Journal of the Korean Nuclear Society
Volume 11, Number 4, December 1979

PMCR-A Power Mapping and Calibration Routing for 600 MWe CANDU-PHW Reactors

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(Received October 28, 1979)

Abstract

In 600 MWe CANDU-PHW reactors PMCR will be used on-site for calibration of the regional overpower system. PMCR will be executed off-line in one of the station computers. The program calculates accurate channel power maps by incorporating a fuel burnup dependent flux to power conversion algorithm. Fuel burnup is calculated by PMCR, hence it is independent of other software. Extensive comparisons with the uniform flux/power conversion approximations were made. Significant improvements in power mapping accuracy are achieved with PMCR.

요 약

PMCR은 600MWe CANDU-PHW의 지역 과출력 제어 계통의 일환으로 발전소 내에 설치된 computer를 이용하여 off-line으로 계산을 수행한다 이 프로그램은 계산된 중성자속 분포로 부터 연료 연소도를 고려한 출력 분포를 계산하여 정확한 channel 출력 분포를 얻는다.

PMCR은 따라서 발전소의 제어 프로그램과 별도로 연료 연소도를 계산한다. 이 논문에서는 기존의 균일 중성자속—출력 전환법을 이용한 계산결과와 비교하여 PMCR이 매우 정확한 출력 분포를 얻고 있음을 보여준다

1. Introduction

One of the trip parameters in 600 MWe CANDU-PHW reactors is a "neutron power" signal. Selfpowered incore platinum detectors are used to provide a measure of this parameter. Since the trip level of high neutron power is based on calcuations using idealized (i.c. homogeneous fuel burnup) power distributions the detector signals must be calibrated periodically to reflect the actual power distribution. For this reason accurate channel power maps are essential.

PMCR (Power Mapping and Calibration

Routine) was developed to calculate accurate channel power maps and detector calibration factors using the station computer DCC-Z. PMCR is executed off-line but uses data generated in the on-line computer. Channel powers are calculated from channel flux maps using a fuel burnup dependent flux to power conversion correlation. Fuel burnup is calculated by PMCR based on the actual fuelling schedule. This paper describes PMCR and presents work done to establish and test the flux/power burnup correlation.

2. Advantages of an On-site Calibration Procedure

An alternative to using PMCR to provide channel power maps is to use off-site fuel management calculations, as is to be done by the Korea Electric Co. for the Wolsung reactor. These simulations are fairly expensive neutron diffusion calculations and require considerable administrative effort to implement. Typically, such simulations will have to be performed every few days. All relevant input data, such as power level, channels fuelled, and average zone controller levels during the interval will be communicated by the station physicist to the Central Fuel Management Group in Seoul where the simulations are going to be performed. Results should be then communicated back to site.

In addition to this rather cumbersome procedure off-site fuel management simulations do not model xenon dynamics and spatial control action. A good calibration therefore requires very stable core conditions for about one day. This is of course often an undesirable constraint.

PMCR will be executed on-site, in the spare station computer DCC-Z, and the results are therefore immediately available to station personnel. The channel power maps calculated by PMCR are based on flux maps, derived from incore flux detectors (these are vanadium detectors used strictly for flux mapping and are independent of the platinum detectors which are to be calibrated via PMCR.) Dynamic effects due to xenon and spatial control following fuelling operations are "seen" by the mapping detectors and are therefore reflected in the channel power maps calculated with PMCR, thus making PMCR potentially more accurate than off-site fuel management calculations.

Since PMCR is executed on a station computer, which is idle most of the time, no additional computer charges are incurred. In principle PMCR may be executed as often as desired and whenever required by station personnel without additional computation cost. Potential errors which could arise in the transmission of data between site and off-site staff are also eliminated.

Clearly the availability of such an analytical tool at site has several advantages. In addition, besides the prime purpose of PMCR as a calibration routine, the power and burnup distributions generated by PMCR can also be used as a basis for selecting fuel channels to be fuelled. This does not however, obviate the requirement of periodic fuel mangement simulations, since these generate additional essential data which must be monitored and recorded on a longer time scale.

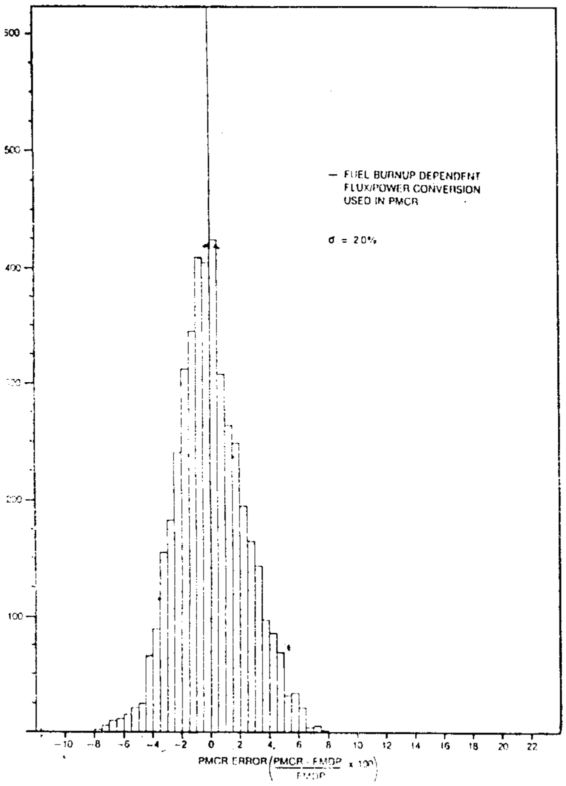

Fig. 3.2.1. Comparison between FLUX MAP and FMDP for Channels≥5.75MW

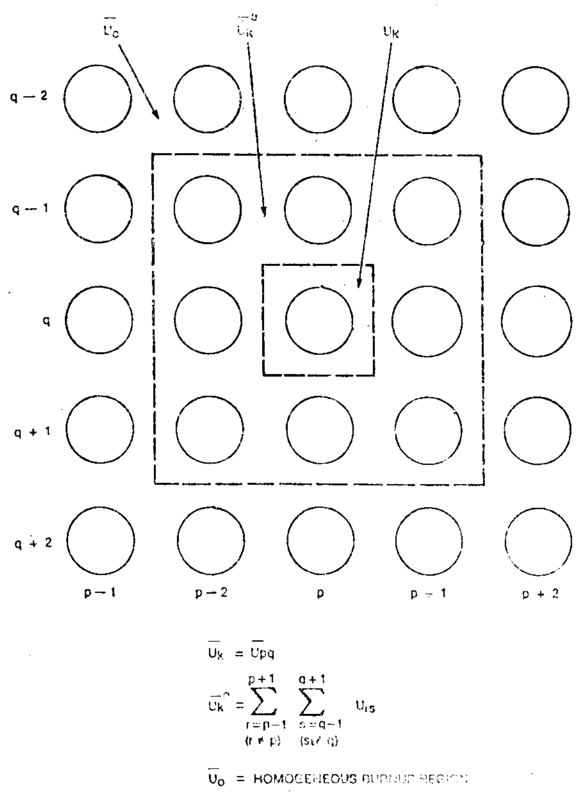

Fig. 3.2.2. Definition of Burnup Environment

3. PMCR-General Description

3.1 Flux Mapping

The starting point for PMCR is a set of flux mode amplitudes calculated by the continuous on-line FLUX MAP program. Details of FLUX MAP are described in reference (1). Suffice it here to say that in 600 MWe CANDU-PHW reactors flux maps are calculated every two minutes, on-line, using a modal expansion technique by fitting the flux at 102 incore detectors using a least squares criterion. These flux modes are stored in PMCR and on inputting their amplitudes a flux map is easily calculated using the linear expansion:

$$\bar{\phi}_k=\sum_{n-1}^{N} \phi_{nk}\ A_n \qquad (3.1.1)$$

where,

$\bar{\phi}_k$=average flux in channel "k"

ϕ_{nk}=coupling coefficient between flux mode "n" and channel "k"

A_n=amplitude of flux mode "n"

3.2 Flux to Power Conversion

As a first approximation one can assume that channel power is directly proportional to average channel flux, i.e.

$$P_k=N\bar{\phi}_k \qquad (3.2.1)$$

where "N" is independent of channel burnup and of the fuel type. "N" may readily be obtained from a normalization to total reactor thermal power:

$$\sum_k P_k=\sum_k N\bar{\phi}_k=P(th) \qquad (3.2.2)$$

i.e. $N=\frac{P(th)}{\sum_k \phi_k}$

This is the procedure used in the on-line program FLUX MAP. Fig. 3.2.1 shows a comprehensive comparison between FLUX MAP and detailed fuel management simulations, and it is seen that the overall accuracy is ~3.5% (one standard deviation, assuming "N" is known exactly).

The accuracy of the flux to power conversion can however be improved by recognizing that it should be a function of the burnup of the channel in question, of the burnup of its environment, and of the fuel type of individual bundles in the channel (e.g. depleted vs natural uranium fuel). PMCR therefore uses a flux to power conversion of the following form:

$$P_k=N(1+\alpha[\bar{u}_k])(1+\beta[\bar{u}_k^e])(\bar{r}_k)\bar{\phi}_k \quad (3.2.3)$$

where,

$\alpha[\bar{u}_k]$ = polynomial function of the average channel burnup $\bar{u}_k$

$\beta[\bar{u}_k^e]$ = polynomial function of the average burnup of the environment of channel "k"; the environment is restricted to the eight surrounding channels, see Fig. 3.2.2.

$\bar{r}_k$ = factor depending on the fuel bundle types and their location within channel "k".

The constant "N" is obtained as in FLUX MAP, by normalizing $\sum_k P_k$ to total reactor power.

4. Fuel Burnup and Fuel Type Correlations

4.1 Effect of Burnup on Flux to Power Conversion

The flux modes which provide the basis for the flux map from which a channel power map is calculated were obtained with MONIC (2) using two homogeneous burnup zones. As a result the calculated flux map essentially a smoothed distribution which does not recognize localized effects due to burnup variations about the assumed homogeneous values. Local variations in burnup cause local variations in cell flux as well as variations in the cell flux to power conversion. In principle these effects could be allowed for independently and their magnitudes could be ascertained from supercell simulations with all possible combinations and over all practicable ranges of fuel burnup. One could calculate channel power using the following relationship:

$$P_k=N\bar{\phi}_c(\bar{u}_o)\times\frac{\bar{\phi}_c(\bar{u}_k^e)}{\bar{\phi}_c(\bar{u}_o)}\times\frac{\bar{\phi}_c(\bar{u}_k)}{\bar{\phi}_c(\bar{u}_k^e)}\times H(\bar{u}_k) \quad (4.1.1)$$

where,

$\bar{\phi}_c(\bar{u}_o)$ = mapped average cell flux assuming homogeneous burnup "$\bar{u}_o$"

$\bar{\phi}_c(\bar{u}_k^e)$ = average cell flux in a localized environment having burnup "$\bar{u}_k^e$"

$\bar{\phi}_c(\bar{u}_k)$ = average cell flux for a channel having burnup "$\bar{u}_k$"

$H(\bar{u}_k)$ = ratio of thermal power to cell flux for a channel with burnup "$\bar{u}_k$".

Due to the extensive supercell calculations which would be required to calculate the above relationships we have chosen a simpler, semi-empirical approach.

4.2 Burnup Correlation Algorithm

We assumed that the flux to power conversion depended on the four independent factors and functions N, $\alpha(\bar{u}_k)$, $\beta(\bar{u}_k^e)$, and $\bar{r}_k$, as given in Equation 3.2.3. The normalization factor "N" was discussed in Section 3.2. "$\bar{r}_k$" is assumed fuel type, but not fuel burnup dependent. Its determina-

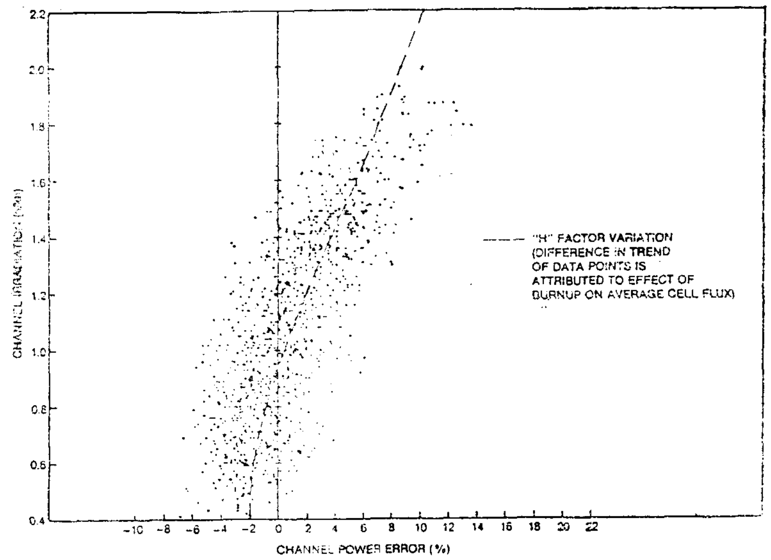

Fig. 4.2.1. Random Sample of Data Points Exhibiting a Burnup Correlation

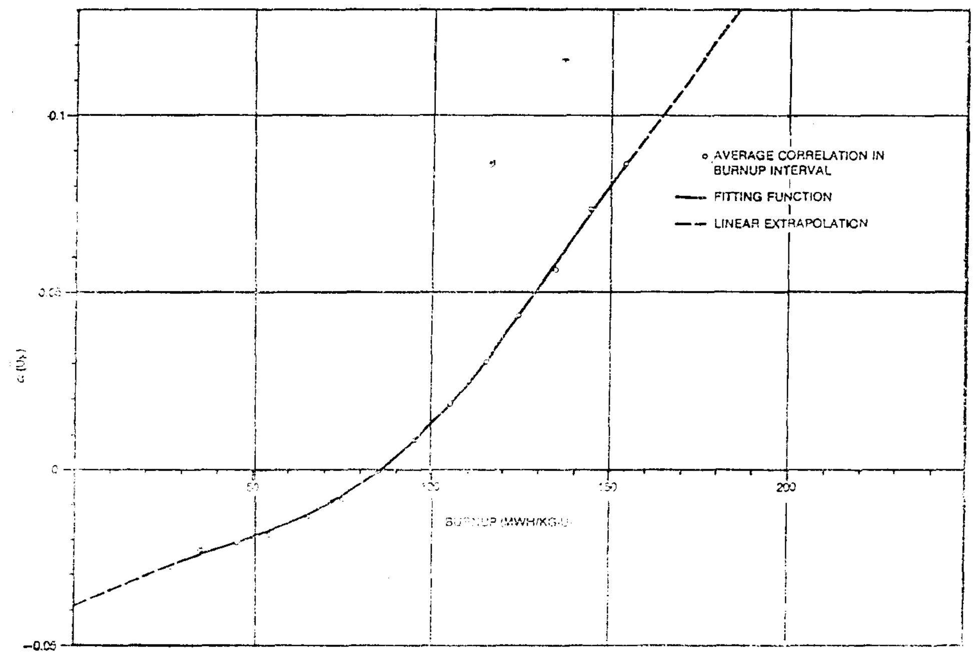

Fig. 4.2.2. Correlation Function Between FLUX MAP Error and Channel Burnup

tion is discussed in Section 4.3.

The function $\alpha(\bar{u}_k)$ and $\beta(\bar{u}_k^e)$ were determined essentially by a Monte Carlo technique. We had available a detailed FMDP (3) time-simulation of the fuelling history and operation of a 600 MWe CANDU-PHW reactor covering more than 600 FPD (Full Power Days) of operation. We assumed that over this period of operation all possible combinations of channel burnup and environmental burnups are encountered in a random way. Flux maps were generated using detector readings extracted from the FMDP simulation and "sprinkled" with random detector errors. These flux maps were compared to the original FMDP simulations. The discrepancies between the channel powers produced by FLUX MAP (using expression of Equation 3.2.1 for the flux to power conversion) and FMDP were correlated first with individual channel burnup "$\bar{u}_k$".

Fig. 4.2.1 shows a small sample of the data comparing FLUX MAP with FMDP as a function of channel burnup. It is evident that a strong correlation between the FLUX MAP "error" and channel burnup exists. For comparison the relative variation of $H(\bar{u}_k)$, i.e., the fuel power to cell flux ratio as calculated with the cell code POWDERPUFS-V (4) is also shown in Fig. 4.2.1. It is evident that the semi-empirically derived burnup correlation is stronger than the variation of $H(\bar{u}_k)$ with burnup. This is to be expected. The difference between the observed correlation and $H(\bar{u}_k)$ is due to the dependence on burnup of the ratio of local cell flux to "homogeneous" cell flux. The semi-empirically derived correlation includes both effects at once.

Fig. 4.2.2 shows a least squares polynomial fit to all data points generated in the FLUX MAP/FMDP comparison. The total number of data points was of the order of 10,000, and the correlation is therefore well founded. A fifth order polynomial is used in the interval 30 to 150 MWh/kgU. Outside these limits linear correlations are used. The function $\alpha(\bar{u}_k)$ then has the following form:

$$\alpha(\bar{u}_k)=\sum_{i=1}^{6} C_i \bar{u}_k^{(i-1)} \qquad (4.2.1)$$

where,

$C_1=-0.400314\times10^{-1}$ $\quad 0\leq\bar{u}_k\leq30$

$C_2=3.872337$

$C_3=C_4=C_6=C_6=0$

$C_1=5.282951$ $\quad 30\times\bar{u}_k<150$

$C_2=-0.148325$

$C_3=0.277537\times10^{-2}$

$C_4=-0.264710\times10^{-4}$

$C_6=0.672786\times10^{-7}$

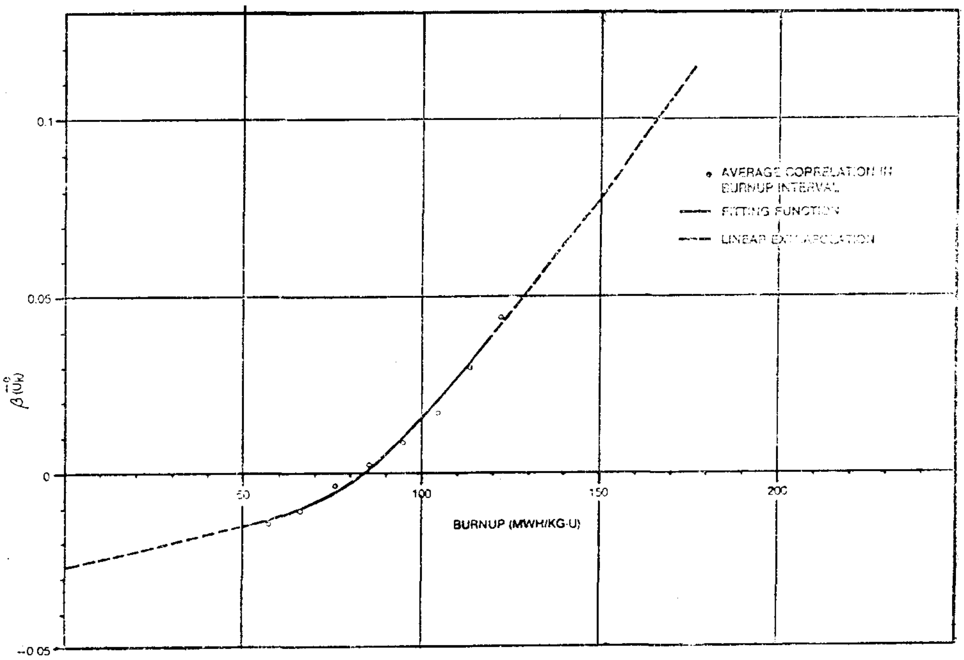

Fig. 4.2.3. Correlation Function Between FLUX MAP Error and Environmental Burnup

$C_6 = 0.239030 \times 10^{-10}$

$C_1 = -0.139426 \qquad 150 \leq \bar{u}_k$

$C_2 = 12.929191$

$C_3 = C_4 = C_6 = C_6 = 0$

After establishing $\alpha(\bar{u}_k)$ as described, FLUX MAP was rerun using:

$$P_k = N(1 + \alpha[\bar{u}_k])\phi_k \tag{4.2.2}$$

in the flux to power conversion. These power maps, now corrected for the effects of individual channel burnup variation were then again compared to the FMDP channel powers. The residual "errors" were now correlated with the average environmental burnup. The environment was restricted to the eight nearest neighbours of a channel. These channels affect the surrounded channel most strongly. Furthermore if the next ring of channels beyond the eight nearest neighbours is considered (see Fig. 3.2.2) one finds that due to the larger number of channels in the ring the average burnup of that ring is close to $\bar{u}_o$, i.e., the average homogeneous burnup. Hence only a very weak effect would exist, and the burnup of channels beyond the first ring of eight was therefore not considered.

Fig. 4.2.3 shows the correlation $\beta(\bar{u}_k^e)$ as a function of the environmental burnup. This correlation appeared parabolic, hence a least squares fit to second order polynomial was made. A linear correlation is used when $50 \leq \bar{u}_k^e \leq 120$ MWh/kgU. The data points shown in Fig. 4.2.3 are the average FLUX MAP residual "errors" in a given environmental burnup interval. These averaged data points were again obtained by considering of the order of 10,000 data points, and the correlation with the environmental burnup is therefore well established. The function $\beta(\bar{u}_k^e)$ finally arrived at has the form:

$$\beta(\bar{u}_k^e) = \sum_{i=1}^{3} B_i \, \bar{u}_k^{e\,(i-1)} \tag{4.2.3}$$

where,

$B_1 = -2.255510 \times 10^{-2} \qquad 0 \leq \bar{u}_k^e \leq 50$

$B_2 = 2.627471$

$B_1 = -0.156322 \qquad 50 < \bar{u}_k^e < 120$

$B_2 = 2.627471$

$B_3 = -0.927930 \times 10^{-3}$

$B_1 = -0.152465 \qquad 120 \leq \bar{u}_k^e$

$B_2 = 14.319388$

4.3 Fuel Type Correlation

In CANDU-PHW reactors both natural and depleted uranium fuel may be used. Depleted fuel bundles are used in the early operating period for power flattening. These bundles are gradually discharged as differential burnup is used to shape the power distribution. Depleted fuel may however, also be used to fuel channels for the purpose of removing defected bundles. If the channel containing defective fuel is located in a high power region the fuelling of up to 12 fresh bundles at one time could aggravate the situation and thereby cause further fuel defects. Depleted fuel may be used to suppress local power peaks in such instances.

PMCR uses for each channel a fuel type dependent flux to power conversion factor "$\bar{r}_k$" (see equation 3.2.3). This factor depends on the fuel bundle type, the number of bundles of each type in a given channel, and their location.

We assume that the axial power distribution within each channel is as calculated by a "time-average" calculation with the fuel management program FMDP, assuming all fuel bundles are natural uranium fuel. The relative bundle power fraction "BPF_{jk}" is stored in PMCR for each bundle "j" for all channels. The fuel type correlation factor $\bar{r}_k$ is calculated as:

$$\bar{r}_k = \sum_{j=1}^{12} BPF_{jk}(1+\delta_{jk}) \qquad (4.3.1)$$

where "δ_{ik}" is a correction factor applied to the relative bundle power fraction. δ_{jk} is zero for natural fuel. For depleted uranium fuel $(1+\delta_{jk})$ is the ratio of the bundle power per unit cell flux of depleted fuel to natural fuel. This ratio is calculated with the lattice code POWDERPUFS-V and is assumed irradiation independent (for 0.52% U-235 depleted fuel, which is the loading used in 600 MWe CANDU-PHW reactors, $\delta_{jk}=-0.22$).

5. Calculation of Fuel Burnup

5.1 Standard Fuelling and Operation

Fuel burnup is calculated in discrete time steps assuming that the power distribution is constant over a given time interval. The time interval is determined by the frequency of executing PMCR. In principle the program could be executed after each fuelling operation or significant reactor configuration change, and hence good time resolution may be achieved. In practice however, it is expected that PMCR will be executed once every few days, or whenever the need for detector calibration arises.

PMCR essentially calculates a channel power map. In order to calculate average channel burnup the two dimensional channel power map is unfolded into a three-dimensional bundle power map. This is necessary to accomodate the effects of fuel bundle shifting and of depleted fuel on average channel burnup.

Bundle powers are obtained from channel powers using the following expression:

$$BP_{jk} = P_k BPF_{jk}(1+\delta_{jk}) \qquad (5.1.1)$$

where BP_{jk} is the thermal power of bundle "j" in channel "k", and other variables are as already defined. Bundle burnup is then calculated from:

$$BBU_{jk}(t_1) = BBU_{jk}(t_0) + BP_{jk}\Delta tU$$

where,

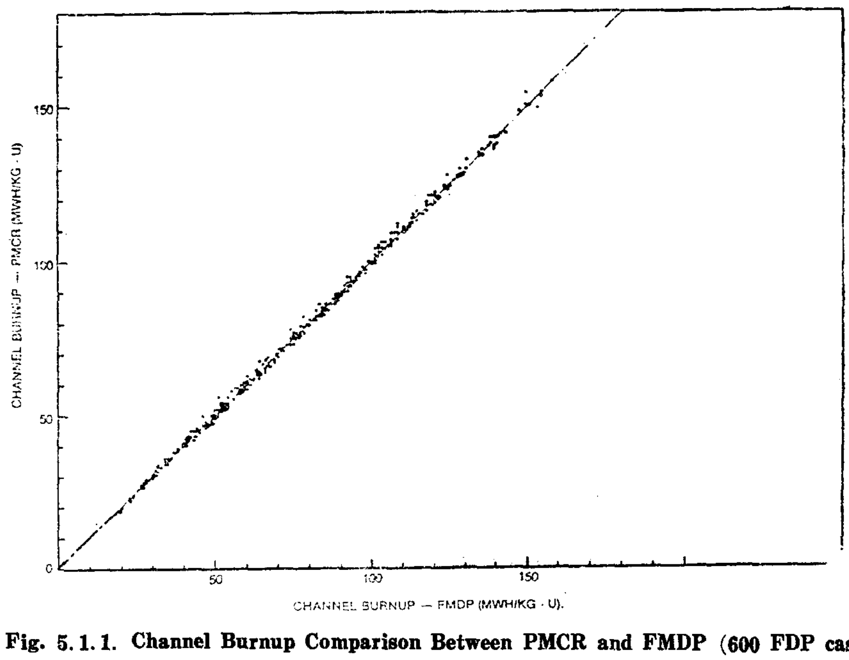

Fig. 5.1.1. Channel Burnup Comparison Between PMCR and FMDP (600 FDP case)

$BBU_{jk}(t)$ = bundle burnup at time t

$\Delta t = t_1 - t_0$ is the burnup step

U = ratio of fission to thermal power.

Bundle burnup is further converted to units "MWh/kgU" by dividing BBU_{jk} by the uranium content per bundle.

If channels were fuelled since the last PMCR execution δ_{jk} is updated if depleted bundles were shifted, and BBU_{jk} is adjusted to reflect the fuelling shift before the burnup step is calculated.

Average channel burnup is calculated simply as the arithmetic average of all bundles in a channel. For fuel scheduling decision making the average of the last eight bundles in each channel is also calculated.

In order that the burnup of all bundles is properly updated the channel identification and the times when they were fuelled must of course be input to PMCR.

We simulated the 600 FPD period of operation referred to in section 4.2 with PMCR and compared average channel burnup calculated with PMCR to FMDP. Fig. 5.1.1 shows such a comparison at 600 FPD. At this point in time the range of burnup in the core covers the entire spectrum expected during equilibrium operation. As seen in Fig. 5.1.1 the agreement between PMCR and FMDP is excellent, despite the fact that fairly coarse burnup steps of ~20 FPD were used in PMCR.

5.2 Non-Standard Fuelling

A non-standard fuelling option in PMCR allows for updating the *BPF* and *BBU* arrays for cases where fuelling may be in a direction opposite to normal fuelling or where a fuelled bundle has non-zero burnup. This option could therefore be used by operators who may wish to recycle some fuel in order to improve fuel burnup of the first fuel charge.

6. PMCR Accuracy

6.1 FLUX MAP Accuracy-Bruce A Data

Bruce A reactors use an on-line flux mapping system which uses the same general methodology as FLUX MAP in 600 MWe CANDU-PHW reactors. Bruce A reactors are also equipped with 22 fully instrumented channels, which provide independent channel power measurements. Extensive comparisons have been made by Ontario Hydro between flux map based channel powers and instrumented channel powers. Some of this work is reported in reference(5). Extensive subsequent analyses were made and results are now available. Using a burnup independent flux/power conversion the discrepancy between flux mapping in Bruce A and instrumentated channel power measurements is found to be ~5% (one standard deviation). The discrepancy may be considered to result from three components:

$$\sigma^2_{total} = \sigma^2_{FLUX\ MAP} + \sigma^2_{RP} + \sigma^2_{IC}$$

where "*RP*" refers to reactort thermal power measurement (used to normalize FLUX MAP), and "*IC*" designates instrumented channels. σ_{RP} and σ_{IC} are estimated to be ~1.5% and ~2.0%, respectively (for non boiling channels). This would imply $\sigma_{FLUX\ MAP} = \sim 4.3\%$ in the Bruce A on-line system, and some of this uncertainty is expected to be due to the burnup independent flux/power conversion.

6.2 Flux Mapping Improvements in 600 MWe CANDU-PHW

Apart from the inclusion of a burnup

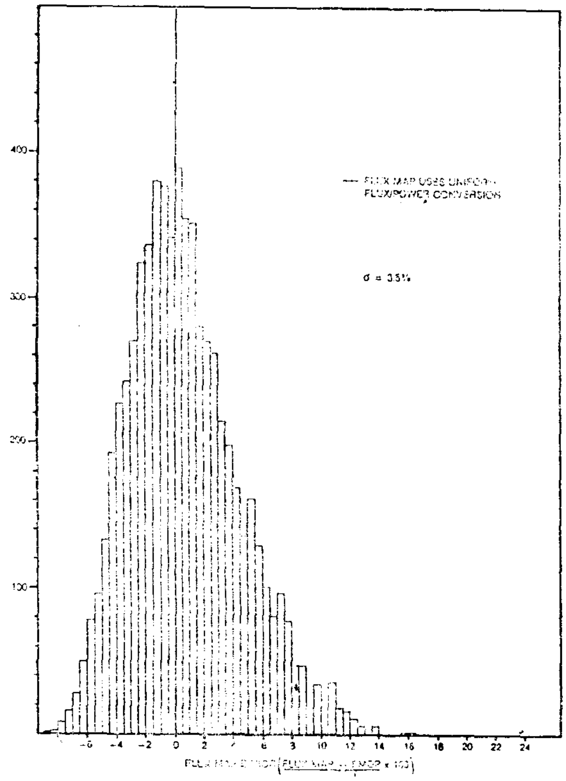

Fig. 6.3.1. Comparison between PMCR and FMDP for Channels≥5.75MW

dependent flux/power conversion in PMCR the accuracy of the on-line FLUX MAP program in 600 MWe reactors (on which PMCR is based) has been improved considerably. Instead of 54 detectors as used in Bruce A 102 detectors are used. Since 600 MWe reactors have smaller cores this gives a much better coverage of the flux distribution. In addition these detectors are better positioned to sense the dominant flux perturbation. FLUX MAP in 600 MWe reactors also uses more flux modes (15 vs 10 in Bruce A) for nominal operation. Lastly the vanadium flux mapping detectors will be calibrated accurately prior to their installation in 600 MWe reactors. This was not done for unit 1 and 2 of Bruce A, for which most of the flux mapping analysis is available.

Analytical studies on flux mapping detector error propagation in Bruce A and in 600 MWe CANDU-PHW (based on data reported in reference (1) and (6)) show that an improvement of ~1% in $\sigma_{FLUX\ MAP}$

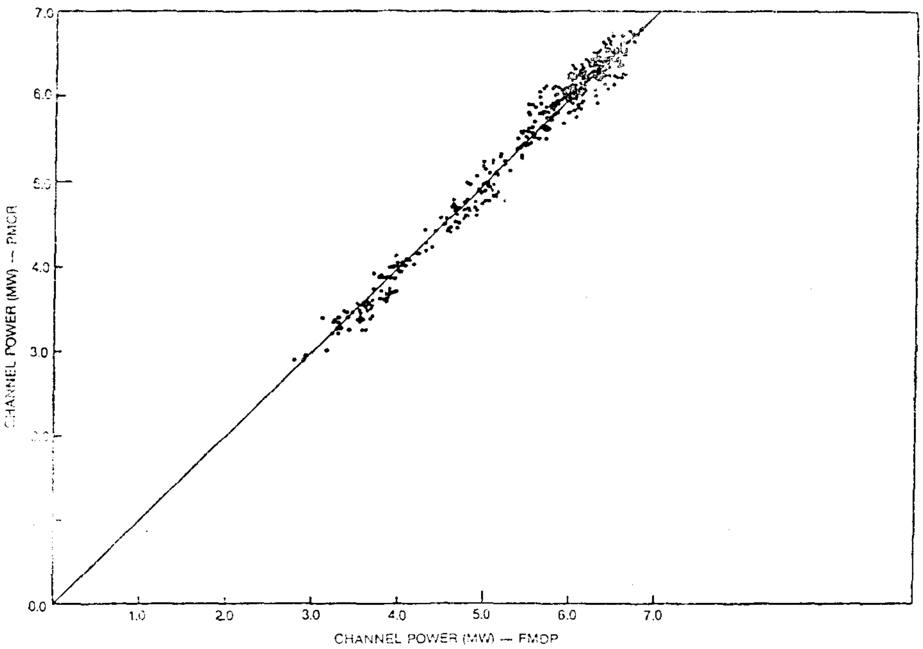

Fig. 6.3.2. Channel Power Comparison between PMCR and FMDP (600 FDP case)

may be expected in the latter reactors. We conclude therefore that $\sigma_{FLUX\ MAP}$ in 600 MWe reactors will be ~3.3%. Combined with the uncertainty in reactor thermal power measurement, used to normalize FLUX MAP we expect:

$$\sigma^2_{total}=\sigma^2_{FLUX\ MAP}+\sigma^2_{RP}$$
$$=3.3^2+1.5^2$$

whence $\sigma_{total}=3.6\%$.

6.3 Improvements Due to Burnup Correction

The magnitude of the improvement expected due to using burnup dependent flux/power conversion in PMCR was ascertained by comparing PMCR with FMDP simulations. Fig. 6.3.1 shows a histogram of channel power errors obtained from comparing PMCR with FMDP at 20 different instances in time between 200 and 600 FPD operation, each case comparing~200 high powered channels. The standard deviation of this error histogram is 2%. This may be compared to the histogram shown in Fig. 3.2.1 for these same comparisons using FLUX MAP, which is identical to PMCR without burnup dependent flux/power conversion. One standard deviation in Fig. 3.2.1 amounts to 3.5%. The improvement achieved with PMCR over FLUX MAP therefore amounts to reducing one standard deviation by 1.5%. The total uncertainty characterizing a channel map obtained with PMCR is therefore deduced as:

$$\sigma^2_{total}=\sigma^2_{PMCR}+\sigma^2_{RP}$$
$$=(3.3-1.5)^2+1.5^2$$

whence $\sigma_{total}=2.3\%$.

Fig. 6.3.2 shows a comparison between a single case of PMCR and FMDP (chosen arbitrarily at 600 FPD). This figure demonstrates the comparison at various channel power levels. One can see that the magnitude of the spread of data points about the PMCR=FMDP line is roughly independent of channel power. This implies however, a relatively larger relative uncertainty for lower channel powers and smaller relative uncertainties for larger channel powers. This is a desirable feature in the present context, and it is due to the unweighted least squares criterion used in determining mode amplitudes(see reference (1)). The density of points in Fig. 6.3.2 is larger at higher channel power levels since a large number of channels are in the "flat" part of the power distribution.

7. Summary

The PMCR program has been developed for use on one of the station computers. By incorporating a burnup dependent flux to power conversion algorithm an improvement over the on-line FLUX MAP program of ~1.5% in the accuracy of channel power mapping is achieved. This improvement, as well as other improvements in FLUX MAP, together with Bruce A operating experience on a similar system allowed us to deduce an overall accuracy for PMCR calculated channel powers of ~2.3% (one standard deviation).

Acknowledgements

We are grateful to Mr. J. P. Lucas for his efforts in adapting PMCR for execution on the station computer. We are also indebted to Ontario Hydro for permission to use Bruce A operating data. In particular Dr. A.M. Lopez has been very cooperative in this respect.

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