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A Study on the Effect of Gamma Background in Low Power Startup Physics Tests

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저출력 노물리 시험에서의 감마 Background의 영향에 관한 연구

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Abstract

Low power physics tests should be performed for the domestic pressurized light water reactors (PWRs) after refueling. The tests are performed to ensure that operating characteristics of the core are consistent with predictions and that the core can be operated as designed. But in some low power physics tests, slow but steady reactivity increasing phenomena were noticed after step reactivity insertion by the control rod movement. These reactivity increasing phenomena are due to the low flux level and the gamma background because an uncompensated ion chamber (UIC) is used as the ex-core neutron detector. The gamma background may affect the results of the low power physics tests. The aims of this paper are to analyze the grounds of such phenomena, to simulate a reference bank worth measurement test and to present a resolution quantitatively.

In this study, the gamma background level was estimated by numerically solving the point kinetics equations accounting the gamma background effect. The reactivity computer check test was simulated to verify the model. Also, an appropriate neutron flux level was determined by simulating the reference bank worth measurement test. The determined neutron flux level is approximately 0.3 of the nuclear heating flux. This level is about 3 times as high as the current test upper limit specified in the test procedure. Then, the findings from this work were successfully applied to Kori unit 4 cycle 7 and Yonggwang unit 1 cycle 7 physics tests.

요　　약

국내 가압 경수로는 핵연료 재장전후 해당 주기 노심핵설계의 타당성 및 안전 제한치의 만족 여부를 확인하기 위하여 저출력에서 노물리 시험을 수행한다. 그러나 고리 3호기 7주기를 포함한 일부 저출력 노물리 시험 중 step 반응도를 삽입한 후에도 반응도가 서서히 증가하는 기이한 현상이 나타났다. 이러한 현상은 시험시 중성자속 준위가 낮고 노외 핵계측기로 비보상형 전리함을 사용

하기 때문에 감마 background가 존재하여 생기는 것이다. 이로 인해 노물리 시험 결과는 많은 오차를 포함할 수도 있는 것이다.

본 연구에서는 반응도가 증가하는 현상을 정량적으로 분석하고 기준 제어봉 제어능 측정 시험을 모사함으로써 노물리 시험 결과의 오차를 줄일 수 있는 방법을 제시하고 이후의 노물리 시험에 적용하여 확인하였다. 또한 감마 background 준위를 산정한 후 중성자속 준위를 조정하여 기준 제어봉 제어능 측정 시험을 통해 감마 background의 영향을 받지 않는 중성자속 준위를 결정하였다. 결정된 중성자속 준위는 핵가열이 발생하는 중성자속의 3/10이다. 이것은 기존의 상한치보다 3배 증가된 것이다. 이 결과는 고리 4호기 7주기 및 영광 1호기 7주기 노물리 시험에 성공적으로 적용되었다.

1. Introduction

The low power physics tests should be performed for the domestic pressurized light water reactors (PWRs) after refueling or other significant reactor core alteration to ensure that the operating characteristics of the core are consistent with predictions and that the core can be operated as designed. A domestic PWR uses ex-core neutron detectors outside the reactor vessel to measure the neutron flux level.

The low power physics test procedures being used by Korea Electric Power Corporation (KEPCO) are divided into two parts of General Test and Nuclear/Safety Test. The items of General Test include initial criticality, determination of the test range for low power physics test and reactivity computer check test. The items of Nuclear/Safety Test include end point boron concentration, isothermal temperature coefficient (ITC), and bank worth measurements(1). Nuclear/Safety Test is performed according to the items and regulations of American Nuclear Standard ANSI/ANS-19.6.1-1985(2).

Table 1 shows regulations for the items. These regulations describe the types, methods and criteria for the predicted values for the low power physics tests to ensure that the core can be operated as designed(3).

The neutron flux signals are recorded on a strip chart recorder through reactivity computer which calculates the reactivity from the neutron flux signal. The signals are coming from the ex-core neutron detectors which are uncompensated ion chambers(4).

An appropriate neutron flux range should be determined carefully for the low power physics test to ensure that reactivity measurements are to be valid. The test range should be below the nuclear heating point where Doppler effect starts

Table 1. Recommended Test Items and Criteria

Test Parameter	Test Criteria
1. HZP Critical Boron (Control Rod Withdrawn)	±50 ppm
2. Differential Boron Worth (Boron Reactivity Coefficient)	±15%*
3. Control Rod Worth -Individual Bank	±15% or ±0.1% $\Delta\rho$ whichever is greater(for rod swap, the reference bank should be within ±10%)
-Sum of Banks	±10%
4. ITC	$\pm 0.2\times10^{-4}\ \Delta\rho/°F$

*Note : For calculating percent difference use(Pred/Meas.−1)×100 to be activated. Also, the test range should be high enough so that the signal from the ex–core detector is not interfered by the constant background current or disruptive noise spikes. In other words, the test must be performed within the power range where the signal is proportional to the neutron flux level and thus a true indicator of the reactivity.

Domestic reactors currently utilize low leakage loading patterns (LLLP) with low powered fuel assemblies at the core periphery not only to increase the neutron utilization but to reduce the neutron fluence to the reactor vessel. Unfortunately, this reduction leads to the low neutron leakage to ex–core detectors. Therefore, the neutron signal at the nuclear heating point becomes lower and the gamma background as compared with the neutron signal happens to be relatively higher than before. This relative increase of the gamma background can thus give a significant impact on the physics test results.

The items of Nuclear/Safety Test are calculated by MEDIUM(5) which is utilized for current reload core nuclear design. But because MEDIUM cannot simulate the reference bank worth measurement under a strong gamma background, SIMPT, a program for solving point kinetics equations numerically, is utilized to simulate the test for measuring reference bank worth. In order to demonstrate the usefulness of this program, a kinetic parameter check of the reactivity computer, an item of the General Test, was first simulated. Also the gamma background level was estimated by simulating the reactivity increasing phenomenon occurred during the tests for the nuclear heating point (NHP) determination and for the reference bank worth measurement. The simulated bank worth agreed well with the measured and the designed values respectively. The findings were successfully applied to Kori unit 4 cycle 7 and Yonggwang unit 1 cycle 7 physics tests.

2. Numerical Model of Point Kinetics Equations

Point kinetics equations can be generally written as follows(6),(7),

$$\frac{dn}{dt} = \frac{k(1-\beta)-1}{\ell^*} n(t) + \sum_{i=1}^{6} \lambda_i c_i(t), \tag{1}$$

$$\frac{dc_i}{dt} = \beta_i \frac{k}{\ell^*} n(t) - \lambda_i c_i(t). \tag{2}$$

where

i : delayed neutron group index(1, 2, ……, 6).

n(t) : time–dependent neutron flux.

$c_i(t)$: delayed neutron precursor concentration for i^{th} group.

λ_i : decay constant of precursor concentration for i^{th} group.

β_i : delayed neutron fraction for i^{th} group.

β : total delayed neutron fraction.

k : multiplication factor.

ℓ^* : prompt neutron lifetime.

Equations (1) and (2) become equations (3) and (4) respectively in terms of neutron generation time, Λ, and reactivity, ρ, where $\Lambda$and ρ are defined as ℓ^*/k and $(k-1)/k$, respectively ; ,

$$\frac{dn}{dt} = \frac{\rho(t)-\beta}{\Lambda} n(t) + \Sigma\lambda_i c_i(t), \tag{3}$$

$$\frac{dc_i}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i c_i(t). \tag{4}$$

For the reactor which is initially at steady state, the initial conditions of equations (3) and (4) can be written as ;

$$n(0) = n_0, \quad c_i(0) = \frac{\beta_i}{\lambda_i \Lambda} n_0.$$

From equation (4), the equilibrium precursor concentration of group i becomes as follows ;

$$c_i(t) = \frac{1}{\lambda_i} \frac{\beta_i}{\Lambda} n(t). \tag{5}$$

In order to consider the effect of the gamma background, neutron flux and precursor concentrations must be replaced by equations (6) and (7), respectively;

$$N(t) = n(t) + \frac{\gamma}{n_0}, \tag{6}$$

$$C_i(t) = \frac{1}{\lambda_i}\frac{\beta_i}{\Lambda}\left[n(t) + \frac{\gamma}{n_0} \right]. \tag{7}$$

where

$N(t)$: time-dependent neutron flux with the gamma background.

$C_i(t)$: delayed neutron precursor concentration for i^{th} group with the gamma background.

n_0 : initial neutron flux.

γ : gamma background level.

There are several numerical methods for solving the above point kinetics equations[8] Following the analogy of reference [8], difference forms of equations for the solutions of equations (3) and (4) are given as[9];

$$n(t+\Delta t)\left[1 - \frac{\rho(t+\Delta t) - \beta}{\Lambda}\frac{\Delta t}{2} \right] = n(t) + \left[\frac{\rho(t) - \beta}{\Lambda} n(t) + \Sigma\lambda_i c_i(t) + \Sigma\lambda_i c_i(t+\Delta t) \right]\frac{\Delta t}{2}, \tag{8}$$

$$c_i(t+\Delta t)\left[1 + \frac{\lambda_i \Delta t}{2} \right] = c_i(t) + \left\{ \frac{\beta_i}{\Lambda}[n(t+\Delta t) + n(t)] - \lambda_i c_i(t) \right\}\frac{\Delta t}{2}. \tag{9}$$

Similarly for the neutron flux and the precursor concentrations with the gamma background, following forms of the difference equations can be written;

$$N(t+\Delta t)\left[1 - \frac{\rho(t+\Delta t) - \beta}{\Lambda}\frac{\Delta t}{2} \right] = N(t) + \left[\frac{\rho(t) - \beta}{\Lambda} N(t) + \Sigma\lambda_i C_i(t) + \Sigma\lambda_i C_i(t+\Delta t) \right]\frac{\Delta t}{2}, \tag{10}$$

$$C_i(t+\Delta t)\left[1 + \frac{\lambda_i \Delta t}{2} \right] = C_i(t) + \left\{ \frac{\beta_i}{\Lambda}[N(t+\Delta t) + N(t)] - \lambda_i C_i(t) \right\}\frac{\Delta t}{2}. \tag{11}$$

Also equation (3) can be converted into the following inverse kinetics equation for the reactivity[10];

$$\begin{aligned} \rho(t) &= \beta + \Lambda \cdot \frac{1}{n(t)} \cdot \frac{dn(t)}{dt} - \frac{\Lambda}{n(t)}\Sigma\lambda_i c_i(t) \\ &= \beta + \frac{\Lambda}{n(t)}\left[\frac{n(t+\Delta t) - n(t)}{\Delta t} - \Sigma\lambda_i c_i(t) \right]. \end{aligned} \tag{12}$$

And the reactivity with the gamma background becomes as follows;

$$\rho(t) = \beta + \frac{\Lambda}{N(t)}\left[\frac{N(t+\Delta t) - N(t)}{\Delta t} - \Sigma\lambda_i C_i(t) \right]. \tag{13}$$

If the initial neutron flux, n_0, and the reactivity changes, $\rho(t)$, are given to SIMPT program, $n(t+\Delta t)$ and $c_i(t+\Delta t)$ from equations (8) and (9) can be obtained respectively. However $n(t+\Delta t)$ and $c_i(t+\Delta t)$ do not include the gamma background. Therefore, to consider the effects of the gamma background, the neutron flux, $N(t)$, and the precursor concentration, $C_i(t)$, must be calculated from equations (6) and (7). These are obtained by inserting $n(t)$ into equations (6) and (7). Then from equations (10) and (11), $N(t+\Delta t)$ and $C_i(t+\Delta t)$ from time t to $t+\Delta t$ can be calculated respectively. Also, by inserting $N(t)$, $N(t+\Delta t)$ and $C_i(t)$ into equation (13), the reactivity with the gamma background effects can be obtained.

3. Test Phenomena

3.1. Test Range Determination for the Low Power Physics Tests

If the reactor core reaches the criticality, the nuclear heating point (NHP) determination test is performed. This test is to determine the nuclear heating point–the starting point where the reactivity decreases due to the Doppler feedback effect. Then, the test range for the low power physics test can be determined according to the current procedure, which generally defines the test range between a tenth and a hundredth of the nuclear heating point.

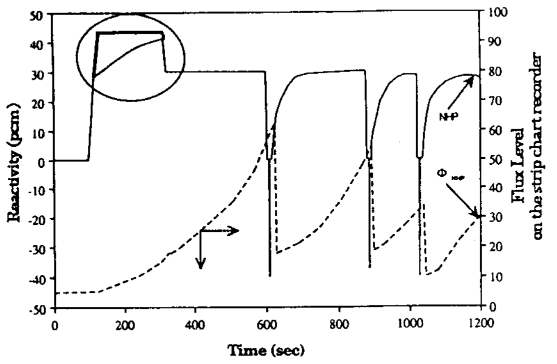

Fig. 1. Determination of Nuclear Heating Point for Kori 3 Cycle 7

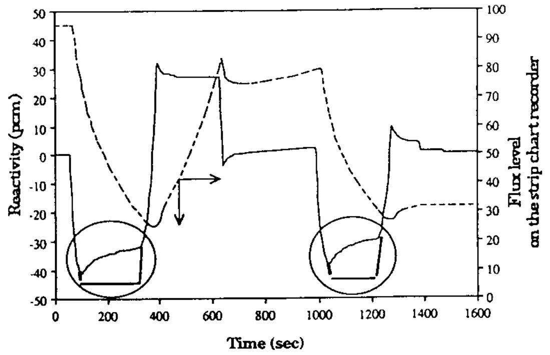

Fig. 2. Measurement of Endpoint Boron for Kori 3 Cycle 7

Fig. 1 shows the nuclear heating point determination experiment for Kori unit 3 cycle 7. The solid line denotes the reactivity change that is drawn on the strip chart recorder during the experiment. The experiment is executed by inserting positive reactivity of about 30 pcm into the core from the critical condition by withdrawing the control bank D. Since the positive 30 pcm is inserted to the core, the neutron flux increases exponentially until it reaches nuclear heating point. The transient parts are due to the adjustment of the operation selector to prevent the neutron flux from deviating the range of the strip chart recorder. Once it reaches the nuclear heating point, the increasing rate of the neutron flux starts to reduce and the core reactivity begins to reduce from the initially inserted 30 pcm due to the Doppler effect.

But as shown in Fig. 1, it was noticed that the reactivity increased slowly to about 40 pcm even though the control bank D group stayed still without further withdrawal.

3.2. End point Boron Concentration

The reactivity increasing phenomenon also appeared during the measurement of end point boron concentration with the reference bank fully inserted as shown in Fig. 2. The solid line denotes the reactivity change that is drawn on the strip chart recorder during the measurement. When the reference bank B was fully inserted, the reactivity increased slowly from about–42 pcm to about–32 pcm. This end–point test was exercised three times, but the same behavior of the reactivity was noticed.

The compensation ion chamber (CIC) is utilized in the intermediate range. Compensation is achieved by the negative voltage signal supplied in CIC, which removes or compensates the signal produced by the gamma background. In other words, by summing up the current (neutron+gamma) of the outer chamber and the current (gamma) of the inner chamber, the CIC finally produces the neutron current only.

But if the neutron flux (power) becomes to increase, the uncompensated ion chamber (UIC) as the power range detector is used. The power range is put upon the intermediate range altogether. The neutron and gamma of the power range produce the current being proportional to the power in the detector. In the high power range, the gamma background is minor in magnitude compared with the neutron flux and does not need to be compensated. But the power in low power physics tests is not high enough to ignore the gamma background.

Due to the existence of this gamma background, the reactivity drift phenomenon appears.

4. Verification of the SIMPT Program

The reactivity computer check test was simulated to verify the SIMPT program. The reactor periods can be obtained from SIMPT outputs by using kinetics parameters of the Nuclear Design Report (NDR) for Kori unit 3 cycle 7(12) and the measured reactivities of 24.5 pcm, 50 pcm and 72 pcm for Kori unit 3 cycle 7 physics tests. The reactor periods are the times that the neutron flux takes to increase from the steady state to a factor e ,that is, the base of natural logarithm. By inserting these reactor periods and kinetics parameters into the inhour equation (14), the simulated reactivities are calculated and compared with the measured reactivities. The results are presented in Table 2.

Table 2. Measured and Simulated Results for Reactivity Computer Check Test

No.	measured reactivity (pcm)	reactor period (sec)	simulated reactivity (pcm)	difference (%)
1	24.5	261.0	24.7	0.8
2	50.0	113.0	50.4	0.8
3	72.0	71.0	72.0	0.0

$$\rho = \frac{\ell^*}{T} + \sum_{i=6}^{6}\left[\frac{\beta_{i,\mathrm{eff}}}{(1+\lambda_i * T)}\right] \tag{14}$$

where

T : asymptotic reactor period.

$\beta_{i,\mathrm{eff}}$: effective delayed neutron fraction for the ith group.

λ_i : decay constant of precursor concentration for the ith group.

ℓ^* : prompt neutron lifetime.

As shown in Table 2, the simulated reactivities agree well with the measured reactivities.

5. Estimation of Gamma Background Level

The reactivity increasing phenomena were described in the previous Sections 3.1 and 3.2. The ramp rate and the reactivity change are the actual measured data of the strip chart recorder. Also, the initial neutron flux level is 0.1 of the nuclear heating flux.

The gamma background level is then inferred by adjusting the input reactivity and the gamma background level so that the SIMPT simulation agrees with the circled parts of Fig.1 and Fig.2. The determined input reactivity is−48 pcm and 42 pcm respectively, and the gamma background level is approximately 0.001. This is 1% of the initial neutron flux level.

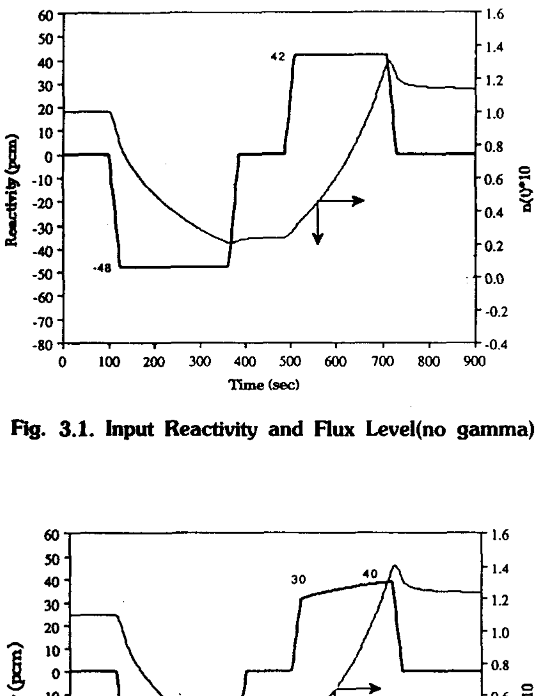

Fig. 3.1. Input Reactivity and Flux Level(no gamma)

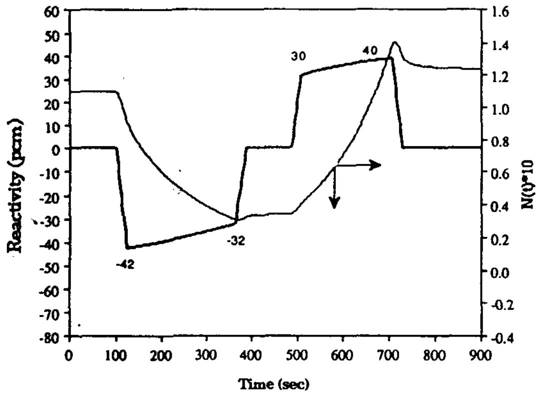

Fig. 3.2. Output Reactivity and Flux Level(gamma=0.001)

The results are presented in Fig.3–1 and Fig.3–2. The gamma background effect is not considered in Fig.3–1 while the gamma background effect is considered in Fig.3–2. The thick lines denote the reactivity changes and the thin lines denote the flux levels. As shown in Fig 3–2, the reactivity changes agree with the circled parts of Fig.1 and Fig.2.

6. Simulation of Reference Bank Worth

The control or shutdown bank having the greatest bank worth is customarily chosen to be the reference bank for the bank worth measurement by Rod Swap method. The reference bank for Kori unit 3 cycle 7 is the control bank B. Fig.4–1 and Fig.4–2 show the measured, the designed and the simulated differential and integral bank worths of the reference bank.

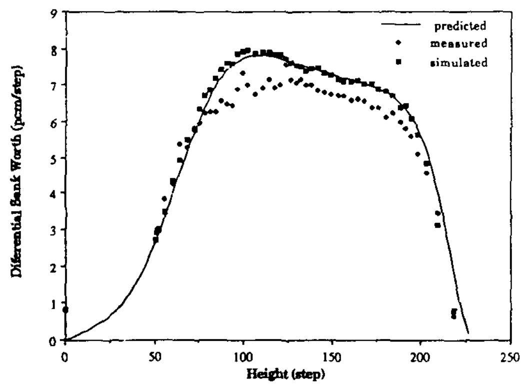

Fig. 4.1. Differential Worth for Reference Bank(Kori-3 Cycle-7)

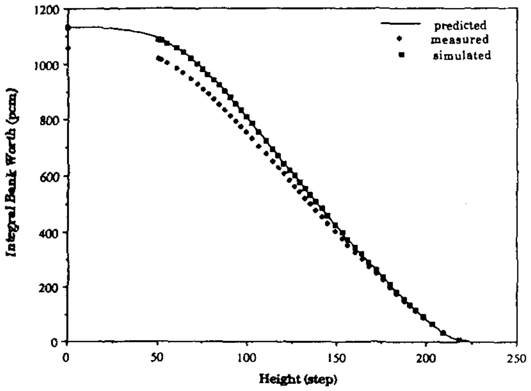

Fig. 4.2. Integral Worth for Reference Bank(Kori-3 Cycle-7)

As shown in Fig.4–2, the measured and the designed integral worths are 1058 pcm and 1132 pcm, respectively. The difference is 6.6%. The result was satisfied since the difference between the measured and the designed for the reference bank worth is within the criterion (±10%). During the measurement, the initial flux was just below 0.1 of the nuclear heating flux. Therefore, the flux level during the measurement includes the gamma background, which causes the measured worth to be underestimated in comparison with the actual worth.

For the simulation of the reference bank worth, the initial flux level was set to be 0.1 of the nuclear heating flux. The designed differential bank worth and the approximated gamma background level determined in Chapter 5 were utilized for the simulation. The simulated integral bank worth is 1055 pcm from the SIMPT run. The simulated worth is very well consistent with the measured worth, 1058 pcm.

To reduce the gamma background effect, the integral worth of the reference bank is simulated by raising the initial neutron flux level to 0.3 of the nuclear heating flux. The results are presented in Table 3.

As shown in Table 3, the simulated worth (1030 pcm) is consistent with the designed worth (1032 pcm).

Table 3. Simulation of Reference Bank Worth for Kori Unit 3 Cycle 7

	designed	measured	SIMPT	initial neutron flux(n_0)
integral bank worth (pcm)	1132	1058	1130	$0.3\Phi_{NHP}$

• $\gamma=0.001$

7. Kori unit 4 and Yonggwang unit 1 Physics Test

Above results were applied to Kori unit 4 cycle 7 and Yonggwang unit 1 cycle 7 low power physics tests. For Kori unit 4 cycle 7 physics test, the reference bank worths were measured twice.

At first, the test was performed where the initial neutron flux level was about 0.03 of nuclear heating flux. The measured worth (750 pcm) showed a large difference in comparison with the designed worth (1074 pcm). The differential and integral worths are presented in Fig. 5–1 and Fig. 5–2. This difference is due to a low flux level during the measurement of the bank worth, so that the measured worth was underestimated in comparison with the actual worth.

In the second measurement, the initial neutron flux level was raised to about 0.14 of nuclear heating flux. The results are presented in Fig.5–3 and Fig.5–4 and Table 4. As shown in Table 4, the measured integral bank worth is 1044 pcm and shows the trivial difference of about 3% with the designed worth (1074 pcm).

During the reference bank worth measurement in Yonggwang unit 1, the similar gamma background effect was observed as in Kori unit 4. To reduce the gamma background effect in the

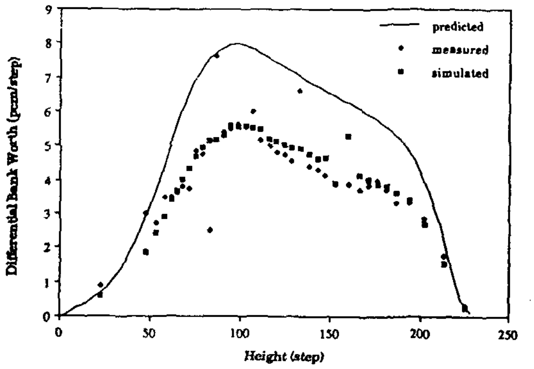

Fig. 5.1. Differential Worth for Reference Bank at Low Flux Level(Kori-4 Cycle-7)

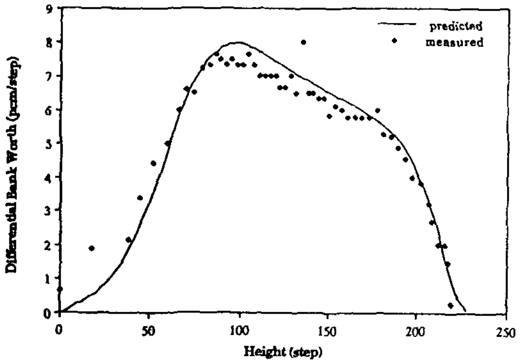

Fig. 5.3. Differential Worth for Reference Bank at High Flux Level(Kori-4 Cycle-7)

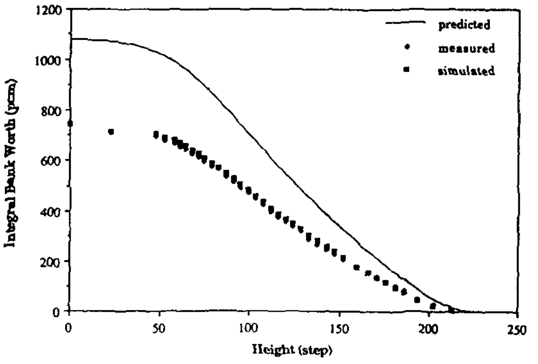

Fig. 5.2. Integral Worth for Reference Bank at Low Flux Level(Kori-4 Cycle-7)

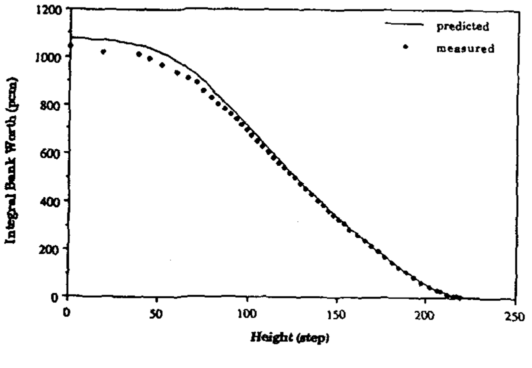

Fig. 5.4. Integral Worth for Reference Bank at High Flux Level(Kori-4 Cycle-7)

measurement of reference bank worth, the upper limit of the flux level was raised from 0.1 to 0.3 of the nuclear heating flux.

The measured worth (998 pcm) was very consistent with the designed worth (1019 pcm) as shown in Table 5.

Table 4. Simulation of Reference Bank Worth for Kori Unit 4 Cycle 7

1st test	designed	measured	SIMPT	initial neutron flux(n_0)
integral bank worth (pcm)	1074	750	743	$0.03\Phi_{NHP}$

2nd test	designed	measured	SIMPT	initial neutron flux(n_0)
integral bank worth (pcm)	1074	1044	1064	$0.14\Phi_{NHP}$

• $\gamma=0.0005$

Table 5. Measurement of Reference Bank Worth for Yonggwang Unit 1 Cycle 7

	designed	measured	initial neutron flux(n_0)
integral bank worth (pcm)	1019	998	$0.1\Phi_{NHP}$

8. Conclusion and Discussion

The reactivity increasing phenomena appeared during the tests for the nuclear heating point (NHP) determination and for the reference bank worth measurement. These phenomena came from the uncompensated ion chamber (UIC) usage and the low neutron flux level. The results of low power physics tests can be significantly affected the gamma background at the low neutron flux because an uncompensated ion chamber (UIC) is used as the ex-core neutron detector. The reasons why the UIC is used instead of the compensated ion chamber (CIC) are due to the position of the detectors and the trip logic. While 4 sets of UIC's are installed each at the quadrantal positions of the core circumference, 2 CIC's are installed only at 0° and 180°of the core circumference. Also, during the low power physics tests, only 1 set of UIC is connected to the reactivity computer to satisfy the trip logic. The physics tests are performed by moving the control and shutdown banks. Therefore, the UIC gives the better measurements of the core power changes induced by the bank motion than the CIC.

The previous upper end of the test range, 0.1 of nuclear heating flux, was established originally for the core of Westinghouse conventional loading pattern of which the neutron leakage is rather great. However, domestic cores utilize the low leakage loading patterns to reduce the neutron fluence to the reactor vessel. Unfortunately, this reduction leads to the low neutron leakage to the UIC. Therefore, the gamma background effect becomes important, and higher upper end for the low power physics test is desirable. The upper end at which the effect of the gamma background can be ignored has been analyzed quantitatively with the SIMPT program which is an efficient coupled point kinetics equations solver.

The upper end of the test range was revised from 0.1 to 0.3 of nuclear heating flux. This revised test range was successfully applied to Kori unit 4 cycle 7 and Yonggwang unit 1 cycle 7 physics tests.

Also SIMPT program can provide appropriate test flux level by simulating the reference bank worth measurement in advance to the actual low power physics tests. This predetermined flux level can be utilized to increase the accuracy of the test results.

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