IMAGING RADIOACTIVE COMPONENTS INSIDE A CANDU® REACTOR USING GAMMA RADIATION SCANNING

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Abstract

A gamma radiation scanning system based on a silicon diode sensor has been developed and used to profile the gamma radiation field along the depth of an in-core start-up instrumentation guide tube inside a [1]CANDU® reactor undergoing mid-life refurbishment. These measurements image the radioactive components close to the scanning path, and provide confirmatory information on radiation field strength for material selection and reliability analysis of in-core start-up instrumentation. The positions of two irradiated adjuster rods adjacent to the guide tube and parked above the core were identified from features in the radiation profile. The successful gamma radiation profile measurement provides assurance that this technology could be used to image radioactive components inside the reactor core.

1. Introduction

Gamma radiation fields inside a CANDU reactor had never previously been measured, even in a shut-down reactor. Various assessments of the gamma radiation exposure rate inside and around a CANDU reactor were required to formulate safe radiological work plans, and to evaluate the suitability of materials installed inside the reactor. Confirmation of these assessments using measurements was desirable. However, it is very difficult to measure the radiation field inside a reactor directly due to the restricted access and high radiation fields involved.

The CANDU 6 reactor at Point Lepreau Generating Station has been shut down for refurbishment since 2008 March. An uncertainty of about 7 cm in the absolute positions of the adjuster rods in this reactor core had been identified in the past, and a measurement of the exact positions of the rods was therefore desired during the refurbishment shutdown. Following AECL's successful experience using radiation profiling to measure the liquid level in a highly radioactive liquid tank [1], it was expected that the radiation scans would permit reduction in the uncertainty of the adjuster rod locations.

This reactor power will be monitored by in-core fission chambers located inside the start-up instrumentation (SUI) guide tube after refurbishment. This is to monitor the lower power levels during refueling and return to service. The specified gamma dose-rate limit for the fission chamber is 10^4 Gy/hr. The total dose limit for the chamber is given to be 10^7 Gy. The same requirements apply to the mineral insulated (MI) cable. Since there was no direct measurement of the gamma dose rate in a shut-down CANDU reactor, the dose rate and the total integrated dose received by the

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[1] *CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL).*

fission chamber were estimated by calculation. A confirmatory measurement of the field was desired by the generating station.

To confirm that the radiation scan is capable to locate the position of the adjuster rods, a preliminary gamma field scan was performed in September 2009 in the SUI guide tube. This paper describes the measurement system and the experiment results.

2. Sensor and Measurement System

2.1 Sensor Probe

With a Si p-n junction diode resident in a gamma radiation field, the total charge generated by the diode is well known to be proportional to the ionization energy deposited in the diode depletion region [2]. Since radiation dose is, by definition, equal to the ionization energy deposited, measurement of the total charge is a direct measure of radiation dose.

Based on our previous success of using Silicon p-n junction diodes operating in current mode to measure high gamma fields [3], we developed a miniature Si-diode gamma sensor, which is attached at the end of a long MI cable as shown in Figure 1.

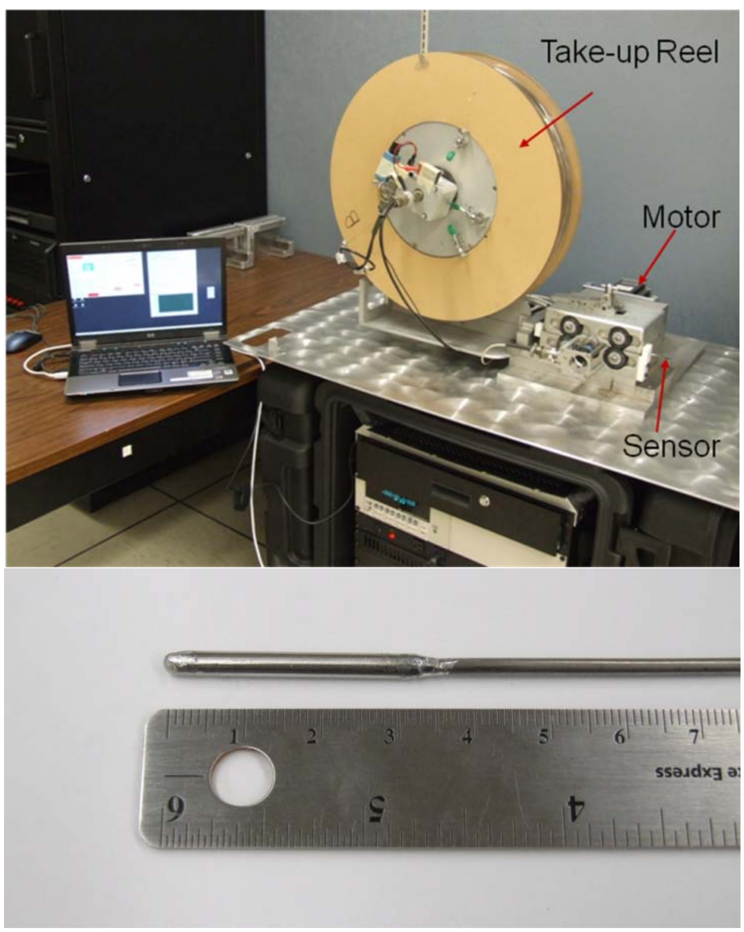

Figure 1 Probe Assembly and Sensor

The probe was designed to be pushed into the reactor through a long guide tube with an inside diameter (I.D.) of about 3.4 mm by an automated drive system. As shown in Figure 1, the MI cable was wound on a take-up reel. The sensor was attached at one end of the MI cable. The other end of the MI cable had a BNC connector, which was connected through a slip ring system to the input of an amplifier.

The 30-m-long MI cable had an outside diameter (O.D.) of 1.57 mm. There were two nickel conductors in the core, insulated from the sheath by compacted magnesium oxide (MgO) insulation. The sheath was made of SS-316 stainless steel, and was annealed. Hence, the cable was very soft, and easily bent. A cold worked MI cable would be an improvement because the stiffness of such a cable is higher, making it easier to push the sensor through restricted diameter tubing.

2.2 Radiation Scan System

An automated drive system was required for a long and accurate scan. The drive was modified from an eddy current probe pusher. The pusher had four drive wheels to pinch and drive the MI cable and sensor forward or backward. A take-up reel was geared to the stepper motor to automatically wind up the MI cable when the drive pulled the sensor back. A rotary encoder contacted the surface of the reel in order to record the position of the sensor.

A Keithley 6487 pico-ammeter, capable of measuring lower than 1 pico-ampere current with high accuracy, was chosen to read the signal from the sensor. The measurements were sent to a computer through the RS232 port of the pico-ammeter, and logged along with the position of the sensor and the time of measurement.

The major modules of the control and data acquisition system included an AC power filter, motor controller, pico-ammeter, encoder interface box and USB communication hubs. The control modules and signal readout system were enclosed inside a portable electronics chassis.

2.3 Sensitivity and Linearity check

The principal contributor to the gamma dose rate inside the shut down reactor was Co-60. The original Co-59 concentration in steel gave rise to this activity due to neutron activation during reactor operation.

A source check of the sensor probe was carried out at Chalk River Labs using a calibrated (nominally 10 Ci) point-like Co-60 source. The source-to-sensor distance was varied to obtain gamma radiation exposure rates ranging from approximately 0.2 Gy/hr to 2 Gy/hr as calculated by the inverse square law. The sensor output current was directly proportional to the exposure rate in this range, as shown in Figure 2. This source check gave a sensor output current sensitivity of 28.3 pA/(Gy/hr).

The proper operation of any semiconductor detector depends on the near perfection of the crystalline lattice. However, radiation-induced lattice damages take place under extensive use of the detector, and this causes signal degradation and loss of sensitivity of Si-diode sensor. To examine the damage to the sensor, it was re-checked with another calibrated Co-60 source after it was returned from the reactor site. As shown in Figure 2, the re-measured sensitivity was 27.5 pA/(Gy/hr), which was slightly lower (2.8%) than the previous calibration, but within the calibration uncertainties of the two sources. Therefore, there was no significant degradation of the sensor sensitivity during the radiation scan that would affect the measurement accuracy.

Although the maximum radiation exposure rate in this source check was 2 Gy/hr, much less than the radiation field, 1000 Gy/hr, in the reactor. Similar sensors had been studied in the past and shown to have very good linearity under 2000 Gy/hr [1][3].

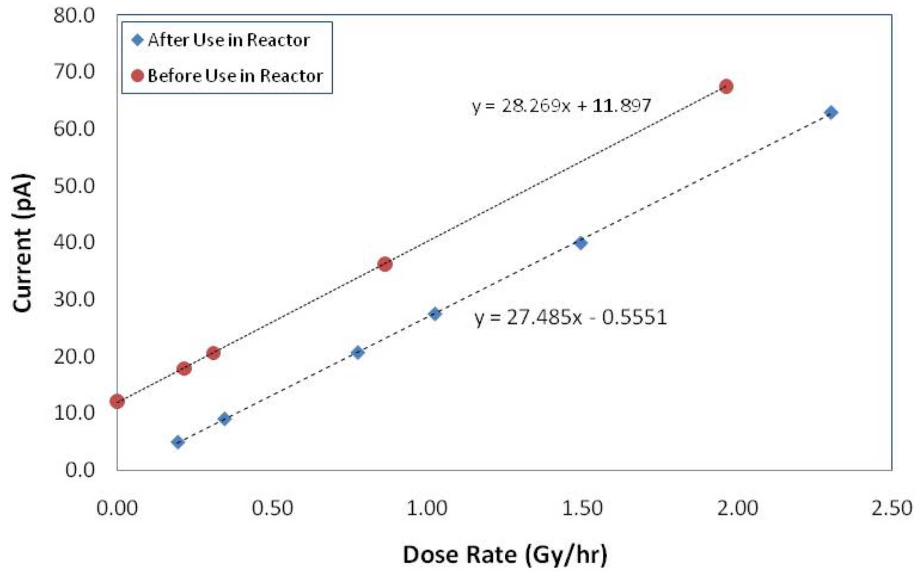

Figure 2 Sensor Sensitivity Check

3. RADIATION FIELD MEASUREMENT

The gamma radiation scans were carried out from the top of the reactivity mechanisms (RM) deck of the PLGS reactor. Figure 3 depicts a generic CANDU 6 reactor structure inside the reactor vault. The radiation scan apparatus was installed on top of the RM deck, marked '9' in Figure 3.

The access port to the reactor was the in-core SUI guide tube as shown in Figure 4. Adjuster rods 15 and 16 were not within the core during the measurement, as depicted in Figure 4; rather all rods were fully withdrawn from the core when the reactor was shut down for refurbishment. All the fuel bundles, pressure tubes (PTs), and calandria tubes (CTs) were removed from the core as part of the refurbishment. The only radiation sources remaining inside the calandria vessel at the time of the gamma scans were the reactivity mechanism assemblies - mechanical control absorbers (MCA), shut-off rods (SOR), vertical and horizontal flux detector assemblies, as well as the calandria vessel itself. The in-core SUI guide tube was not radioactive because it is a brand new tube assembly recently installed in preparation for the return to service.

The starting point of the scan was approximately 1 m above the bottom of the guide tube, and then the sensor was withdrawn step by step for a total travel of 10 meters. Because the calandria wall was expected to be the major radiation source, the peak value of the radiation field was expected to be used to pinpoint the location of the calandria edge. The position of other components could be inferred using the location of the calandria edge as a reference point.

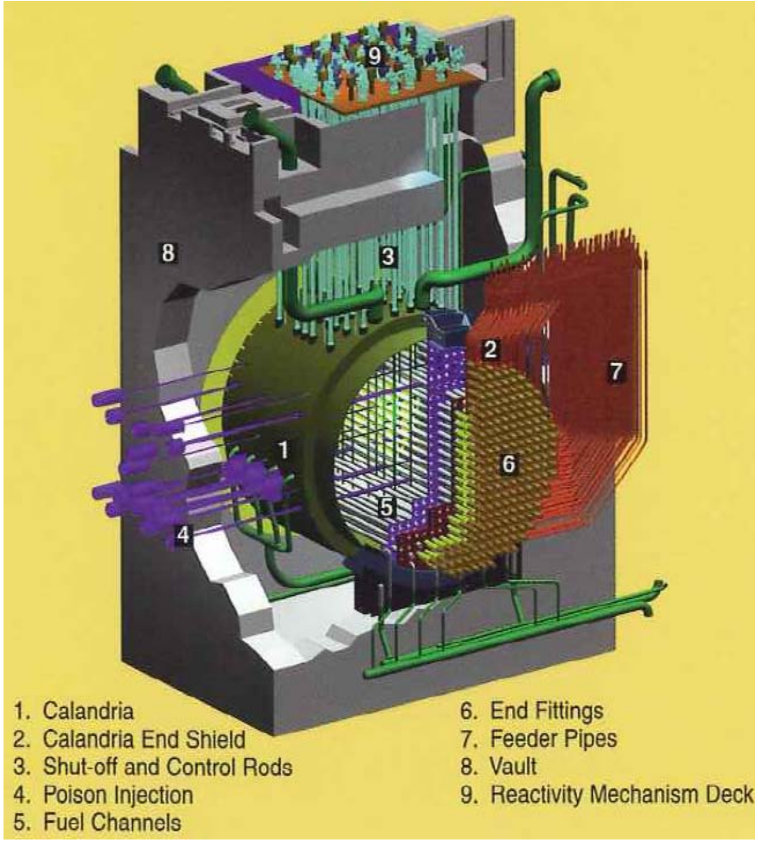

Figure 3 Calandria Assembly in Reactor Vault

4. EXPERIMENTAL RESULTS

The raw data measured in the reactor was noisy because of the construction environment inside the reactor building. Therefore, multiple samples (30 samples) were taken with the sensor parked at each spot. Most of the measurements were located in the center of the measurement range for each data point. The raw data was filtered to remove the noise. The filtered data is shown in Figure 5.

Figure 5 shows the complete data set of radiation exposure rates as a function of position. The position readings (x-axis of figures) are in reference to the home position of the sensor (at the exit of the drive system). For further analysis, the radiation profile curve is divided into 3 sections, referring to Figure 5.

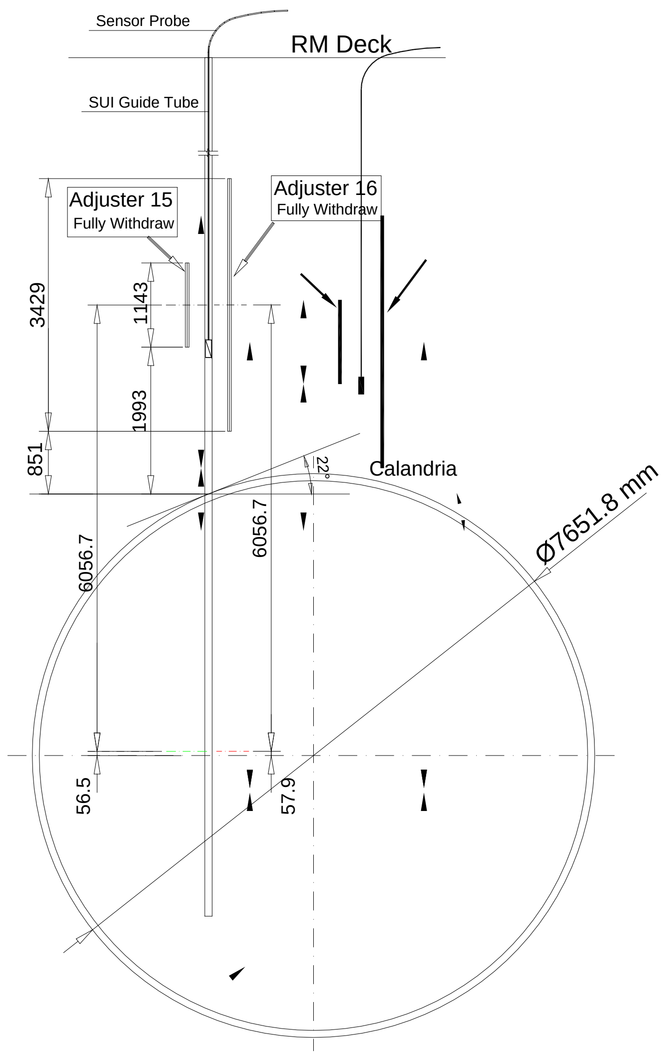

Figure 4 Location of the Scan (Front View)

The first section, marked as 'A', starts from inside the reactor core (20000 mm in Figure 5), and ends at the calandria edge (~17013 mm). The radiation field in this section has a peak at the calandria edge, and drops down in an exponential-like curve toward inside the core. The radiation exposure rate measured at the peak was 1080 Gy/hr inside the in-core SUI guide tube. The PTs, CTs and adjusters were removed from the core. The MCA and SOR were not withdrawn from the core at the time of the measurements. The dominant source of radiation was the calandria. Other low-level sources of radiation include the reactivity mechanism assemblies and the vertical and horizontal detector assemblies. Given the dominance of the calandria as a source, it makes sense that the radiation field dropped when the sensor was far from the calandria edge.

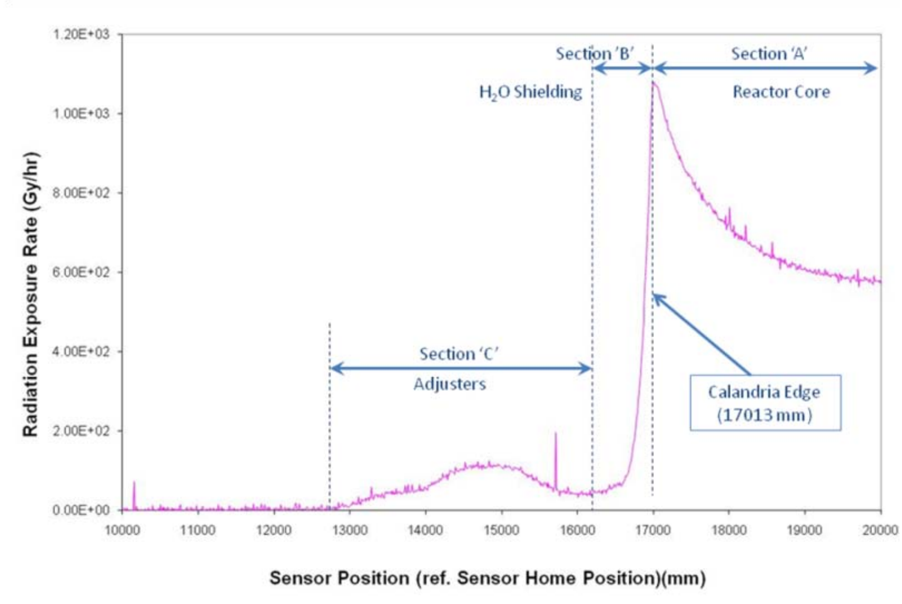

Figure 5 Radiation Field Profile of the Reactor in the SUI tube

The second section of the profile, marked as 'B', is between the peak (~17013 mm) and the local dip (~16200 mm), which corresponds to the distance between the calandria wall and the bottom end of adjuster 16. In this section, the radiation exposure rate drops very quickly. It takes about 330 mm to drop from 1080 Gy/hr to less than 100 Gy/hr, and then the field stays at ~50 Gy/hr with little fluctuation for about 600 mm. This section contains H_2O shielding to reduce the radiation, and this sharp drop in the radiation curve shows that the H_2O shielding has good shielding efficiency.

The third section, marked as 'C', is the region affected mainly by adjusters 15 and 16, which have as-built lengths of 1143 mm and 3429 mm, respectively. At the time that the radiation scan was performed, these rods were fully withdrawn from the core. Assuming that the top edge of the calandria was located at 17013 mm based on the sharp change in slope of the radiation profile curve in Figure 5, the computed locations of the adjusters based on the commissioning data, when the rods are fully withdrawn, are summarized in Figure 4.

At around the 16000 mm position on the curve in Figure 5, the radiation field came from both the adjuster rods and the calandria wall. By fitting a curve to the sharp drop (based on the measurements from 16500 mm to 17000 mm) and extending the fit to the area of the adjuster rods, the radiation field contribution from the calandria is estimated. The radiation profile from only the adjuster rods is computed by subtracting the calandria radiation from the total measurement, as shown in Figure 6. The expected radiation profile is symmetrical since adjuster rods 15 and 16 were arranged in geometrical symmetry. However, the actual radiation profile is not. There is a long tail on the left side. This has been investigated by the generating station staff, and the postulated cause is that there is a bracket on top of each of the adjuster rods. These brackets are made of Zirconium, and are activated and produce gamma radiation after 20 years in reactor.

In Figure 6, the adjuster's expected fully withdrawn locations are marked on the radiation profile. In this section of the profile, the gamma field from the calandria wall only affected the profile shape at the bottom of the adjuster rod 16. Since the central positions of adjuster rods 15 and 16 are almost lined up, a peak is expected in the middle of the rods. However, the measured peak is skewed about 482 mm from the expected position of the center of the rods as shown in Figure 6, far in excess of the 70 mm known uncertainty. The cause is being investigated by the generating station staff, and more flux scans will be performed during Phase B/C tests. This will help estimate the locations of the adjuster rods.

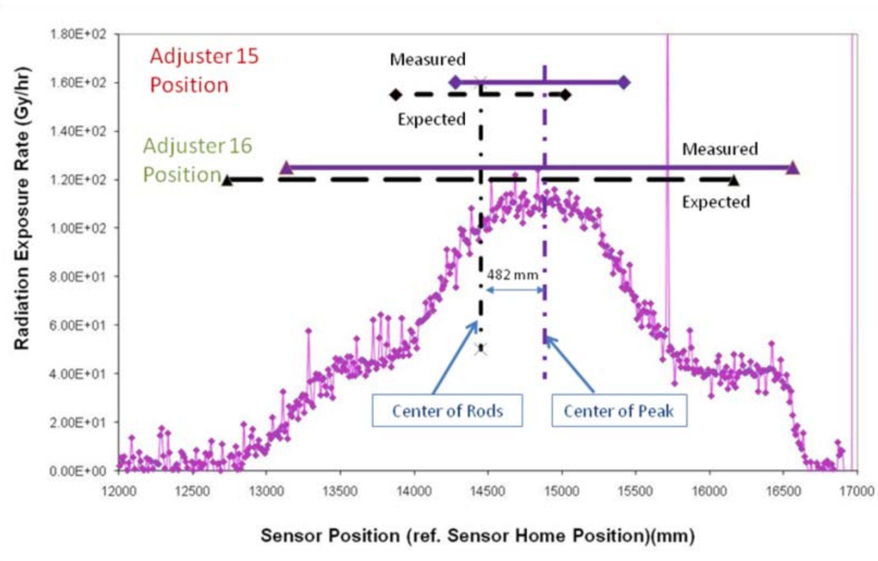

Figure 6   profile at the Adjuster Section

5. CONCLUSION

This experiment produced a profile of the gamma radiation field, for the first time, inside a shut-down CANDU reactor. The features of the profile match the inside structure of the reactor. The maximum radiation exposure rate measured was 1080 Gy/hr at the position corresponding to the calandria wall inside the reactor. This measurement was about 4 times higher than the previously computed value using ORIGEN-S code [4].

The second result of this experiment was the identification of the locations of adjuster rods by observing the features of the radiation profile. The peak and slope changes were observed at the locations of adjuster rods 15 and 16. This result indicates the adjuster rods can be located using the radiation profile. However, a simulation should be performed to provide guidance in how to use the features of the radiation profile to accurately determine the rod location, due to the mechanical complexities involved.

The sensor sensitivity was re-checked after the sensor was returned from the reactor. The re-measured sensitivity of the sensor had a very minor change consisted with uncertainties in source calibration. This check provides the confidence in the use of the diode sensor data from the shut-down reactor measurements, as no significant degradation was observed post-measurement.

The noise level in the readings was high, and needed to be reduced for analysis. This was done using signal processing techniques to post-process the data, but in future this can be accomplished through modification of the sensor and measurement system to reduce the noise in the system.

The radiation sensor in this experiment was a Si-diode based sensor which has been deployed in many different applications [1][3]. The success of this preliminary measurement proves that this technique can be used to measure accurate positions for gamma-emitting sources, such as irradiated adjuster rods, inside a shut-down reactor.

6. REFERENCES

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