APPLICATION OF THE GAMMA THERMOMETER AS BWR FIXED IN-CORE CALIBRATION SYSTEM

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Abstract

The application of Gamma Thermometers (GT) for Local Power Range Monitor (LPRM) calibration is being considered for replacing the Traversing In-core Probe (TIP) system currently used in BWRs. LPRM/GT assemblies, designed by GE Reuter-Stokes, have been tested in the factory and have undergone thermal hydraulic tests under simulated BWR operating environment in Toshiba facility. The applicability of GT technology to the BWR has been further evaluated through the design and manufacture of actual LPRM/GT assemblies by GE Reuter-Stokes.

The Fixed In-Core Calibration (FIC) system with LPRM/GT has many advantages over the TIP system. The TIP system is designed to traverse the reactor core with a neutron (or gamma) sensitive detector. The TIP system is a complex electromechanical system with considerable operation and maintenance need. LPRM/GT system uses GTs in fixed in-core locations and requires supporting electronics. A reduction in maintenance time during annual inspection is expected with the LPRM/GT system. A joint effort involving GE Nuclear Energy, GE Reuter-Stokes and Toshiba has been established to apply the new GT technology. These three companies share the effort: GE Nuclear Energy for engineering and system design, GE Reuter-Stokes for design and manufacture of the LPRM/GT assemblies and Toshiba for thermo-hydraulic performance testing.

Two LPRM/GT assemblies have been manufactured by GE Reuter-Stokes and installed in a US BWR for performance testing. During the factory calibration, the GT assemblies were placed in a tube filled with room-temperature water. The GTs were heated electrically with a large current flowing through the length of the GT. In this manner, it was possible to obtain heating rates similar to those which the GTs would be subjected to in an operating BWR. In separate tests, the heater cable was used to supply heat to the GT sensors. The collected data were used to calculate a heater rating for each GT sensor.

The thermo-hydraulic testing was performed by Toshiba at the MUSE facility which can simulate BWR core conditions, including void fraction. In this thermo-hydraulic test, a GT test piece of about 1 meter in length was used by Toshiba. The test piece was

manufactured to the same specification as the in-plant test specimen except for the length. The test piece had two sensing parts, each of which had two thermocouples. The basic test conditions were: a coolant flow velocity of 1 m/s, a temperature of 277°C and a void fraction of 0%. Perturbations of each of these parameters allowed the determination of the sensitivity of the detector response to each parameter. Within the range of 0.2 to 1.5 m/s coolant flow velocity, 263° to 282°C temperature and 0 to 55% void fraction, the variation in the GT sensitivity was less than 5%.

In summary, a BWR fixed in-core calibration system based on GT technology has been developed and evaluated as a replacement for the TIP system. An in-plant test is now under way at a commercial nuclear power plant in the USA. A similar demonstration of GT technology is planned for Japan under a Japanese BWR Joint Development Program beginning in 1996.

Introduction

The history of gamma thermometers dates back to the beginning of the 1950s when single chamber gamma thermometers were, for the first time, installed in the heavy water moderated reactors at Savannah River in the US. These devices replaced the original gamma ion chambers that proved to be unstable with a high failure rate. Later at the OECD Halden Reactor in Norway, single chamber gamma thermometers were installed in 1963.

The Radcal Gamma Thermometer (RGT) was developed as a result of studies conducted by Scandpower for Framatome and EdF in 1974. A major conclusion was that the gamma thermometer, long used in heavy water reactors, should be examined as a practical instrument in light water reactors. The interest was in the possible replacement of the Traversing In-core Probe system (which performs the functions of calibrating the LPRM sensors and providing input to the Core Monitoring System [1]). A fixed, gamma thermometer type system would have many advantages over a TIP system including real time measurement and mechanical simplicity.

Wimpee, *et al*. [2] of GE Nuclear Energy developed a concept for a Fixed In-Core Calibration device for BWR flux monitoring in the early 1990s. Based on this concept and application, extensive studies and a design review of a FIC with GTs were conducted during the Simplified Boiling Water Reactor (SBWR) design process. Then the application of GTs for an optimised Neutron Monitoring System was adopted in the certified SBWR [3] design.

In 1991 Tokyo Electric Power Company (TEPCO) [4], embarked on a study program titled “Improved Evolutionary Reactor (IER)” to study various design considerations for the decade of 2010. This study [5] was conducted by GE Nuclear Energy, Toshiba Corp. and Hitachi Ltd. As part of the Phase I IER study, the following three design concepts were evaluated.

1. Fixed In-core Calibration System using Gamma Thermometer;

2. Core Monitoring with Long Self-powered Neutron Detector (SPND) with Gamma Thermometer;

3. Cerenkov Monitor for In-core Power Measurement.

Subsequently a FIC system with GTs was selected as a suitable in-core instrumentation for replacement of the TIP system and to realise many other benefits [4]. Later in IER Phase II (1993-95), further evaluations of the accuracy, merits and economy of a GT application were performed. At the conclusion of IER Phase II [6], the FIC design was adopted as part of the reference plant design for future applications.

Limerick GT test program

The purpose of the LPRM/GT in-plant test program, established jointly by GE Nuclear Energy and GE Reuter-Stokes, is to assess the accuracy and reliability of the gamma thermometer as a replacement for both thermal neutron and gamma sensitive TIP systems.

The LPRM/GT test program began in February, 1995 with the installation of two Gamma Thermometer assemblies with standard LPRMs in the Limerick 2 plant. The Limerick 2 plant is an 1100 MWe BWR4. It has 764 bundles of the “C” lattice type and a total of 43 LPRM strings.

Each GT string in this test consists of four Gamma Thermometers, each of which was positioned adjacent to an LPRM fission chamber. The calibration (TIP) tubes were left intact so that the TIP system would operate normally and so that a direct comparison could be made between the Gamma Thermometer and Gamma TIP readings.

The test plan calls for automatically recording at least once a day all the GT readings, as well as the corresponding LPRM readings. Whenever a TIP set is taken (normally every 1000 full-power-hours), the GT calibration process will be triggered (manually) and the GT, LPRM and gamma TIP readings will be recorded.

The in-plant test is scheduled to last for two complete fuel cycles each of which will last for two years. This is the equivalent of four one-year cycles. This will establish long-term reliability. The first cycle of the test program began in February, 1995 and will continue until January, 1997. The second cycle will begin in March, 1997 and continue until April, 1999.

The test program is now in the middle of its first cycle. Gamma Thermometer readings are being recorded on a daily basis. Calibration and inter-comparison with the TIP readings is scheduled to occur approximately every six weeks.

LPRM/GT assembly mechanical design

Two LPRM/GT prototype assemblies were manufactured and delivered to Limerick in December, 1994. A schematic of the assemblies is shown in Figure 1. The two test assemblies are functionally identical to the existing standard NA300 LPRM assemblies used at Limerick; they contain the same number of LPRM sensors (4) and a TIP calibration tube. In addition, each LPRM/GT assembly contains a GT rod.

The LPRM/GT assembly contains the standard LPRM plunger and the standard LPRM gland interface features. Therefore, the fit-up to the RPV top guide and in-core flange is the same as for a standard LPRM assembly. The standard LPRM mounting hardware is used to attach the LPRM/GT assembly to the in-core flange. The cover tube guide rings also have the same configuration and location as for the standard LPRM assembly. Differences between the standard LPRM and the LPRM/GT assembly are:

1. The LPRM/GT assembly shield tube used to protect the cables and connectors during installation in the RPV was lengthened to accommodate the additional GT cable and connector.

2. The calibration (TIP) tube of the LPRM/GT assembly is slightly off-centre.

3. Additional flow holes were placed near the top of the LPRM/GT assembly to enhance flow past the GT.

Description of the GT

The GT is a solid stainless steel rod with argon-filled annular chambers located at each LPRM fission chamber level. Differential thermocouples are embedded in the rod at each chamber location so that a temperature difference, proportional to the gamma flux impinging on the rod, is effected between the thermocouple junctions. The GT also contains a centrally located heater cable, which provides a means of calibrating the GT in-situ. This is done by supplying a known electrical current to the heater which causes an increase in heating at each sensor and by measuring the change in the thermocouple output.

The GTs installed in Limerick were manufactured by Delta-M Corporation in Oak Ridge, Tennessee. Each GT contains four sensors (i.e. four differential thermocouples), with one sensor located at each LPRM level. There are ten leads in the GT, eight for the four differential thermocouples and two for the central heater. These leads are terminated in a single 10-pin connector plug.

The heater consists of a single lead nickel cable with 305 mm sections of nichrome placed at each sensor location. The nickel/nichrome lead is connected to the GT body at the top of the GT. The positive or high voltage lead is terminated in one pin in the connector, while another pin is connected to the GT body.

LPRM/GT factory data

The GTs were calibrated in the factory using a method developed by Scandpower. The GT is placed in a tube with cooling water at room temperature flowing by it. The GT is heated electrically by passing large electrical currents (up to 250 A or about 4 W/g) through the stainless steel core and jacket tubes. This is termed “Joule” heating, and it is only with Joule heating that heating rates similar to those caused by gamma heating in the reactor can be generated in the factory.

The amount of sensor heating is calculated knowing the resistance of the stainless steel and the electric current flowing through it. The volumetric heating values, w, are then correlated with measured output signals from the GT thermocouples to yield values of the GT sensitivity, S_o, and second order correction coefficient, α. The values of S_o and α represent the best fit to the data,

$$U = S_o w + \alpha (S_o w)^2 \qquad \text{Eq. (1)}$$

where U[mV] is the measured thermocouple signal and w[W/g] is the sensor heating calculated using the method described above.

Measurements were also performed using only the heater cable to supply heat to the GT sensors. Using the known values of sensitivity, S_o, from Joule calibration, the amount of heat deposited by the heater cable as a function of heater current was determined. These “heater rating” values were then adjusted for heater wire temperatures in a BWR to obtain the BWR Heater Ratings. Results of the Joule and heater cable calibration are shown in Table 1.

Table 1. Cold calibration results and BWR heater rating

GT	Sensor	Joule S_o [mV-g/W]	Joule α [mV^{-1}]	BWR Heater Rating [$W/g/Amp^2$]
RSGT-01	A	2.068	-0.0168	0.100
	B	2.054	-0.0173	0.100
	C	2.115	-0.0166	0.098
	D	2.072	-0.0174	0.100
RSGT-02	A	1.988	-0.0164	0.098
	B	2.011	-0.0167	0.096
	C	2.014	-0.0168	0.098
	D	2.022	-0.0175	0.097

Thermo-hydraulic testing

Test conditions

To apply a FIC system to BWR plants it is necessary to know how the environmental conditions of an LPRM/GT assembly affect the GT sensitivity. Toshiba has performed thermo-hydraulic testing on an experimental GT assembly using the Multiple-Use Safety Experimental Facility (MUSE) which can simulate BWR core conditions of saturation temperature, saturation pressure, and void fraction. The voids can be generated by a heater which precedes a test pipe in which the test piece was installed. Table 2 shows the specification of the test piece. The test piece was manufactured to the same specifications as the in-plant test specimen except for the length. The test piece had two sensing parts, each of which had two thermocouples.

Table 2. MUSE GT test piece specification

Item	Specification
GT length	1 m
Outer diameter	7.95 mm
Chamber size	26.5 $\times$ 0.5 mm
Chamber gas	Ar (10 bars)
Material	SUS 316L
Differential thermocouple	Type K

The basic conditions were: a coolant temperature of 277°C, a coolant flow velocity of 1 m/s and a void fraction of 0%. The basic coolant temperature was determined by the saturation temperature and inlet subcooling (~10°C). The basic coolant velocity was calculated from the differential pressure of the core plate and the dimensions of an LPRM/GT assembly. The basic void fraction was calculated from the in-core gamma heating power and flow rate in LPRM/GT assembly. Perturbations of each of these parameters allowed the determination of the sensitivity of the detector response to each parameter. The range of each parameter is as follows: 1) coolant temperature: 263 ~ 282°C, 2) coolant flow velocity: 0.2 ~ 1.5 m/s, and 3) void fraction: 0 ~ 55%. The ranges of these parameters were determined based on the BWR plant conditions and the performance capability of the MUSE facility. Although the void fraction is evaluated to be 0% in an actual LRRM/GT assembly, it was tested to confirm if the GT sensitivity will change with void variations. In this test an inlet heater was used as a substitute for gamma ray heating to simulate an average BWR gamma flux heating in the range of 3 to 4 W/g. The inlet heater is used to calibrate the GT sensitivity. The heating power range of the inlet heater is less than 1W/g because of restrictions in the inlet heater performance.

Muse test results

The relationship between the GT output signal and the heating power is described in Eq. (1). The effects on parameters are evaluated using the sensitivity S_o in Eq. (1). α, in Eq. (1), characterises the deviation from linearity and mainly embodies the change in thermal conductivity of the material with temperature.

Effect of coolant temperature

The coolant temperature was measured at the inlet point of the test pipe. The coolant velocity and void fraction were held constant while changing the coolant temperature. The sensitivity deviation including measuring instrument error is about 1% for the perturbation of the coolant temperature.

Effect of coolant velocity

The coolant velocity was measured by an orifice flow meter. The coolant temperature and void fraction were held constant while changing the coolant velocity. Figure 2 shows the relationship between heating power and GT output signal while changing the coolant velocity. The sensitivity deviation including measuring instrument error is about 0.5% for the perturbation of the coolant velocity.

Effect of void fraction

The void fraction is not a measured value, but a calculated value that is obtained by Zuber's equation using coolant temperature, pressure, coolant velocity and heater power.

Figure 3 shows the relationship between heating power and GT output signal while changing the void fraction. The sensitivity deviation for the perturbation of void fraction is about 5%. This is not a problem in the application of GTs to a BWR because voids are not ordinarily generated in an LPRM/GT assembly.

Thermo-hydraulic test inference

This thermo-hydraulic test shows that the deviation of sensitivity for the perturbation of the coolant temperature and coolant velocity is not large, thus making GTs very suitable for BWR applications.

Conclusion

A BWR fixed in-core calibration system based on GT technology has been developed and evaluated as a replacement for the TIP system. This technology holds a great potential for replacement of TIP systems in operating BWRs and future BWR designs. An in-plant test is now under way at a commercial nuclear power plant in the USA. A similar demonstration of GT technology is planned for Japan under a Japanese BWR Joint Development Program beginning in 1996.

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Figure 1. LPRM/GT with Cal Tube

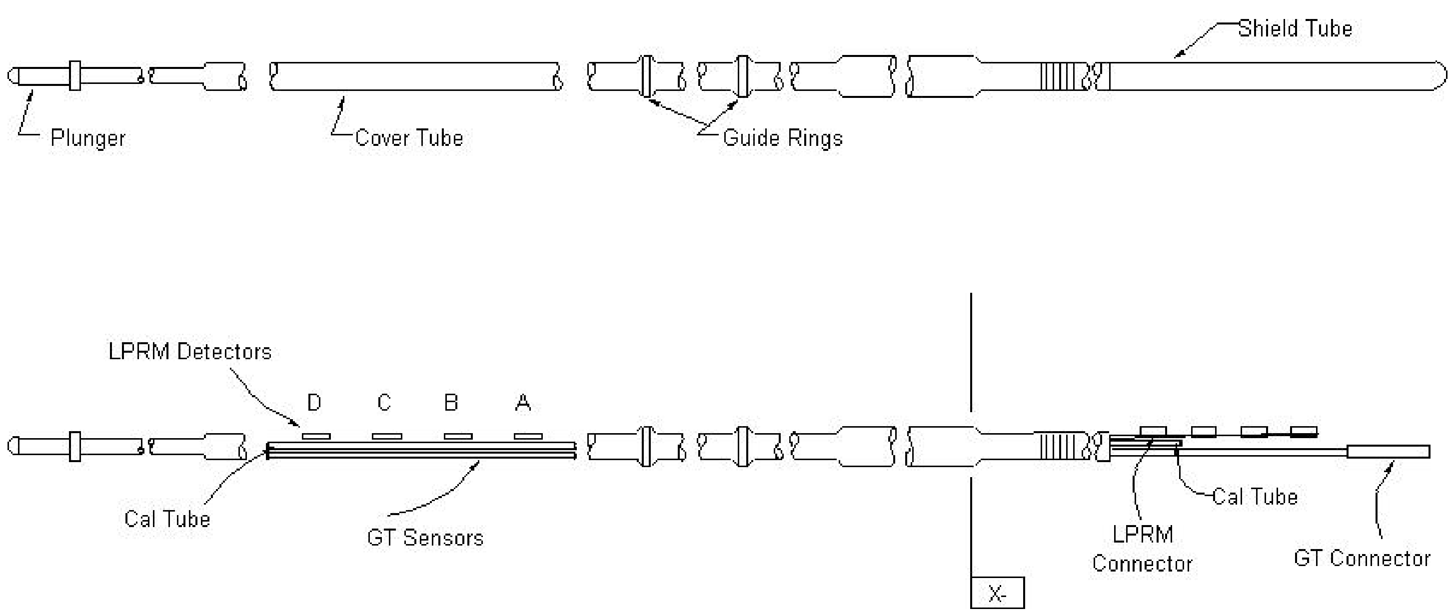

Figure 2. GT output signal vs. heating power under varying coolant velocity

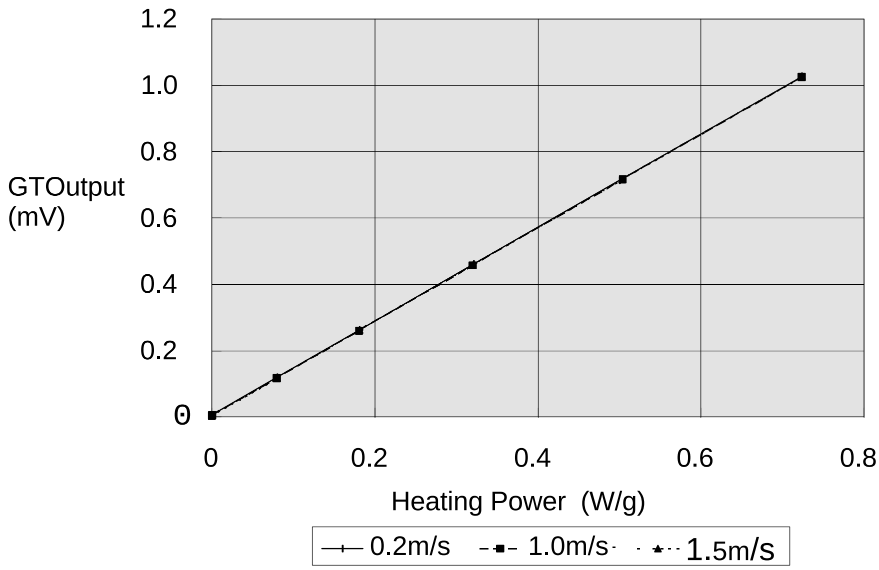

Figure 3. GT output signal vs. heating power under varying void fraction