Journal of the Korean Nuclear Society
Volume 29, Number 6, pp488~499, December 1997

<Technical Note>

Measurement of the Moderator Temperature Coefficient of Reactivity for Pressurized Water Reactors

Sung Sik Yu, Se Chang Kim, and Young Whan Na
Korea Power Engineering Company, Inc.
150 Dukjin-dong, Yusung-gu, Taejon 305-353, Korea

H.S. Kim, J.Y. Doo, D.K. Kim, and S.W. Long*
Korea Electric Power Cooperation
167 Samsung-dong, Kangnam-ku, Seoul 135-791, Korea

(Received April 20, 1996)

Abstract

The measurements of the moderator temperature coefficient (MTC) are performed to demonstrate that the calculational model produces results that are consistent with the measurements. Since negative MTC is also a technical specification value that may limit the cycle length, it is important to measure it as accurately as possible. In this report, preferred choice of test method depending on the time in cycle, best power indication and temperature definition in MTC calculation were determined based on the MTC test results taken during initial startup testing and at 2/3 cycle burnup in the Yonggwang nuclear power plant. The results show that the ratio and rodded methods provided good agreement with the predictions during initial startup testing. However, near end-of-cycle the depletion method gives better results, and so is suggested to be used in the MTC measurements at 2/3 cycle burnup. The use of primary Delta T power as a power indicator in the MTC calculations is highly advisable since it responds with good consistent results very quickly to changes unlike secondary calorimetric power. For the appropriate temperature definitions used in the MTC calculations, it is considered that the arithmetic average temperature measured simply by inlet and outlet thermocouples is preferred. Although volumetric average temperature provides better results, the improvement is not sufficient to compensate for the simplicity of calculations by arithmetic average temperature.

1. Introduction

The moderator temperature coefficient of reactivity relates a change in core reactivity to a change in reactor moderator temperature. The MTC is a major designed-in safety feature in pressurized water reactors (PWR). These reactors are designed to maintain a negative MTC over a

---

*ABB Combustion Engineering International Inc. Technical Advisor large range of core cycle operating conditions. Although most abnormal power transients are best controlled with a strongly negative MTC, some cool-down accidents such as a steam line break can be aggravated by the temperature feedback. Conversely, longer core cycle lengths of 18-24 months make initial MTC values more positive due to the high boron concentration. For this reason, it is important to determine the MTC accurately[1].

The MTC includes all reactivity effects associated with a change in the moderator temperature. The decrease of the water density due to the temperature increase leads to a reduction in neutron moderation, which makes the MTC more negative. As the water density decreases, the absorption rate by boron decreases because the boron density is directly proportional to the water density. However, the addition of soluble boron to the water makes the MTC more positive. The redistribution of flux shape is furthermore considered as a secondary effect due to the changes in moderation.

Measurements of the MTC are needed to ensure that predicted values of the MTC used in accident and transient analyses are conservative. At beginning-of-cycle (BOC), the measured MTC is required for comparison to the value originally targeted in the design analysis. Usually, a BOC hot full power value is required to be no greater than zero since an MTC which is negative throughout the cycle simplifies reactor operations. Also, the measured MTC is compared to the most positive value input into the safety analysis and contained in the technical specifications to determine its acceptability for the present cycle. For end-of-cycle (EOC), the best estimate MTC is calculated using the BOC measurement bias, then compared to the most negative value found in the technical specifications in order to provide an estimate of the margin available.

At Yonggwang nuclear power plant unit 3 (YGN Unit 3), the MTC measurements were performed at 20%, 50%, 80%, and 95% power plateaus during initial startup testing. Surveillance measurement of MTC was also performed at 2/3 cycle burnup. In this report, several different test methods employed in YGN Unit 3 are described. YGN Unit 3 MTC measurement results are evaluated to investigate the preferred method. This preferred method depends on plant operating conditions and time in cycle. Effects on the MTC calculation from the use of different plant power indications and temperature definitions are also analyzed.

2. Measurement of the Moderator Temperature Coefficient of Reactivity

Against the change of moderator temperature during the MTC measurements, core reactivity is maintained as close to zero as possible by adjusting control rod position, by changing the reactor power level or soluble boron concentration, or by permitting the core depletion. The measured isothermal temperature coefficient (ITC) at power is then obtained from the ratio of the reactivity change to the change of measured average moderator temperature as follows[1]:

$$\alpha_T = \frac{\Delta \rho}{\Delta T_{ave}} \tag{1}$$

where α_T = ITC at power, which is the sum of the fuel temperature coefficient (FTC) and the MTC when the change in the average fuel and average moderator temperatures is the same

$\Delta\rho$ = change of reactivity due to control rod movement or to the change in the soluble boron concentration, power, or burnup

ΔT_{ave}=change of average moderator temperature

The measured MTC, in turn, is taken by subtracting a predicted FTC from the measured ITC:

$$MTC = ITC - FTC \tag{2}$$

There are a number of ways to measure the MTC. The preferred choice depends on the type of plant, time in cycle, and plant operating conditions. Several methods applied at YGN Unit 3 are presented in the following sections.

2.1. Ratio Method (Power Exchange)

With the reactor at steady state and equilibrium xenon, the turbine load is adjusted to establish a new reactor coolant system (RCS) cold leg temperature. The change in moderator temperature results in a reactivity feedback and a resultant power change, which produces an opposite reactivity feedback. In this method, the measured ITC is calculated using the resultant power and temperature changes along with a predicted power coefficient of reactivity (PC). The initial power must be slightly below full rated power (typically 95%) because the test performance invokes power swings and the power is not permitted to exceed 100% of full power. Control rod positions and the soluble boron concentration should not be changed during the test. The reactor coolant system (RCS) cold leg temperature is initially increased to the prescribed value by decreasing the turbine load, then the new power level and RCS cold leg and hot leg temperatures are recorded. The temperature change should be accomplished within a relatively short period of time. The RCS cold leg temperature is then decreased by twice the amount of the initial increase by increasing the turbine load. Temperatures and power level are recorded upon reaching the new steady state conditions. The temperature swing is repeated several times (typically four times), and the test is completed by returning to the initial conditions.

Using the data collected, the ITC can be taken from the following general reactivity balance equation[3]:

$$\alpha_T * \Delta T_{ave} + \alpha_P * \Delta P + \Delta\rho_{CEA}$$
$$+ DBW * \Delta B + \Delta\rho_{xe} + \Delta\rho_d = 0 \tag{3}$$

where

α_T =isothermal temperature coefficient

ΔT_{ave} =change of average moderator temperature

α_P =predicted power coefficient

ΔP =change in power level

$\Delta\rho_{CEA}$ =change of reactivity due to the change of the control rod positions

DBW =differential boron worth

ΔB =change of boron concentration

$\Delta\rho_{xe}$ =change of reactivity caused by the transient xenon change

$\Delta\rho_d$ =change of reactivity caused by core depletion

The reactor is assumed to be critical at all times. Above reactivity balance equation is simplified for the ratio method as follows:

$$\alpha_T * \Delta T_{ave} + \alpha_P * \Delta P + \Delta\rho_{drift} = 0 \tag{4}$$

where $\Delta\rho_{drift}$ is the unknown reactivity drift caused by the system change due to the change in soluble boron, xenon redistribution, etc. Consequently, the measured ITC is calculated as follows:

$$\alpha_T = -\frac{(\alpha_P * \Delta P + \Delta\rho_{drift})}{\Delta T_{ave}} \tag{5}$$

The measured MTC is derived from the above ITC by subtracting out the predicted FTC as shown in

Eq. (2).

2.2. Rodded Method(Control Rod Exchange)

With the reactor at steady state and equilibrium xenon, the turbine load is adjusted to establish a new reactor coolant system (RCS) cold leg temperature. The change in moderator temperature results in a small mismatch between turbine load and reactor power with an accompanying reactivity feedback. This reactivity is matched with an equal and opposite reactivity change by movement of control element assembly (CEA) group 5, while holding reactor power constant. In this method, the measured ITC is calculated using the temperature changes and the resultant change of the control rod position along with the predicted CEA group 5 integral worth curve. It is important for improving the accuracy to make an initial insertion of the CEA group 5 (typically 80±2.5% withdrawn) to the linear range of the group integral worth curve. Of course, the initial insertion of control rods along with other initial conditions for the test shall be established sufficiently before the test performance to ensure equilibrium xenon. The MTC measurement by rodded method can be combined with a PC measurement requiring that the intial power level be reduced to about 95% of rated thermal power.

When the RCS temperature is stabilized and the reactor power is steady for each temperature swing, the RCS cold leg and hot leg temperatures, the power level, and the control rod position are recorded. Following the data collection, the changes in average moderator temperature, power level and control rod worth for each temperature swing are calculated and the reactivity balance for the rodded method is written as follows:

$$\alpha_T * \triangle T_{ave} + \alpha_P * \triangle P + \triangle \rho_{CEA} + \triangle \rho_{drift} = 0 \quad (6)$$

Therefore

$$\alpha_T = -\frac{(\alpha_P * \triangle P + \triangle \rho_{CEA} + \triangle \rho_{drift})}{\triangle T_{ave}} \quad (7)$$

Finally, the measured MTC is obtained by subtracting the predicted FTC from the above ITC.

2.3. Depletion Method

The reactor power is kept as constant as possible by adjusting the turbine load and the RCS cold leg temperature is allowed to decrease until reaching its lower technical specifications operating limit. During the test, steady state conditions are maintained by minimizing changes in the power level, control rod positions and soluble boron concentration. In-leakage of primary make-up water is prevented to ensure that the soluble boron concentration will not change during the test. Temperatures and power should be continuously recorded with prescribed time intervals. The measured ITC can be obtained from trading the reactivity loss caused by the core depletion for a reactivity gain due to a drop in the moderator temperature. This method can be performed at full power without initial reduction of the power level.

Prior to the measurement, the rate of reactivity loss caused by core depletion is determined using the measured critical boron letdown curve and the differential boron worth. This reactivity loss rate is multiplied by the test duration to obtain the reactivity loss due to the depletion, which is compensated for by the reduction in the moderator temperature. The reactivity balance is as follows:

$$\alpha_T * \triangle T_{ave} - \frac{\partial \rho_{Bu}}{\partial t} * \triangle t + \alpha_P * \triangle P + \triangle \rho_{drift} = 0 \quad (8)$$

where $\partial \rho_{Bu} / \partial t$=rate of reactivity loss with depletion

Δt = length of the test

The measured ITC is calculated as the following:

$$\alpha_T = \frac{\frac{\partial \rho_{Bu}}{\partial t} * \triangle t - \alpha_P * \triangle P - \triangle \rho_{drift}}{\triangle T_{ave}} \quad (9)$$

The test duration is directly dependent upon the rate of change of the critical boron concentration with core burnup. At BOC, the critical boron concentration changes very slowly because the reactivity loss due to the fuel depletion is offset by the depletion of the burnable absorber. Accordingly, this method can be used only at those points (i.e near EOC) in the operating cycle where the critical boron concentration is changing significantly with burnup. The test performance takes a little bit long time than the others (typically 12 hours to 72 hours).

2.4. Xenon Maneuver Technique

With the reactor at steady state and equilibrium xenon, the turbine control valve is closed to reduce the power level typically by an amount of 10%. This reduced power level is held while xenon slowly builds in. Throughout xenon transient, a reactivity balance accounts for changes in power, average moderator temperature and xenon. When sufficient data are obtained, the measured MTC is calculated by performing a least square fit of all the power and temperature data. It is important to maintain other reactivity effects constant (such as boron and control rods) because only power, moderate temperature and xenon are considered in the reactivity balance.

The reactivity balance is assumed as follows:

$$\alpha_T * \triangle T_{ave}(t) + \triangle \rho_{xe}(t) + \alpha_P * \triangle P(t) = 0 \quad (10)$$

where $\triangle\rho_{xe}(t)$ is the transient xenon differential worth. The values of $\triangle T_{ave}(t)$ and $\triangle P(t)$ are taken from measurements. The resulting xenon worth can be computed by ROCS[8] using a simplified power and temperature history. If these values are substituted into Eq. (10), the result would not always be zero. However, the data can be least square fit as follows:

Let

$$\delta(t) = \alpha_T * \triangle T_{ave}(t) + \triangle\rho_{xe}(t) + \alpha_P * \triangle P(t) \quad (11)$$

where $\delta(t)$ is the difference from criticality.

We can find the minimum of :

$$\begin{aligned} D^2 &= \int_{t_0}^{t_1} \delta^2(t) \\ &= \int_{t_0}^{t_1} (\alpha_T * \triangle T_{ave}(t) + \triangle\rho_{xe}(t) + \alpha_P * \triangle P(t))^2 dt \end{aligned} \quad (12)$$

The integral can be made into discrete summations:

$$D^2 = \sum_{i=1}^{N} (\alpha_T * \triangle T_i + \triangle X_i + \alpha_P * \triangle P_i)^2 \triangle t_i \quad (13)$$

where $\triangle X_i$ is the transient xenon differential worth, $\triangle\rho_{xe}(t)$. Summation is taken over N data points to approximate the integrals in Eq. (12).

Since it is desired to find the α_P and the α_T which minimize D^2, we can differentiate Eq. (13) with respect to α_P and α_T and solve for the unknowns.

$$\begin{aligned} \frac{\partial D^2}{\partial \alpha_P} &= 2\sum_{i=1}^{N} (\alpha_T \triangle T_i + \triangle X_i \\ &\quad + \alpha_P * \triangle P_i) \triangle P_i \triangle t_i = 0 \end{aligned} \quad (14)$$

$$\begin{aligned} \frac{\partial D^2}{\partial \alpha_T} &= 2\sum_{i=1}^{N} (\alpha_T \triangle T_i + \triangle X_i \\ &\quad + \alpha_P * \triangle P_i) \triangle T_i \triangle t_i = 0 \end{aligned} \quad (15)$$

Using above equations, α_T can be written as follows:

$$\alpha_T = \frac{(\sum_{i=1}^{N} \triangle P_i \triangle X_i \triangle t_i)(\sum_{i=1}^{N} \triangle T_i \triangle P_i \triangle t_i) - (\sum_{i=1}^{N} \triangle T_i \triangle X_i \triangle t_i)(\sum_{i=1}^{N} \triangle P_i \triangle P_i \triangle t_i)}{(\sum_{i=1}^{N} \triangle T_i \triangle T_i \triangle t_i)(\sum_{i=1}^{N} \triangle P_i \triangle P_i \triangle t_i) - (\sum_{i=1}^{N} \triangle T_i \triangle P_i \triangle t_i)^2} \quad (16)$$

Although the equation appears complicated, it is easily solved by maintaining running totals of the summations using the changes in temperature, power and xenon. The coefficient α_T can be solved at any time in the transient and it results from a least square fit of all prior data.

3. Analyses of Test Results and Discussions

3.1. Overview of MTC Test at YGN Unit 3

At Yonggwang nuclear power plant Unit 3, MTC measurements were performed at 20%, 50%, 80%, and 95% power plateaus during initial startup testing. The MTC was determined from the measured ITC and compared to the predictions. The MTC determined at each power plateau was projected to full power to ensure conformance to technical specification limit. The ITC was measured by two test methods (ratio and rodded) at each power plateau. Data reduction was completed by the VARTAV[9] code, which is a workstation version code developed for automated data analysis. The MTC was also measured at 2/3 cycle burnup according to the surveillance requirement of technical specifications. This surveillance test was performed by the ratio method and the depletion method. The former was the official method used in both cases but the latter was additionally performed to investigate the possibility of use for next cycles. Prior to the MTC measurement by the ratio method, it was required to reduce the power level to 95% and stabilize the plant for two days to establish xenon equilibrium. The test was performed for 8 hours after reaching the xenon equilibrium condition. The depletion method requires keeping power level as constant as possible as described in Section 2. However, during the surveillance test by depletion, the power level was decreased due to the fuel depletion without any adjustment of turbine control valves. Hence, the use of the predicted power coefficient was involved in this MTC calculation. Of course its use adds more uncertainty, but the overall result should still be reasonable. The measurement by the depletion method was started at almost full power (99.7% of rated thermal power) and the data were collected for 12 hours.

The data set was evaluated for the impacts on test results according to the use of different plant powers for power indications and the use of different average temperatures. The preferred test method was also selected depending on cycle burnup at the time of the test. In addition, the feasibility of the xenon transient technique was investigated using the test results from the depletion method. Xenon transient worths generated during fuel depletion and power reduction were calculated by the ROCS code.

3.2. MTC Test Results

Tables 1 and 2 summarize the test results obtained by each method during the initial startup testing and at 2/3 cycle burnup. All MTC measurements satisfied the acceptance criteria (±5.5 pcm/°C for initial startup tests) showing the adequacy of design analysis with the conformance to the technical specification limit.

As shown in Table 1, initial startup test results showed good agreement with the predictions. Especially, the rodded method provided better results since the calculated worth of a change in CEA position at BOC has smaller uncertainties than near EOC. At 2/3 cycle burnup near EOC, the MTC by the ratio method exhibited a large mismatch with the prediction. The swings of temperature at EOC caused large power changes due to a large temperature coefficient. Larger power change may contribute to more measurement uncertainty because the predicted

Table 1. MTC Test Results During YGN Unit 3 Initial Startup Testing

Test Method	Power Level(%)	Measured ITC (pcm/°C)	Predicted FTC (pcm/°C)	Measured MTC (pcm/°C)	Predicted MTC (pcm/°C)	Projected MTC at 100% Power (pcm/°C)*	MTCmeas – MTCpred (pcm/°C)
Ratio Method	20	-2.8256	-2.82	-0.0056	-1.61	-5.6035	1.6044
	50	-4.8809	-2.62	-2.2609	-3.11	-5.80	0.8491
	80	-5.6149	-2.37	-3.2449	-4.25	-4.6214	1.0051
	95	-6.8037	-2.30	-4.5037	-5.44	-4.6482	0.9363
Rodded Method	20	-2.7828	-2.82	0.0372	-1.61	-9.6268	1.6472
	50	-5.0065	-2.62	-2.3865	-3.11	-6.0393	0.7235
	80	-7.2133	-2.37	-4.8433	-4.25	-6.2250	-0.5933
	95	-7.0938	-2.30	-4.7938	-5.44	-5.5536	0.6462

(*Note: MTC projected as function of power including 0% power measured MTC)

Table 2. Results of MTC Test at YGN Unit 3 2/3 Cycle Burnup

Test Method	Measured ITC (pcm/°C)	Predicted FTC (pcm/°C)	Measured MTC (pcm/°C)	Predicted MTC (pcm/°C)	Projected MTC at 100% Power (pcm/°C)*	MTCmeas – MTCpred (pcm/°C)
Ratio Method	-45.9128	-2.79	-43.1228	-28.63	-44.2478	-14.4928
Depletion Method	-31.0515	-2.77	-28.2815	-28.90	-28.3815	0.6185
Xenon Transient Method	-48.1830	-2.77	-45.4130	-28.90	-45.6130	-16.5130

(*Note: MTC is projected by adding 'measured – predicted' bias to MTC prediction at 100% power)

power coefficient is used in the calculations of measured MTC. The MTC measurement by the depletion method was successfully completed with the results more closely agreeing with the prediction. This method can be proposed for an EOC measuring technique since reducing the power is not required and it facilitates the test performance. The xenon transient technique may be suggested as another EOC measuring technique. However this method requires a ROCS calculation to determine xenon transient worth during the test. In addition to the above test methods, variation of the boron concentration can be an alternative control method. However, the use of the boron concentration will be unreliable because it is difficult to measure accurately small changes in concentration. Figs. 1 to 4 show typical plant conditions during the MTC measurements by each method. The reactor powers shown in the figures are the primary Delta T power (BDT) and the neutron flux power (PHICAL), both calculated by the core protection calculator system (CPC), and secondary calorimetric power (BSCAL) calculated by the core operating limit supervisory system (COLSS). BDT power was selected for use in the calculations.

3.2.1. Power Indications

The ITC calculations according to three different power indications were reviewed to investigate the best power indication. Figs. 5 through 7 show the scatter in the calculated ITC to be comparable for the three different power indications. For the ratio method, BDT gave consistent results and agreed with the PHICAL results. The BSCAL results were

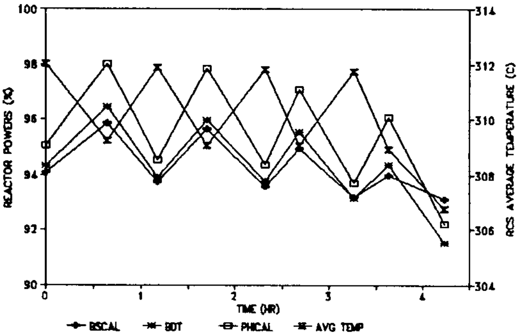

Fig. 1. 95% Power MTC Measurement by Ratio Method During Initial Startup Testing

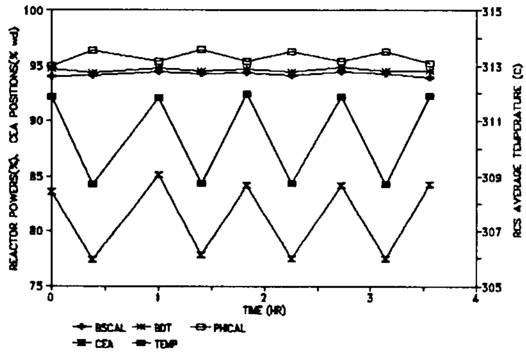

Fig. 2. 95% Power MTC Measurement by Rodded Method During Initial Startup Testing

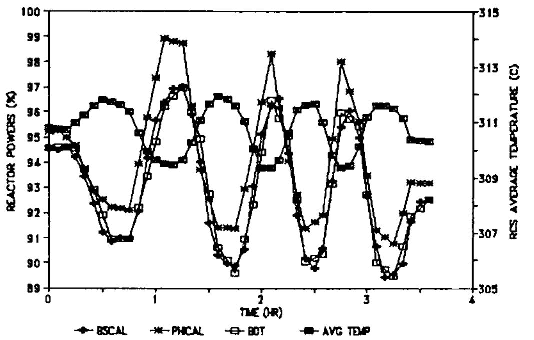

Fig. 3. 2/3 Cycle Burnup MTC Measurement by Ratio Method

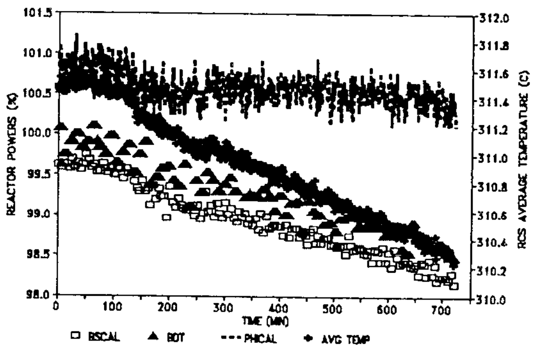

Fig. 4. 2/3 Cycle Burnup MTC Measurement by Depletion Method

also reasonable but had a relatively large amount of scatter. In the case of the rodded method, the ITC calculations from each power indication had similar scatter trends. Since the power change was small during the measurement by the rodded method, the results were consistent because of dependence on parameters other than the power change. In the MTC measurement by the depletion method at 2/3 cycle burnup, BDT and BSCAL had similar power changes but PHICAL showed a small power drop as seen in Fig. 4. PHICAL power, which is automatically adjusted by each CPC channel to offset decalibration caused by change of the cold leg temperature, is consequently not an appropriate power indication for the depletion method or any MTC test method. This PHICAL error is minimized in the ratio and rodded methods because heatup and cooldown cycles are averaged; for the depletion method, the error is obvious since only a cooldown is used. In conclusion, the best indicator of power is probably BDT since it responds very quickly to changes (unlike BSCAL) and is not affected by CPC temperature compensation.

3.2.2. Temperature Definitions

Since the reactivity feedback in a reactor is dependent on the three-dimensional distribution of the temperature and flux, the MTC calculation including all reactivity effects is potentially highly complex. Accordingly, in the current MTC measurements, it is a common practice to use the arithmetic average temperature of the reactor inlets and outlets (i. e., the average cold and hot leg temperatures) because it is easily measured. However, this average per Eq. (17) is not the only possible average for the MTC calculation. Below are some possible definitions of an average moderator temperature listed in their order of increasing complexity[5].

$$T_{avg} = \frac{1}{2} * (T_{inlet} + T_{outlet}) \tag{17}$$

$$T_{enth} = T(\frac{1}{2} * (H_{inlet} + H_{outlet})) \tag{18}$$

$$T_{vol} = \frac{1}{V} \int T dV \tag{19}$$

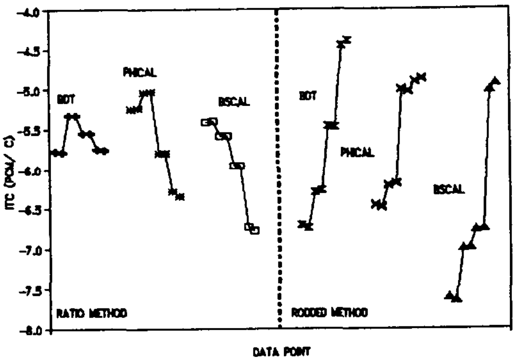

Fig. 5. ITC According to Different Power Indications at 50% Power During Initial Startup Testing

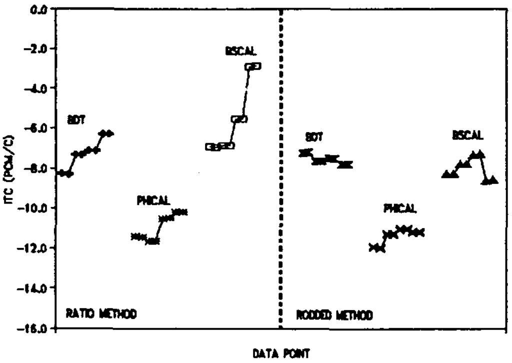

Fig. 6. ITC According to Different Power Indications at 95% Power During Initial Startup Testing

$$T_{flux} = \frac{1}{\Phi V} \int T \Phi dV \tag{20}$$

where T_{inlet} = inlet temperature (average)

T_{outlet} = outlet temperature (average)

H_{inlet} = enthalpy corresponding to each inlet temperature (average)

H_{outlet} = enthalpy corresponding to each outlet temperature (average)

V = core volume

Φ = spatial Flux in core

The simplest as stated above is Tavg, the arithmetic average. It can be obtained from the average inlet and outlet temperatures. It is therefore popular and frequently used. The mid-enthalpy temperature per Eq. (18) is also a possible average. Like Tavg, it only depends on the inlet and outlet conditions of the coolant. However, it requires the use of the steam tables to evaluate. The volume average temperature per Eq. (19) depends on the distribution of temperature within the reactor. The fourth definition per Eq. (20) is a flux-volume average temperature. This is a highly inconvenient average because it requires knowledge of the flux shape and its change. All the above averages could be equally valid. However, it is desirable to choose an average which is proportional to the reactivity change in the reactor. Normally, the reactivity will be a simple function of the average parameter so that the MTC can be easily defined.

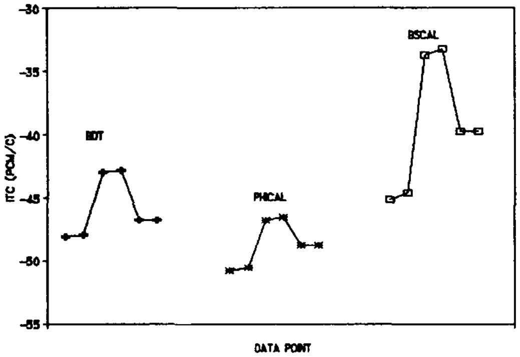

Fig. 7. ITC According to Different Power Indications by Ratio Method at 2/3 Cycle Burnup

A suggested way of eliminating the temperature discrepancy is to convert measured temperatures to volume average. This can be done by using the following equations[5]:

$$H_{vol} = H_{inlet} + P/P_0 * (\triangle H_0 + a * ASI) \quad (21)$$

$$T_{vol} = T(H_{vol})$$

where

T_{vol}, H_{vol} = volumetric average temperature and corresponding enthalpy

H_{inlet} = enthalpy corresponding to inlet temperature

P/Po = fraction of full power

△Ho = rise to mid enthalpy at full power, $(H_{0out}-H_{0in})/2$

a = sensitivity coefficient of the volume average enthalpy change to the change in ASI

This correlation states that the volume average temperature is equal to the temperature at mid enthalpy adjusted linearly by an ASI change component. The term $H_{inlet}+(P/Po)^*\triangle Ho$ is the mid-enthalpy $(H_{in}+H_{out})/2$, and the term a*(P/Po)*ASI accounts for the fact that the volume average enthalpy is somewhat lower than the mid-enthalpy for top peaked power shapes and somewhat higher for bottom peaked power shapes. The precalculated value of 'a' is the sensitivity coefficient of the volume average enthalpy change to the change in ASI. Once the volume average enthalpy is known, the volume average temperature can be obtained from the steam tables. A constant value of 'a' (about 20 Btu/lb ASIunit for a CE plant similar to YGN) appears to correlate the change in volumetric average temperature to changes in cold leg temperature, power and ASI[5]. The value of 'a' can be precalculated and appears not to be very sensitive to burnup. Above correlation has been found to provide a good agreement (±0.01℃) with the core volumetric average temperature. It is suggested therefore that measurement of T_{in},

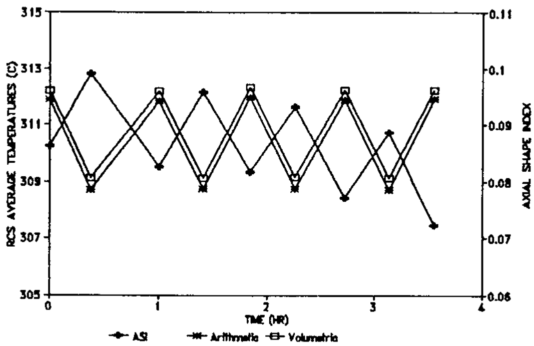

Fig. 9. RCS Average Temperatures at 95% Power MTC Measurement by Rodded Method

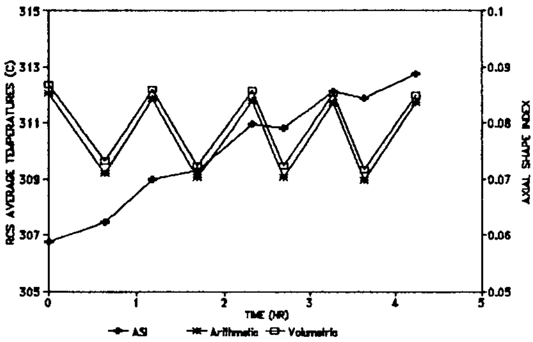

Fig. 8. RCS Average Temperatures at 95% Power MTC Measurement by Ratio Method

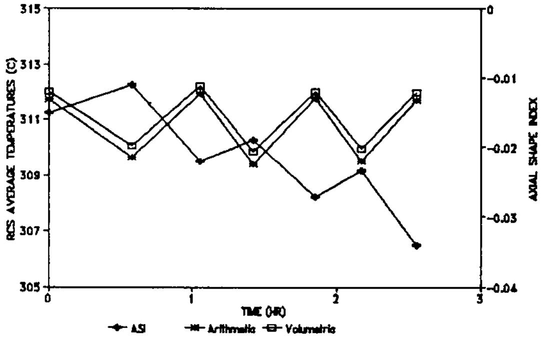

Fig. 10. RCS Average Temperatures at 2/3 Cycle Burnup MTC Measurement by Ratio Method

Table 3. MTC Results Using Different Temperature Definitions

Test Plateau	Test Method	Predicted MTC (pcm/°C)	Temperature Indication	Measured MTC (pcm/°C)	MTC_{meas} – MTC_{pred} (pcm/°C)	%Difference $[(MTC_{vol}-MTC_{avg})/MTC_{avg}]*100$
95% During Initial Startup	Ratio	- 5.44	Arithmetic Tavg	- 4.5037	0.9363	6.74%
			Volumetric Tavg	- 4.8071	0.6329	
	Rodded	- 5.44	Arithmetic Tavg	- 4.7938	0.6462	4.82%
			Volumetric Tavg	- 5.0247	0.4153	
2/3 Cycle Burnup	Ratio	- 28.63	Arithmetic Tavg	- 43.1228	- 14.4928	8.58%
			Volumetric Tavg	- 46.8218	- 18.1918	
	Depletion	- 28.9	Arithmetic Tavg	- 28.2815	0.6185	9.26%
			Volumetric Tavg	- 30.90	- 2	

Power and ASI be included during MTC measurements in order to enable more consistent and accurate comparisons between calculations and measurements.

Data from MTC measurements at YGN Unit 3 were reanalyzed using a volumetric average temperature (T_{vol}) per Eq. (21) as a substitute for the conventionally used arithmetic average temperature (T_{avg}). Because the volumetric average temperature is defined as a function of axial core power distribution, some variations in ASI during the course of a MTC measurement are expected to produce the differences between MTC (T_{vol}) and MTC (T_{avg}). The MTC measurement by the ratio method, which does not involve CEA motion, induces relatively small variations in ASI during the measurement and the ASI changes that do occur are usually in only one direction (decreasing or increasing throughout the measurement). The measured data from YGN Unit 3 had small variations in ASI and, as expected, there were small differences between MTCs based on T_{vol} and T_{avg}. Figs. 8 through 10 show the differences between T_{vol} and T_{avg} and the variations in ASI during initial startup testing and 2/3 cycle burnup test. Table 3 summarizes the results from the comparison. The differences were less than 10%. In most cases, MTC (T_{vol}) was more negative than MTC (T_{avg}). Especially for initial startup test data, the volumetric average temperature provided slightly better agreement with the predictions. In conclusion, even though volumetric average temperature yields better results, it is still effective to use the arithmetic average temperature considering the simplicity of calculations.

4. Conclusions and Recommendations

The maximum negative value of the MTC is restricted by the Technical Specifications. Therefore, it is desirable to measure the MTC as accurately as possible, especially near EOC, to ensure that the cycle length is not needlessly limited. In this report, several test methods depending on the time in cycle, best power indication and temperature definition in the MTC calculation were analyzed based on the MTC test results taken at YGN Unit 3 for the purpose of selecting a preferred choice. In particular, the depletion method and the xenon transient technique were applied to the measurement of MTC at 2/3 cycle burnup concurrently with the official ratio method in order that those applicabilities were demonstrated for the future MTC measurements near EOC.

In conclusion, the ratio and rodded methods provided good agreement with the predictions during initial startup testing. However, near EOC, the depletion method gives better results, and so is suggested to be used in the MTC measurement at 2/3 cycle burnup. It is also highly advisable to use primary Delta T power as the power indicator in the MTC calculations since it responds with good consistent results very quickly to changes unlike secondary calorimetric power. In the use of appropriate temperature definitions in the MTC calculations, it is considered that the arithmetic average temperature simply measured by inlet and outlet RTDs is preferred. Although the volumetric average temperature provides slightly better results at BOC, the results are worse at EOC; overall, the improvement is not sufficient to compensate for the simplicity of calculations with the arithmetic average temperature. Therefore, it is recommended that these preferred methods be applied to the MTC measurements for Yonggwang next cycles and for the Ulchin nuclear power plants now under construction.

References

1. ANSI/ANS 19.11, "American National Standard for the Calculation and Measurement of the Moderator Temperature Coefficient of Reactivity for Water Moderated Power Reactors," Final Draft, May (1995)
2. Yonggwang Final Safety Analysis Report Chapter 16, Technical Specifications, Korea Electric Power Co., (1993)
3. Test Procedure 3S-I-000-02, "Variable Tavg Test," Korea Electric Power Co., (1994)
4. U. Decher, "The Potential of Measuring MTC and Power Coefficients During a Xenon Maneuver," PHA-86-026, Feb. 5, (1986)
5. U. Decher, "Temperature Definitions and Their Impact of Measured and Calculated MTC," PHA-87-034, March 4, (1987)
6. Regulatory Guide 1.68, "Initial Test Programs for Water-Cooled Nuclear Power Plants," U. S. Nuclear Regulatory Commission, August (1978)
7. "Nuclear Design Report for Yonggwang Unit 3 Cycle 1," Korea Atomic Energy Research Institute and ABB Combustion Engineering, Inc, Dec. 1994.
8. R. Loretz et. al., "ROCS User' s Manual - Coarse Mesh Diffusion Theory Neutronics Code," CE-CES-4 Rev. 4-P, Dec. (1989)
9. 10587-SE-OG185-03, "VARTAV Operations Manual," Korea Atomic Energy Research Institute and ABB Combustion Engineering Inc, Dec. (1994)
10. R.L. Hellens, et. al., "Core Physics Measurements During Xenon Transients in Power Reactors," ABB Combustion Engineering, Inc., ANS Annual Meeting, Boston, June (1985)