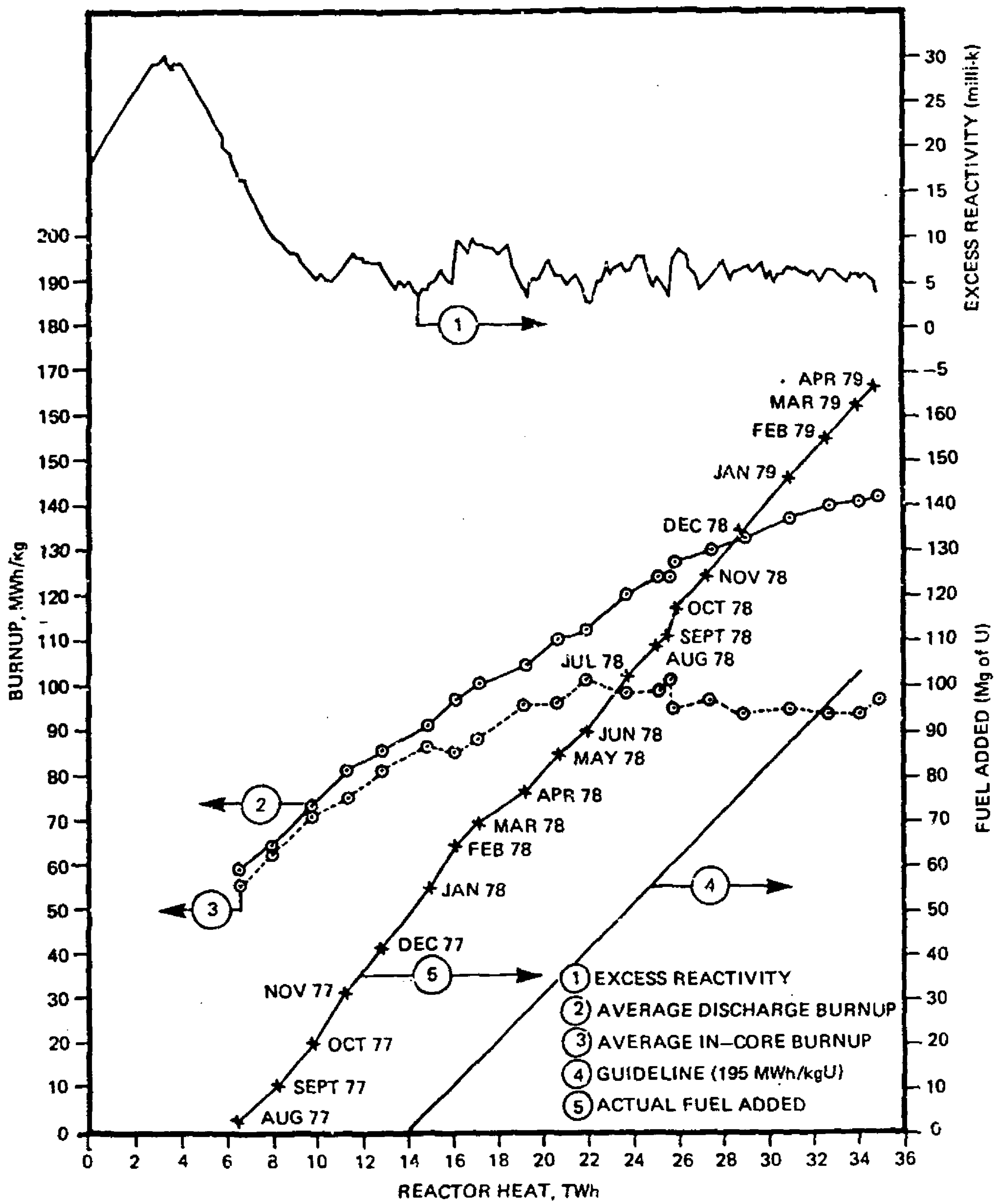


FIGURE 6.12
BRUCE UNIT 1 FUELLING PERFORMANCE

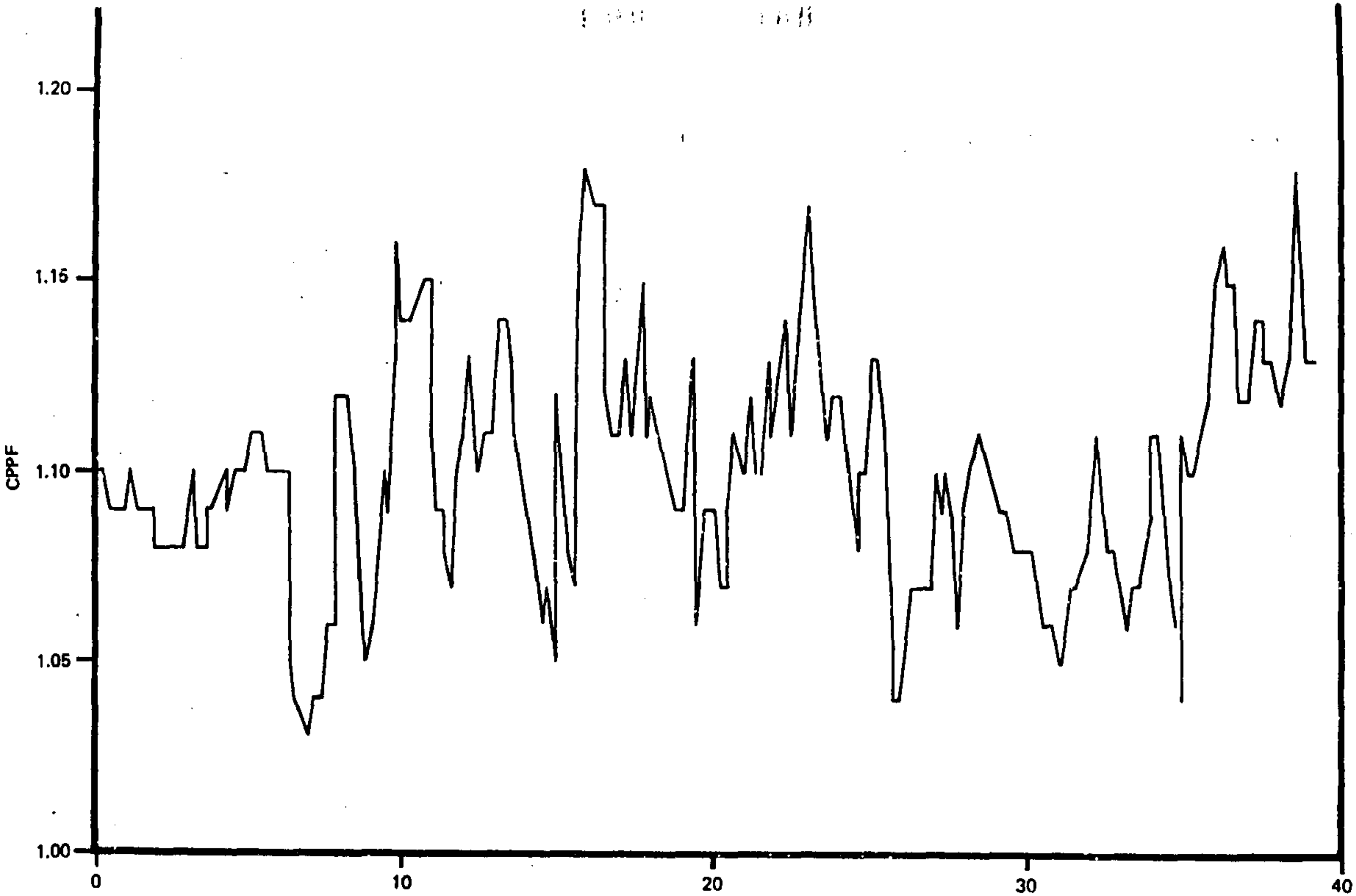


FIGURE 6.13
BRUCE UNIT 1,
CHANNEL POWER PEAKING FACTOR

7.0 GLOSSARY

Adjuster rods - control rods normally fully inserted in the core to provide positive reactivity for xenon override or reactivity shim.

Bidirectional fuelling - adjacent channels are fuelled in opposite directions.

Booster rods - rods of highly enriched uranium which provide positive reactivity when inserted in the core for xenon override or reactivity shim. CANDU reactors have either booster rods or adjuster rods, but not both.

Bundle power envelope - a fictitious bundle power history which gives a power for every burnup which is greater than or equal to the power produced by any bundle in the core at any time which has that burnup.

Bundle shifting scheme - the number of new bundles charged to a channel at one fuelling. For example in an "eight bundle shift", eight bundles are inserted in one end of the channel, the bundles in the channel are shifted along by eight positions, and eight irradiated bundles are discharged.

Burnup - the integrated energy produced by the fuel per unit mass of heavy elements initially in the fuel. It is usually expressed in units of MWh/kg.

Calandria - cylindrical vessel which holds the moderator. It is also called "reactor vessel".

Calandria tube - zirconium alloy tube which surrounds the pressure tube. It separates the cold moderator from the pressure tube containing the hot coolant.

Channel age - the fraction of the dwell time for a channel since its last refuelling.

Channel power peaking factor (CPPF) - the ratio of the channel power at a particular time to the reference channel power for that channel. The CPPF for a region, on the whole core, is taken as the maximum CPPF of all channels in the region.

Continuous bidirectional fuelling - an approximation used in calculations which assumes the fuel moves continuously through the channels in opposite directions in adjacent channels.

Core code - a computer program which computes flux distribution and reactivity from lattice cell cross sections, using discrete diffusion theory.

Depleted fuel bundles - fuel bundles having U-235 concentration lower than natural uranium, used for flux flattening or for fuel defects replacement.

Discharge burnup - the burnup corresponding to the discharge irradiation.

Discharge irradiation - average irradiation of fuel bundles discharged from a channel. As an approximation in calculations, the average discharge irradiation in a region is fixed at a constant value. It is also referred to as "exit irradiation".

Dwell time - the length of time between fuellings for a channel, in full power days.

Excess reactivity - the reactivity of the core compensated by removable poisons.

Flux distribution - the variation of the relative value of neutron flux from point to point in the core.

Flux-squared-weighted-mean-flux - the integral of the flux over the core, weighted by the flux squared.

FMPD - acronym for "Fuel Management Design Program" - a series of linked computer programs or "modules" used by AECL for reactor physics and fuel management calculations, and fuelling simulations. Ontario Hydro has a version of this program called OHRFSP for "Ontario Hydro Reactor Fuelling Simulation Program".

Fresh core - core consisting entirely of irradiated (fresh) fuel.

Fresh fuel - unirradiated fuel, sometimes called "new" fuel.

Fuel - the fissionable material, uranium or plutonium, which generates the heat, and the neutrons to sustain the chain reaction, in the form of a metal or oxide, including the associated cladding and other required structural materials.

Fuel accounting - is a record of each bundle which is or has been in the core, its burnup, serial number, and other relevant data.

Fuel bundle - assembly of fuel elements into a single structural unit. There are 28 or 37-fuel elements in commercial CANDU fuel bundles. The bundles are about .5 m long and .1 m in diameter. See Figure 1.2.

Fuel channel - assembly of pressure tube which contains the fuel bundles, and associated end fittings, feeders, closures and other hardware. Also used loosely to mean the pressure tube containing the fuel.

Fuel defect - any hole, crack or leak in the fuel sheath which allows the escape of fission products. Also called "fuel failure".

Fuel element - rod of zirconium alloy (sheath) and the cylindrical pellets of fuel material, usually UO_2, contained therein. It is sometimes referred to as a "pin" or "pencil".

Fuel engineer - a professional member of the station operating staff responsible for fuel scheduling.

Fuel handling system - all the mechanisms which take part in charging the fuel to the reactor, and removing irradiated fuel. It includes new and irradiated fuel bays, transfer mechanisms, trolleys, fuelling machines, fuelling machine carriages, and associated cooling, hydraulic and electrical systems, and control computers.

Fuel management - those aspects of loading, whether related to physics, engineering, or economic decisions, which are associated with fuel utilization and fuelling system performance. In this report, "fuel management" always refers to "in-core fuel management".

Fuel scheduling - the selection of channels for fuelling during the operation of a reactor.

Fuelling - the act of charging fresh fuel to the reactor and removing spent fuel. It is done on-power in CANDU reactors. The term "refuelling" is sometimes used interchangeably with "fuelling". The act of putting new fuel into the fresh core is referred to as "fuel loading", rather than "fuelling", and is usually done manually.

Fuelling capability, or fuel handling capability - the maximum number of channels or bundles which the fuel handling system can fuel per unit time over an extended period of time.

Fuelling machine - mechanical device for charging new fuel to a fuel channel and removing irradiated fuel. Fuelling machines usually work in pairs, one at each end of the channel .

Fuelling rate - number of channels or bundles which must be fuelled per unit time to keep the reactor critical.

Fuelling scheme - a more general term than "bundle shifting scheme". It refers to the replacement pattern of fuel in the channel and applies to systems where schemes more elaborate than simple push through fuelling are allowed.

Fuelling strategy - the selection of channels for fuelling, or the set of rules by which channels are selected for fuelling.

Full power day (FPD) - the energy generated in 24 hours of normal full power operation.

Homogeneous method - a method of calculating the flux distribution by assuming the irradiation dependent fuel cross-sections are constant axially in the core. The values of the cross-sections are determined by making the "continuous bidirectional fuelling approximation".

Initial core - core which has not yet been fuelled. The "initial core" extends from the fresh core to onset of fuelling.

Initial fuel loading - pattern of depleted and natural fuel bundles in the initial core.

Instantaneous power distribution - the power distribution at a particular time in a real reactor, or a power distribution calculated with a varying irradiation distribution.

Irradiation - the integrated flux to which the fuel has been exposed. It is usually expressed in units of neutrons/kilobarn (n/kb). Since burnup and irradiation are almost directly proportional, they are frequently used interchangeably in qualitative discussions.

Lattice cell code - a computer program which computes neutron balance and flux distribution for a unit cell in an infinite repeating array of unit cells. These codes are used to calculate cross-sections as a function of irradiation.

Liquid zone controllers - tubes in the core having compartments partially filled with light water. Reactivity is controlled by emptying or filling the compartments.

Milli k - unit of reactivity, sometimes written "mk". It is numerically 1000 times the value of reactivity.

Nominal power distribution - the time-averaged or reference power distribution used in the CPPF and other calculations. The ROP design and fuelling strategy are based on this distribution. The fuelling engineer uses this as a "target" distribution in fuel scheduling.

Onset of fuelling - time at which the core is first fuelled. It must occur before the excess reactivity has dropped below zero.

Overpower - fuel bundle or channel power in excess of specified safety related limits.

Power distribution - the variation of the relative value of bundle (or channel) power from point to point in the core.

POWDERPUFS - a computer code used for lattice cell calculations for CANDU reactors. POWDERPUFS is included within FMDP.

Pressure tube - zirconium alloy tube which runs horizontally through the core, it contains fuel bundles and coolant.

Regional overpower system (ROP) - the system which detects an overpower condition somewhere in the core, and causes a rapid shutdown (trip).

Residence time - length of time a bundle has resided in the core, in full power days.

Sheath - the rod which contains the fuel pellets, usually made of zirconium alloy. It provides structural support for the fuel and prevents escape of fission products. It is sometimes called "clad" or "cladding".

Simulation - a mathematical model of the reactor is set up on a large digital computer, and the behaviour of the system is approximated by calculating the flux and power distributions. In a "fuelling simulation" the irradiation is computed by integrating the flux distribution, and lattice cell cross-sections are calculated as functions of irradiation.

SMOKIN - a computer program which simulates reactor transients by expanding the flux distribution in a series of modes based on the higher harmonics of the diffusion equation.

SORO - acronym for "Simulation Of Reactor Operation", a computer program used by Ontario Hydro for fuelling simulations.

Spent fuel - fuel which has been irradiated in the core and discharged. Fuel is usually discharged because of low reactivity (high burnup) or because of a defect detected in the channel. Fuel bundles are not recycled in current CANDU reactors, so all discharged bundles are "spent fuel".

Supercell - a special unit cell which contains a reactivity device in addition to the fuel channnel. Since the reactivity devices are perpendicular to the fuel channels, the supercell is inherently three-dimensional and requires special computer programs for calculation of the cross sections.

Tilt - an imbalance in power between one location in the core, and the symmetrically opposite location.

Time-averaged method - a method of calculating the flux distribution by assuming cross sections for each bundle which are averaged over the bundle's residence time at each position in the channel. The resulting power distribution is a good approximation to the "time-averaged power distribution".

Time-averaged power distribution - the power distribution of channels or bundles, averaged over a sufficiently long time. For an equilibrium core the time-averaged power distribution is a constant.

Trip - a rapid shutdown of the reactor in response to the detection of certain abnormal and potentially dangerous conditions.

Unit cell - a fuel bundle, pressure tube and calandria tube, and associated coolant and moderator, used in the calculation of cross-sections by lattice cell codes. See Figure 2.2. It is also called a "lattice cell".