5 Year In-Core Behavior of Gamma Thermometer Technology: Proof of Prototype Life Expectancy

Andrew Kebert, Christopher Freeman
Reuter-Stokes, a Baker Hughes Business
Twinsburg, OH, USA

Abstract

This paper summarizes the findings following a 5 year period of in-core operation of the Gamma Thermometer Local Power Range Monitor (LPRMs) calibration system. The 6 prototype assemblies, each containing a string of 7 thermocouples, showed a modest decrease in sensitivity of less than 0.02 mV/g/W (2.5% loss of sensitivity) over the course of a total accumulated exposure of 33,000 MWd in an operating commercial nuclear reactor. These results reinforce the feasibility of this technology for use in active commercial reactor cores with a minimum proven operating life of 5 years (33,000 MWd). The trend behavior of the sensitivity as the string is exposed to irradiation suggests that the operating life may be in excess of 10 years before a noticeable sensitivity decrease is observed following "burn-in". These results shed a favorable light on the technologies use in the upcoming GEH BWRX-300 Small Modular Reactor which incorporates GT technology as the sole calibration method for LPRMs during normal operation.

Introduction

The Gamma Thermometer (GT) is a self-calibrating, fixed in-core, robust calibration technology that is seen as a much-needed step forward in the realm of Local Power Range Monitor (LPRM) calibration. With current technology requiring external cable drive systems and a network of tubing, located under the reactor vessel, to allow calibration, the fixed in-core GTs provide a number of advantages and was chosen as the primary LPRM calibration technology in the GEH (General Electric Hitachi) BWRX-300 advanced reactor design.

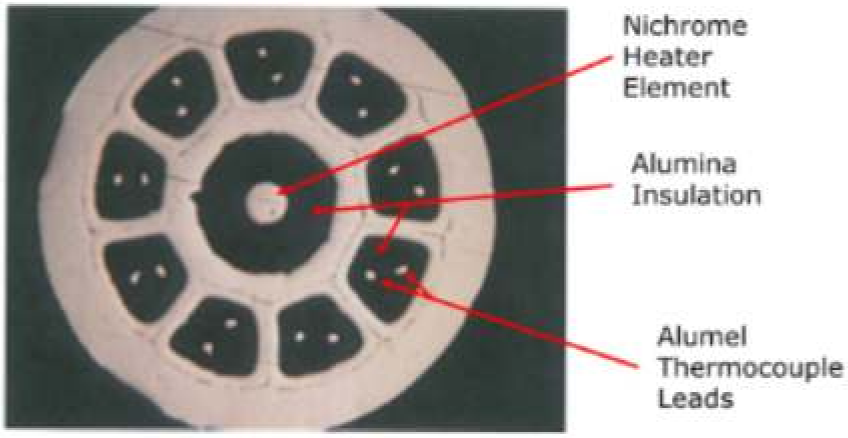

Figure 1: Cross Section of GT

The GT is a tubular structure containing seven individual thermocouples at step heights throughout the tube. These thermocouples are positioned to give vertical accuracy of reactor power. The fission events that occur within the reactor core produce a gamma flux that, at power, is proportional to fission rate. These gamma rays cause a heating effect via photoelectric effect, Compton scattering and pair production in the metal surrounding the thermocouples in the GT. This heating effect is known as "Gamma Heating." Great care and a robust quality control/manufacturing/testing program ensure that the heat generated within the thermocouple, in excess of the heat gained from nearby reactor coolant, gas heating, irradiation effects, is directly related to the gamma flux of the core, and thus, reactor power level. A central heater element is used to allow “at will” re-calibration/proof of status for each GT installed in the core.

The theory of operation and efficacy of GT technology was confirmed through a number of prototype installations; Limerick Power Station installed 2 GTs and collected operational data over a 3 year period, Tokai installed 2 GTs and Kashiwazaki-5 installed 4 and collected data over 12months, or one cycle. The prototype performance was evaluated and found to be satisfactory and the GT technology was designed into the next set of Advanced Reactor Designs. A concern that had not been mitigated through the 8 prototype installs was the signal output behavior over time as the GT approaches its end of life.

A batch of six GTs was produced and installed within the Laguna Verde Nuclear Reactor for a 5 year life expectancy test. The goal being to find that the signal degradation over time would be minor enough to allow a comparable, if not superior, operating life when compared to current LPRM calibration technology.

Gamma Thermometer Signal Analysis and Inputs

Gamma Thermometer gamma sensitivity, as designed, is expected to remain relatively constant throughout the detector life. However, this has not been the case in any real-world GT study. In each study, a particular pattern of sensitivity decrease has been observed that will be detailed below. The cause of this deviation from expectation is still under investigation. Using the equation for non-linear response of a GT when subject to a gamma flux:

$$U = \frac{Se\,\rho L^2 w}{2k_{ss}}$$

where: U = measured signal from differential TC, mV
Se = Seebeck coefficient, mv/°C
ρ = SS density, g/cm^3
L = chamber half length, cm
w = power, watts per gram
k_{ss} = SS thermal conductivity, w/cm°C

Figure 2: GT Signal Output Formula [2]

From which follows:

$$S = \frac{Se\rho L^2}{2k_{ss}}$$

Figure 3: GT Sensitivity Formula [2]

Where S is GT sensitivity in units of mv/w/g.
Of note to this equation is the inverse proportionality of signal output, and thus sensitivity, to the thermal conductivity of the stainless steel (SS). General values of thermal conductivity for stainless steel vary from 0.148 w/cmC at 20C to 0.180 w/cmC at 286C PER REFERENCE 2. Therefore, a correction factor is applied to allow direct comparison of anticipated output at operating temperatures as follows:

$$S(T_2) = S(T_1) \bullet \frac{k_{ss}(T_1)}{k_{ss}(T_2)}$$

Figure 4: GT Temperature Reactive Sensitivity Formula [2]

This relation/correction indicates that a correction factor of 0.82 is applied to a measurement taken at 20C to arrive at an anticipated 286C measurement value.

During normal operation, a nuclear reactors LPRMs are periodically calibrated using a secondary set of detectors whose calibration is confirmed and documented. This second set of detectors varies in form from fixed in-core detectors to mechanically driven/traversing detectors that “scan” through the core and produce an output signal that is compared to that of the LPRM.

During the testing performed at Laguna Verde, the GTs were not considered the second set of detectors, but a tertiary, non-operation affecting set. This allowed the reactor to operate and maintain conformance with technical specifications while also allowing a real-world look at the function of the GTs. During periodic calibration operations, GT data was collected in addition to the standard calibrating detector data output to provide a comparison and trend in response over time.

Gamma Thermometer Life Expectancy Testing Output and Analysis

Six GTs were installed within the core at Laguna Verde for a period of 5 years. Installation locations were chosen to provide a good variety of reactor operating conditions ranging from lower neutron and gamma flux outer core regions to inner core high neutron and gamma flux regions. The output data, in the form of sensitivity, was provided as an output at the conclusion of the 5 year testing.

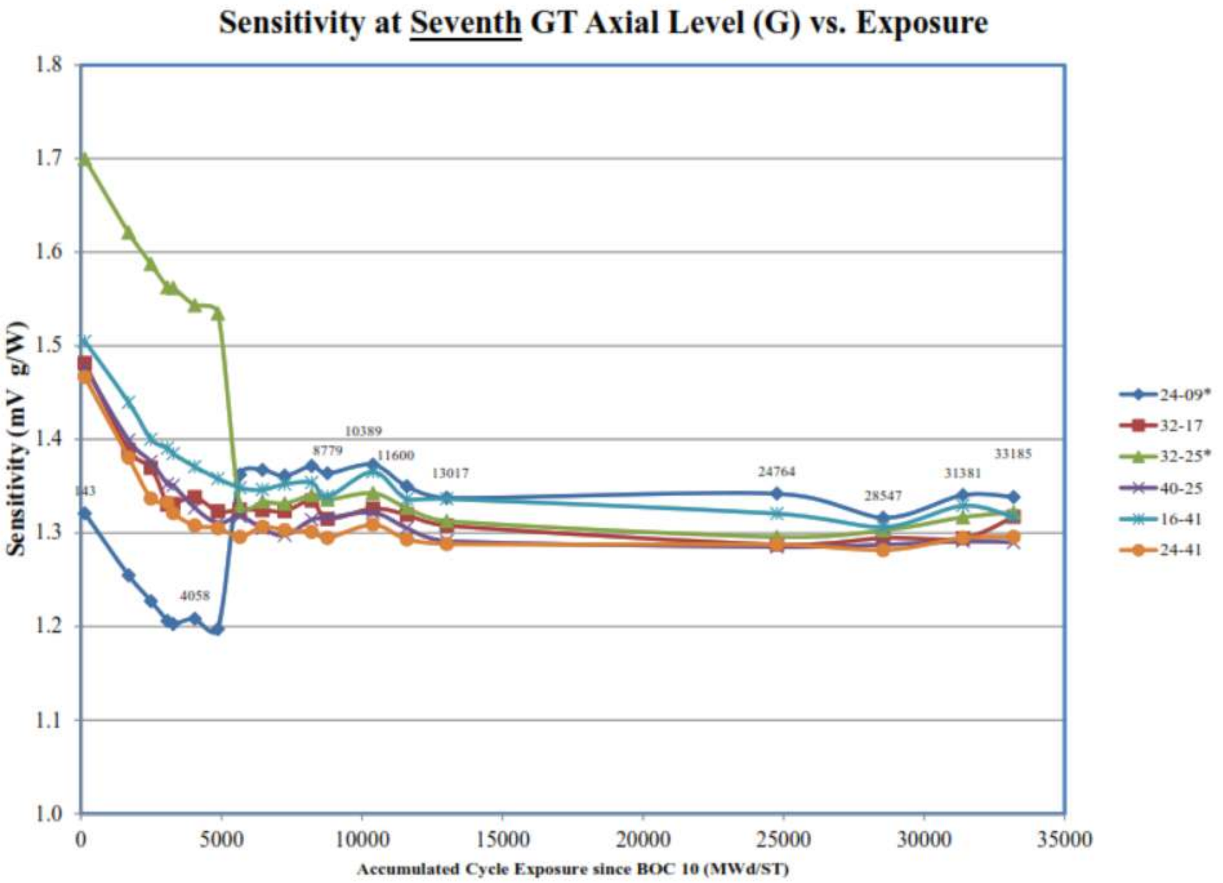

Figure 5: 7th Level GT Sensitivity Data

Figure 5 shows the GT sensitivity as the device is exposed to radiation. Figure 5, specifically, shows the 7th thermocouple output from each GT installed in the core, where the 7th thermocouple is located closest to the bottom of the reactor core for each GT string.

From Figure 5, it can be seen that the GT design is subject, like many detector technologies, to a “burn-in period” where materials, dimensions and interactions all settle into a from of equilibrium. For GTs, this “burn-in period” resolves around the 5000MWd exposure level.

This behavior was first presented following testing of a GT design in 1980 at Dodewaard by the OECD Halden project, similar trends of a 2 year burn-in period were noted and examined. Per the analysis provided by the Halden project, the early life decrease in sensitivity can be attributed to material and fill gas changes caused by local irradiation of the materials. One noted potential cause of fill gas changes is a migration of hydrogen into the gas, adversely affecting the heat transfer that the GT requires to function properly. As in-core time progresses, these affects reach equilibrium. OECD Halden reported changes in sensitivity of 10%, named as “sensitivity drift”, during the first two years and then negligible drift following that period.

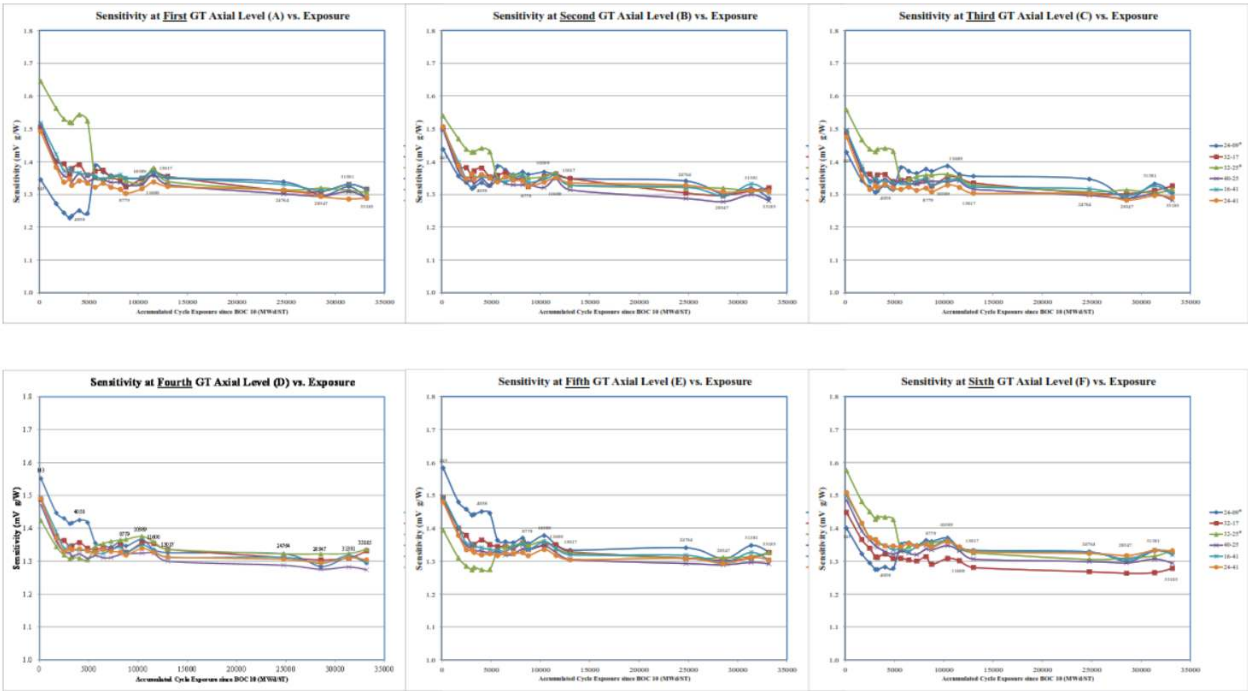

Figure 6: GT Data All Levels

The data collected for the remaining six levels of thermocouples per GT are displayed in Figure 6. Of note is the abnormal behavior of the majority of the thermocouples within GTs 24-09 and 32-25. Both GTs exhibit a much further from centerline initial sensitivity, followed by a large correction down to match performance of the other 4 GTs. The cause of the correction is well documented as explained prior, but the cause of the initially large discrepancy from the rest of the batch is unknown at this time. Possible causes are manufacturing irregularities, argon gas impurity, material impurity, but no root cause has been identified at this time.

Each thermocouple shows varying degrees of this anticipated “burn-in” of around 10% (up to 21% for 32-25 and 24-09) over the first 6000MWd. The degree to which they exhibit the behavior is tied directly to the location in the core and thus the flux the thermocouple sees. For example, a thermocouple located at the top or bottom of the core will generally see less radiation exposure per unit time than would a thermocouple installed closer to the center of the core’s active fuel height.

With starting sensitivities ranging from 1.475 to 1.505 mv/g/W (1.2 to 1.7 mV/g/W including 24-09 and 32-25), an average starting sensitivity is found to be nearer the 1.499mV/g/W mark. Following the “burn-in period,” the average sensitivity for all six GTs is nearer, and stable at, 1.35mV/g/W. This is the “starting” sensitivity value of interest when comparing long term operational output and EOL signal output. R-S LPRMs are specified with a 7-year operational lifetime, integral GTs are expected to match or outlive the LPRM.

Over the course of the 33000MWd testing performed at Laguna Verde, the six GTs showed varying degrees of sensitivity drift based on the axial and radial location of the GT in the core. For example, the First Level thermocouple (top of core) showed a sensitivity value of 1.32mV/g/W at the 5 year mark (2.3% decrease over burn-in) while the Fourth Level thermocouple (center of core) showed a sensitivity value of 1.30mV/g/W at the same mark (3.8% decrease). This behavior is not unexpected, as previous in-core testing of GT technology showed similar behaviors over the first several years of operation.

Of note is the observed decrease and subsequent recovery of sensitivity seen by the majority of the GT levels between exposures of 25,000 and 30,000 MWd. This response could be caused by changes in the core due to refueling operations, operational state changes, power reductions or power uprates. Each of these examples would certainly affect the gamma flux profile throughout the core and thus the GT response at each location.

Laguna Verde reported a number of in-core changes throughout the GT testing period, including a new fuel bundle design, a fuel rod failure event, but none of these changes occurred during the final 2 years of testing. Therefore, none of these changes directly account for the sensitivities behavior.

With a lack of information regarding any changes made at Laguna Verde between exposures of 25,000 and 30,000MWd, this behavior is a non-ideal output that adversely affects the analysis of long term sensitivity response to radiation exposure. This behavior makes analysis of the expected steady sensitivity decrease unachievable with any meaningful degree of accuracy using the “as reported” values. Further analysis is required to determine if a meaningful %/yr sensitivity drift can be established for this particular model of GT from the Laguna Verde output data or if additional testing must be performed to gather such data.

Averaging the GT levels at each timestamp, the trend of sensitivity over time and exposure more closely matches the expected steady decrease supplied as an output from the testing performed at Limerick Power Station in the late 1990’s. This steady decrease along with the ability to perform “on request” heater calibration of individual GTs, allows for an improved level of certainty in the long term performance and LPRM calibration ability of the GT technology.

If this is the case, the potentially limiting failure mechanisms of the GT technology that must be assessed are: loss of argon gas purity due to irradiation of stainless steel in its vicinity (and hydrogen migration), reactor aging of the stainless steel GT structure, heat cycling of the thermocouple materials within the GT chambers, etc. While of concern, these failure mechanisms are not anticipated to reach fruition during normal operational use of the GT during the anticipated 10 year life of the LPRM that houses the GT based on material studies performed on materials approved for nuclear in-core use. None of these factors have been documented to have caused a premature GT failure in any of the prior referenced testing of GT technology, nor during the Laguna Verde testing.

References

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[2] Bernnat, W., & Siegel, K. (1987). Determination of local power in a PWR core based on measured gamma thermometer signals. Kerntechnik (1987).