Verification of Core Monitoring System with Gamma Thermometer

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A Core Monitoring System with Gamma Thermometers (GT-CMS) was verified by means of comparison between bundle gamma scan measurement and the CMS calculated results. To make a verification of the GT-CMS, seven LPRM/GT/TIP assemblies were loaded in a 1/8 core region of Kashiwazaki-Kariwa-5. After one cycle operation, a bundle gamma scan measurement was performed for the bundles. Two Power distributions (Ba-140 concentration) at the end of cycle were calculated; one was calculated by the TIP-CMS and the other by the GT-CMS. These two power distributions were compared with the bundle gamma scan measurements. The results, the accuracy of GT-CMS is 4.1% RMS and 3.9% RMS for the TIP-CMS. In addition, the thermal characteristic parameters, ML HGR and MCPR, are compared through the operation cycle. The RMS of the MLHGRs between GT-CMS and TIP-CMS was 0.4 kW/m, and the RMS of the MCPRs was 0.008. From these results, it can be concluded that the GT-CMS is practical as a substitute for the TIP-CMS.

KEYWORDS: core monitoring system, gamma thermometer, TIP, gamma scan

I. Introduction

At present, we are using local power range monitors (LPRMs) and traversing incore probes (TIPs) for core monitoring of boiling water reactors (BWRs). The LPRM is the fission-chamber measuring the fission phenomena of U-235 induced by neutrons, and detects thermal neutron flux at LPRM positions fixed in the core. The TIP detector is movable, and measures the axial continuous power distribution along the TIP guide tube in the core. Four LPRM detectors and a TIP guide tube are assembled as one package called a “string”. Several strings are arrayed in radial positions of the core. For example, 43 strings are arrayed for the 1100MWe class BWR. TIP readings are used to evaluate the bundle power distribution, and to evaluate the fuel thermal characteristics by the core monitoring system. In addition, the TIP readings are used to calibrate LPRM. Therefore, the TIP plays an important role for core monitoring.

Investigations of the new incore instrumentation were initiated in Japan around 1990.11 This investigation was executed under a Japanese BWR Joint Development Program. In this program, the gamma thermometer (GT) was selected instead of TIP.

Historically, GTs were installed in the heavy water moderated reactors at Savannah River in the U.S. in the beginning of the 1950s. And later, GTs were installed at the OECD Halden Reactor in Norway in 1963. The above selection was made such that those technologies of GT could be applied to BWRs. Several papers reported the application of GT to BWRs or PWRs in 1996 2-5).

In Japan, two in-plant tests were conducted to evaluate the applicability of the GT system to BWRs; the first test was in TOKAI-2 (BWR-5) from 1996 to 1999 and the second test was in Kashiwazaki-Kariwa-5 (BWR-5) from 2000 to 2002. The first test was executed to confirm the applicability of hardware which includes the sensor, the data acquisition and calibration system of GT. The results of this test were satisfaction.6-8) In addition, we can see some investigation reports on the GT hardware system in References 9-11).

The second test was executed to confirm the applicability of the software, that is, to confirm that the CMS with GT (GT-CMS) had an acceptable accuracy to the evaluation of core performance.

This paper reports the results of the second test. For the second test, the following items were evaluated.

1) The accuracy by comparison with bundle gamma scans.
   (a) The accuracy of GT-CMS.
   (b) The accuracy of TIP-CMS.
   (c) Comparison between the accuracy of GT-CMS and TIP-CMSs
   (d) Comparison between the accuracy of GT-CMS and the index value 5.2% that is used in the regulatory analysis in Japan, called “uncertainty of TIP readings”.

2) Comparison between the core performance values of GT-CMS and TIP-CMS’s.
   (a) MLHGR
   (b) MCPR

II. Gamma Thermometer

The structure of a gamma thermometer is shown in Fig.1. The GT consists of a stainless steel rod, a thermal insulator,
a thermocouple and a heater wire. The hot junction of the thermocouple is located at the center of the insulator, and the cold junction is out of the insulator. When the temperature of the insulated section rises, the thermocouple measures the temperature difference between the insulated and the non-insulated section. Therefore, the thermocouple reading is the response to gamma energy deposition. The gamma ray is related to the fission density, thus the thermocouple reading is related to the power of the surrounding fuel bundles on the GT. A string of GT/LPRM assembly includes nine GT detectors. It means that the GT system can measure the power distribution of the core.

The differences between the neutron TIP system and the GT system are the following.

1. Objects to be measured
   a. TIP system: thermal neutron flux
   b. GT system: gamma flux

2. Measurement points (axial points)
   a. TIP system: 24 points
   b. GT system: 9 points

These differences affect the core performance evaluated by the CMS. The purpose of the second in-plant test is to evaluate the effect of the above differences.

III. In-Plant Test

For the in-plant test, seven LPRM/GT/TIP assemblies were installed in Kashiwazaki-Kariwa-5. These test assemblies were arrayed in the 1/8 core region shown in Fig.2. A normal GT system is a LPRM/GT assembly. However, the LPRM/GT/TIP assemblies were used for this in-plant test. The assembly includes 4 LPRM detectors, 9 GT detectors and a TIP guide tube in a string. The arrangement of the LPRMs and GTs in the assembly is shown in Fig.3. In this figure, the fuel bundle is described with 24 divided nodes, each corresponding to evaluated points in the CMS. 4 GT detectors are arranged at the same positions as 4 LPRM detectors.

At the end of the operation cycle, bundle gamma scan was conducted. The measured bundles were 104 shown in Fig.2 and the measured points of each bundle were 17 shown in Fig.3.

IV. Core Monitoring System

The core monitoring system evaluates power distribution, thermal characteristic parameters, MLHGR, MCPR, etc. with the three-dimensional core simulator. The core simulator of on-line CMS on Kashiwazaki-Kariwa-5 is based on the modified one-group neutron diffusion theory with TIP/LPRM adaptive function. The basic equation is given by the equation (1).

\[
\frac{1}{D_i} \nabla \cdot D_i \nabla \phi + (B^2 - \Delta L) \phi = 0, \tag{1}
\]

where \( \phi \) is the neutron flux, \( D_i \) the diffusion coefficient, \( B^2 \) the buckling and \( \Delta L \) the adjustment parameter.
\( \Delta L \) of the TIP-CMS is calculated by an iterative method so that the calculated TIP reading distribution may agree with the measured one. This process is the following shown in Fig.4.

1. Calculate the TIP readings by means of the guessed bundle power distribution.
2. Calculate the \( \Delta L \) so that the calculated TIP readings may agree with the measured ones.
3. Calculate the neutron flux with \( \Delta L \).
4. Calculate the power distribution from the neutron flux distribution and go to step (1).

\[ \text{CALTIP}(K, L) = \frac{1}{4} \sum_j R\text{TIP}(K, J, L) \cdot P(K, J, L), \quad (2) \]
and

\[ \text{RTIP}(K, J, L) = f \left( \text{EXP}_{K, J, L}, U\text{H}_{K, J, L}, U_{K, J, L}, m_{K, J, L} \right), \quad (3) \]
where CALTIP(K,L) is the calculated TIP reading at elevation K of the TIP string L, P(K,J,L) the power of the bundle J surrounding the TIP string L, RTIP(K,J) the correlation factor, EXP the exposure, UH the historical relative moderator density, U the instantaneous relative moderator density and m is the control blade state. The GT readings are calculated in the same manner.

\[ \text{CALGT}(M, L) = \frac{1}{4} \sum_j R\text{GT}(M, J, L) \cdot P(M, J, L), \quad (4) \]
and

\[ \text{RGT}(M, J, L) = g \left( \text{EXP}_{M, J, L}, U\text{H}_{M, J, L}, U_{M, J, L}, m_{M, J, L} \right), \quad (5) \]
where M is the elevation at GT detector. The different point is that the correlation factor RTIP(K,J,L) is related to the neutron flux, while the RGT(M,J,L) is to the gamma flux.

In the next step, CMS evaluates the core performance including the linear heat generation rate (LHGR) of fuel rod and the critical power ratio (CPR) of bundles.
**V. Evaluation Method**

In the bundle gamma scan, 1.567 MeV gamma ray is measured. This gamma ray is caused by the $\beta$ decay of La-140 into Ce-140 with a half-life of 40.3 hours. La-140 is generated from the $\beta$ decay of Ba-140 with a half-life of 12.8 days. The half-life of Ba-140 is longer than the one of La-140, therefore, the Ba-140 concentration distribution of the fuel bundle is measured by the bundle gamma scan.

On the other hand, the Ba-140 concentration is evaluated from the bundle power in the operating period by the following balance equation.

$$\frac{dN_{Ba}}{dt} = -\lambda \cdot N_{Ba} + S,$$  \hspace{1cm} (6)

where $N_{Ba}$ is the Ba-140 concentration, $S$ the Ba-140 generating rate and $\lambda$ the Ba-140 decay constant.

Two calculated Ba-140 distributions obtained from CMSs. The one is the evaluation from TIP-CMS, and the other is from the GT-CMS. For these evaluations, 36 datasets of TIP and GT were collected at the rated operation during the in-plant test. The data set collected one every week in the 2 months of beginning cycle, one every 2 weeks in the middle of cycles and one every week in the 3 months of end cycle. The burnup calculation was executed by off-line CMS with these TIP/GT dataset to adaptive. The burnup in the interval of dataset were executed every 3 days using the latest adjustment parameter $\Delta L$. At each burnup calculation point, MLHGR and MCPR were evaluated, and traced Ba-140 concentration by Equation (6).

A TIP/GT dataset includes TIP data for all strings and GT data for 7 strings. However, GT-CMS needs data for all strings to adaptive calculation. Therefore GT data for non-GT installed strings, GT data were made in the following manner.

(1) Calculate the GT readings $CALGT(M,L)$ for all strings by means of the power distribution calculated by TIP adaptation, where L denotes the string number and M denotes the elevation.

(2) Calculate the ratio $R(M,L)$ of the measured GT reading $GT(M,L)$ to the calculated one in the step (1) for each GT detector on the GT-installed strings.

$$R(M,L) = \frac{GT(M,L)}{CALGT(M,L)} \hspace{1cm} (7)$$

(3) Calculate the average ratio $RR(M)$ within the same elevation by means of the $R(M,L)$.

$$RR(M) = \frac{1}{7} \sum_{L} R(M,L) \hspace{1cm} (8)$$

(4) Calculate the GT readings $GTC(M,L)$ for the non-GT installed strings by means of the following equation.

$$GTC(M,L) = RR(M) \cdot CALGT(M,L) \hspace{1cm} (9)$$

GT-CMS evaluates the core power distribution by GT adaptation using $GT(M,L)$ for the GT installed strings and $GTC(M,L)$ for non-GT installed strings.

**VI. Evaluation Results**

**1. Comparison with Gamma Scan Measurements**

The calculated Ba-140 concentration distributions by CMS were compared with the measurement by gamma scans. The root-mean-square RMS of deviation was adopted for the evaluation parameter. The definition of the RMS is given by

$$RMS = \sqrt{\frac{\sum_{n} DB(n)^2}{N}} \times 100 \%, \hspace{1cm} (10)$$

and

$$DB(n) = BC(n) - BM(n) \hspace{1cm} (11)$$

where $BC(n)$ is the calculated value, $BM(n)$ the measured value, $DB(n)$ the deviation, $n$ the data point and $N$ is the number of data.

Three RMSs are shown in Table 1. The RMS[1D] is the RMS of the axial average distribution for the gamma-scanned bundles. 1D stands for one-dimensional distribution. The RMS[2D] is the RMS of the radial distribution for the gamma-scanned bundles. 2D stands for two-dimensional distribution. And the RMS[3D] is the deviation of the nodal distribution for the gamma-scanned bundles. 3D stands for three-dimensional distribution.

<table>
<thead>
<tr>
<th>Item</th>
<th>RMS of deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIP-CMS vs. GS*</td>
<td></td>
</tr>
<tr>
<td>RMS[1D]</td>
<td>1.7</td>
</tr>
<tr>
<td>RMS[2D]</td>
<td>2.5</td>
</tr>
<tr>
<td>RMS[3D]</td>
<td>3.9</td>
</tr>
<tr>
<td>GT-CMS vs. GS</td>
<td></td>
</tr>
<tr>
<td>RMS[1D]</td>
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<tr>
<td>RMS[2D]</td>
<td>2.3</td>
</tr>
<tr>
<td>RMS[3D]</td>
<td>4.1</td>
</tr>
</tbody>
</table>

* GS stands for gamma scan

Each RMS is a value small enough for core monitoring. Especially, both RMS[3D] values are sufficiently smaller than the index value 5.2%. Furthermore, the RMSs of GT-CMS are similar to the RMSs of TIP-CMS.

The comparison of the axial average Ba-140 distributions is shown in Fig.5. The distributions of TIP-CMS and GT-CMS are in good agreement with the gamma scan. The comparison of the deviation distribution between the calculated and the measured bundle Ba-140 concentration is shown in Fig.6. And a comparison of the deviation distribution of the nodal Ba-140 concentration is shown in Fig.7. Every deviation is small enough, and differences in distributions between TIP-CMS and GT-CMS are small.

A comparison between the calculated distribution of Ba-140 concentration by TIP-CMS and the measured distribution by the gamma scan is shown in Fig.8. In this figure, the distributions for the bundles surrounding TIP strings are shown. Likewise, the figure for GT-CMS is
Fig. 5  Comparison of axial average relative Ba-140 distribution

(a) TIP-CMS vs. Gamma Scan
(b) GT-CMS vs. Gamma Scan

Fig. 6  Deviation distribution between calculated and measured bundle relative Ba-140 concentration

(a) TIP-CMS vs. Gamma Scan
(b) GT-CMS vs. Gamma Scan

Fig. 7  Deviation distribution between calculated and measured nodal Ba-140 concentration

Two distributions by TIP-CMS and GT-CMS are in good agreement with the distribution by the gamma scan.

As described in the section II, GT-CMS has two different points to TIP-CMS.
(1) GT-CMS uses the measured gamma flux instead of the thermal neutron flux.
(2) GT-CMS uses only 9 measured GT values in a string instead of 24 points for TIP.

The above results are shown that the accuracy of GT-CMS is same as the accuracy of TIP-CMS. This means that
(1) The gamma flux at GT detectors can be evaluated with same accuracy to the thermal neutron flux.
2. Core Characteristic Parameters

MLHGR and MCPR are very important parameters for monitoring of core characteristics. These values were evaluated through the one cycle operation by means of the TIP-CMS and GT-CMS. A comparison of MLHGR is shown in Fig.10, and a comparison of MCPR is shown in Fig.11. These figures are shown good agreement between TIP-CMS and GT-CMS.

The RMS of the deviation of MLHGR was 0.4 kW/m and the maximum difference was 1 kW/m. And the RMS of the deviation of MCPR was 0.008 and the maximum difference was 0.02. These RMS values and the difference values are small enough for monitoring and core management.

VII. Conclusions

GT-CMS has two different points to TIP-CMS, that is, there are difference in the measuring principle and the number of axial measured points. In order to make sure of capability of this GT-CMS to the core monitoring, the in-plant test for the GT system was accomplished, and the feasibility of the GT system for core monitoring was evaluated by means of gamma scan, and comparison between the core characteristic parameters of TIP-CMS and GT-CMS.

The results of the comparison with the gamma scan were that the accuracy of GT-CMS was 4.1% in RMS, this was similar with the accuracy of TIP-CMS, 3.9%, and enough smaller than the index value 5.2%.

And the results of the comparison between with the TIP-CMS and GT-CMS are that the calculated core performance values were very similar, the RMS in MLHGR was 0.4 kW/m, and the RMS in MCPR was 0.008.

The above results are shown that the gamma flux at GT detectors can be evaluated with same accuracy to the thermal neutron flux, and the adjustment parameter with 9 GTs in a string can be evaluated in sufficient accuracy. From these results, it can be mentioned that GT-CMS can monitor the core performance with sufficient accuracy similar to TIP-CMS. And, it can be concluded that the GT-CMS is practical as a substitute for the TIP-CMS.

Acknowledgment


References

Fig. 8  Comparison of Ba-140 relative concentration distribution between TIP-CMS and gamma scan.
Fig. 9  Comparison of Ba-140 relative concentration distribution between GT-CMS and gamma scan
Fig. 10  Comparison between MLHGR by GT-CMS and by TIP-CMS

Fig. 11  Comparison between MCPR by GT-CMS and by TIP-CMS