# MEASUREMENT AND SIMULATION OF THE GAMMA RADIATION PROFILE INSIDE A CANDU® REACTOR

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## Abstract

A gamma radiation profiling system, based on a small, silicon diode, was developed and used to measure the gamma radiation exposure rate within a start-up instrumentation guide tube in a CANDU® reactor undergoing refurbishment. The shape of the measured profile agreed with simulations performed using MCNP5; two adjuster rods, located above the core and adjacent to the guide tube, could be clearly identified from the features of the radiation profile measurement and simulation. This technology can be used to accurately measure the positions of irradiated reactor components, such as adjuster rods, and other sources of gamma radiation inside a reactor.

## 1. Introduction

To create safe radiological work plans and determine the suitability of the materials used within a reactor, it is important to know the γ-radiation field intensities within the reactor. Unfortunately, due to restricted access and high radiation fields inside a reactor, it is very difficult to directly measure the fields' intensities.

We have developed a novel method to directly measure the γ-radiation fields inside a shut-down CANDU reactor. Prior to our measurements, nobody had ever measured the γ-radiation fields inside a CANDU reactor. We performed our radiation field measurements at the Point Lepreau Generating Station CANDU reactor, which has been shut down since March 2008 for refurbishment.

After the refurbishment of the reactor is complete, it will undergo the startup phase in which in-core fission chambers, installed in the startup instrument (SUI) tube, will monitor the reactor's power. The fission chambers, which have a dose rate limit of $10^4$ Gy/hr and a dose limit of $10^7$ Gy, are designed to monitor the power of the reactor as it is being refueled and returned to service. The PLGS personnel needed to know the total γ-ray dose and the dose rate to which the fission chamber had been exposed. However, since the γ-radiation field within a shutdown CANDU reactor had never before been measured, they estimated these quantities via calculations. The PLGS staff needed a measurement of the γ-ray field in the reactor to confirm their calculations.

Our measurement not only provided information on the γ-radiation fields in the shutdown reactor, it also provided information on the locations of the reactor's features. The uncertainty within which the positions of the adjuster rods had been determined when the reactor was commissioned was within 7 cm. Given its success in measuring the liquid level in a highly radioactive tank by measuring the tank's γ-radiation profile, AECL was also performed its measurement of the PLGS' γ-radiation profile in an effort to determine the positions of the adjuster rods more accurately.

AECL performed its measurements of the γ-radiation profile in the PLGS reactor's SUI tube in September 2009. This paper describes the results of these measurements and the results of MCNP5 simulations of the reactor's γ-ray profile.

## 2. The γ-ray detector system

### 2.1 The Silicon Diode Sensor

The measurements of the PLGS' vertical γ-ray profile utilized a Silicon (Si) p-n junction diode. This measurement technique was based upon the fact that the total current generated by a diode is proportional to the ionization energy rate (or dose) it receives from radiation. Thus, by measuring the total current emitted by a diode in a radiation field, one can obtain the dose it received [1].

In the past, we successfully implemented this technique by measuring high γ-ray fields with a Si p-n diode that we operated in current mode [2]. Our success with this Si diode inspired us to develop a miniature Si diode sensor that we attached to the end of a 30-m-long mineral insulated (MI) cable as in Figure 1. Attaching the Si diode to the end of a long MI cable enabled us to vary the vertical position of the sensor via our automated drive system.

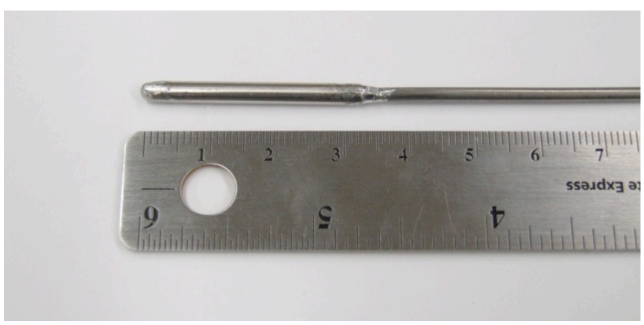

Figure 1 The silicon p-n junction diode sensor attached to a 30-m-long MI cable.

### 2.2 The Sensor Scan Drive

We built an automated, sensor scan drive system to drive the little diode sensor down, and then up the guide tube. The drive system also positioned the sensor accurately, and thus provided accurate vertical position information for each radiation measurement. The sensor scan drive system consisted of two parts: a modified eddy current pusher and a stepper motor, which was geared to a take-up reel. The modified eddy current pusher contained four wheels through which the MI cable passed. The pusher's wheels pinched the MI cable, and could push it forward or backwards.

The stepper motor turned the take-up reel around which the MI cable was wound. Thus, when the pusher pulled the sensor and cable upwards, the stepper motor caused the take-up reel to wind up the cable. A rotary encoder measured the sensor's position by touching the surface of the take-up reel.

The other end of the MI lead cable is connected into a Keithly 6487 pico-ammeter. The Keithly 6487 then read the sensor's current, and sent that information to the data acquisition (DAQ) computer. The DAQ computer also recorded the position of the sensor.

## 2.3 Tests of the Sensor's Response as a Function of γ-Ray Dose Rate

An accurate determination of the γ-ray dose rate from measurements with our Si p-n diode requires knowledge of the diode's output current as a function of γ-ray dose rate. We measured the diode's response by exposing it to a nominally 10 Ci, point-like Co-60 source, whose distance from the diode was varied so that the dose rate ranged from 0.2 Gy/hr to 2 Gy/hr. Figure 2, a plot of the measured current versus γ-ray dose, shows that the measured diode current varied linearly with the dose. The slope of this plot provides the diode output current per dose rate, which was 28.3 pA/(Gy/hr).

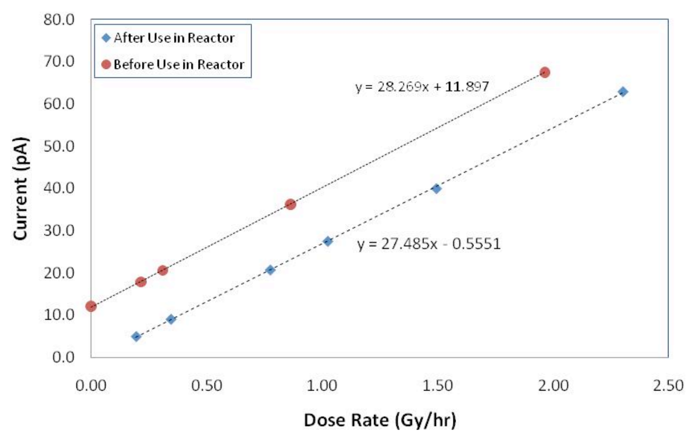


Figure 2 Plots of the diode current versus dose rate for the silicon diode sensor.

After exposing it to the PLGS reactor, we re-measured the diode's output current as a function of dose rate with another calibrated Co-60 source, and found that the diode's sensitivity had decreased by 2.8%. However, the calibration uncertainties of the two Co-60 sources were greater than this, and thus, the accuracies of our radiation profile measurements were unaffected.

## 3. Measurements of the γ-radiation profile

The γ-ray scan equipment and DAQ were installed on the reactivity mechanisms (RM) deck of the Point Lepreau Generating Station reactor. One of the in-core start-up instrumentation (SUI) tubes provided the sensor with access to the reactor.

The reactor was being refurbished at the time of the γ-ray profile measurements. Hence, the calandria was filled with air, rather than heavy water, the adjuster rods were fully withdrawn, and the fuel bundles, pressure tubes (PT) and calandria tubes (CT) had been removed. The only remaining components within the calandria vessel were the SUI tubes, the mechanical control absorbers (MCA), the shut-off rods (SOR) and the vertical and horizontal flux detector assemblies.

With the exception of the SUI tubes, the calandria walls and all of these components emitted Co-60 γ-rays. The Co-60 was formed by the bombardment of steel, which contains trace amounts of Co-59, by neutrons. The SUI guide tubes were not radioactive, since they were brand new, and thus had never been exposed to neutrons. In addition to the γ-ray radiation from the calandria walls and the components within the calandria vessel, the withdrawn adjuster rods also contributed γ-ray radiation outside the calandria.

The γ-ray profile measurements began with the sensor positioned about 1 metre above the bottom of the SUI guide tube. The scan drive system pulled the sensor up the SUI tube in 1 cm increments for an overall travel distance of 10 metres. The sensor was parked at each incremental position for long enough periods of time to acquire 30 readings of sensor current. We thus measured the vertical γ-ray profile of the PLGS reactor at 1000 positions. Figure 3 provides a diagram of the reactor components that were relevant to the measurement.

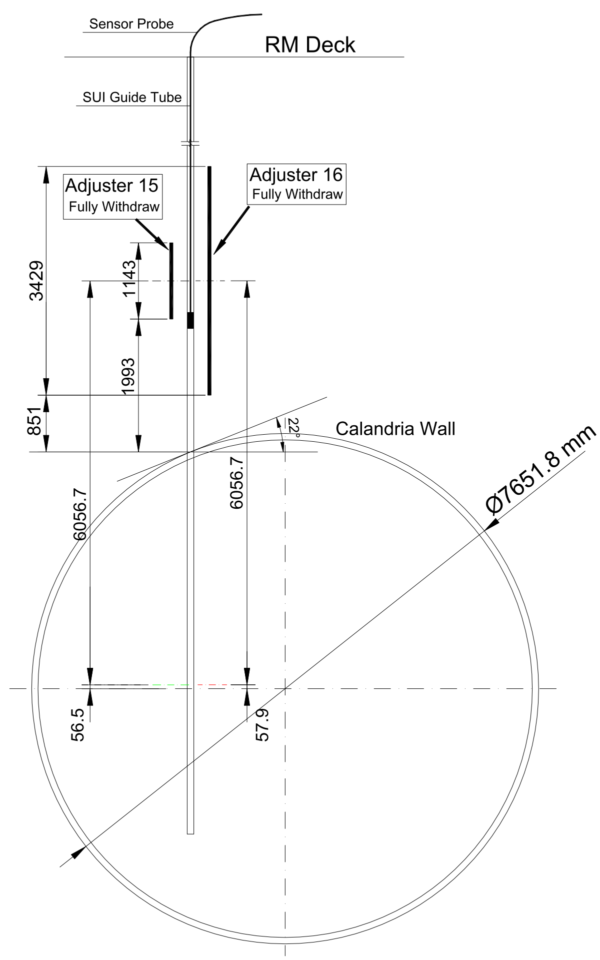


Figure 3 A diagram of the outer calandria wall, SUI guide tube and Adjuster Rods 15 and 16.

## 4. Experimental results

Thirty readings were taken at each location to compensate for the noise in the data, due to the construction work that was taking place within the reactor building. By filtering the noisy, raw data with a mode filter, and applying the 28.3 pA/(Gy/hr) current-to-dose conversion, we obtained the dose rate plot in Figure 4.

Since the largest expected sources of Co-60 γ-rays were the calandria walls, we used the location of the largest measured dose to mark the location of the edge of the calandria. We then used this as a reference to determine the positions of the other two largest expected sources, Adjuster Rods 15 and 16, which sat on either side of the SUI guide tube.

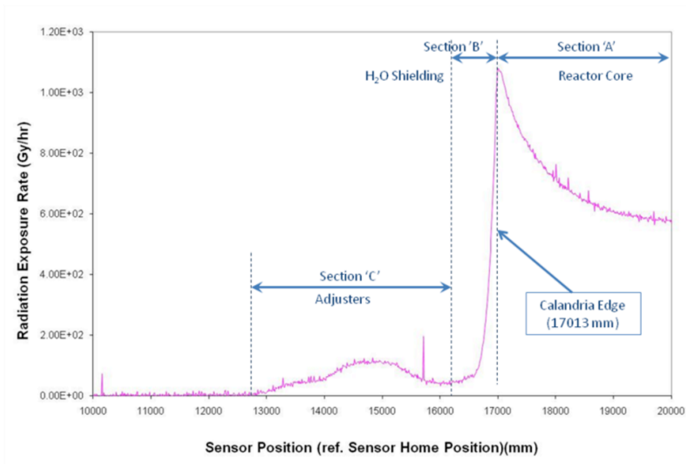


Figure 4 A plot of the γ-ray dose rate profile measured within the SUI tube.

We divided the horizontal axis of Figure 4 into three regions: A) the calandria interior or reactor core, B) the calandria edge and C) the adjuster rods. The calandria interior region, marked as "A", runs from the calandria wall at ~17013 mm to the interior of the reactor at 20000 mm. A glance at Figure 4 reveals the fact that the measured dose rate died away exponentially with distance from the calandria edge. The rate of attenuation of the radiation field inside the reactor was smaller because of the contribution of the bottom of the calandria. Outside and above the calandria, its bottom is quite a bit farther away, and hence contributes very little to the field. This results in a much more rapid decrease in the radiation field.

The B region, which covers the calandria edge, runs from ~17013 mm to the local minimum at ~16200 mm. The local minimum corresponds to the location of the bottom of Adjuster Rod 16, which is the longer of the two rods surrounding the SUI tube. The volume surrounding the calandria was filled with light water, which acts as a radiation shield. The presence of the water also accounts for the rapid drop in the γ-ray dose rate outside the reactor.

The third region, region C, runs from the bottom of Adjuster Rod 16 at ~16200 mm to the sensor home position at the RM deck (~10000 mm). The dominant sources of γ-radiation in region C were Adjuster Rods 15 and 16. Adjuster Rod 16 is 3429 mm long, and Adjuster Rod

15 is 1143 mm long. All of the adjuster rods were withdrawn from the reactor core during these measurements, so the increase in dose rate outside the calandria makes sense.

By subtracting the radiation contribution by the calandria walls from the measured dose rate, we obtained the plot in Figure 5, from which we estimated the positions of Adjuster Rods 15 and 16. The first step entailed fitting an exponential curve to the data in Figure 4 from 16500 mm to 17000 mm to obtain the a function describing the calandria wall's contribution to the dose rate. The next step involved subtracting this function from the measured data in Figure 4. The result is Figure 5, which contains only the contributions of the adjuster rods to the dose rate.

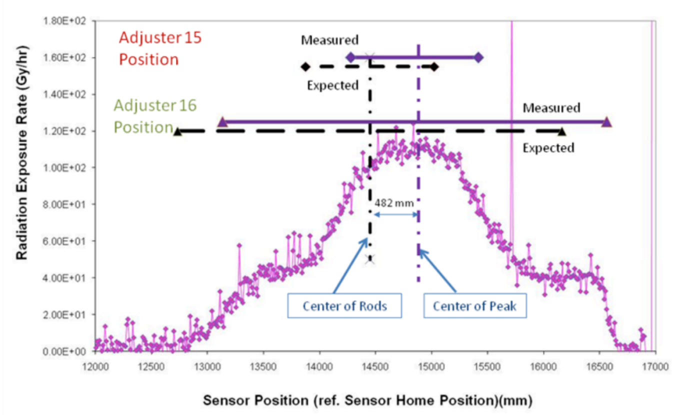


Figure 5 A plot of the measured γ-ray dose rate with the calandria's contribution removed.

Since the centres of Adjuster Rods 15 and 16 were aligned vertically, one would expect the plot in Figure 5 to be symmetrical about the centres of the two rods. This is not the case, however. The PLGS personnel have suggested that the long tail on the left side of the plot is due to brackets on the tops of the adjuster rods. These brackets are made of zirconium, which, when activated via neutron bombardment, produce γ-rays.

The next step in estimating the positions of Adjuster Rods 15 and 16 involves finding the middle of the dose rate peak in region C, which is at 14390 mm. Based on this measurement, this means that the centres of the adjuster rods were 2623 mm above the calandria edge. However, according to the commissioning data, the withdrawn adjuster rods' centres were 482±70 mm higher than this, which is well outside of the uncertainty in their positions. PLGS personnel are investigating this discrepancy. A possible explanation for this is that the chains holding the adjuster rods may have stretched as they held their weights over the 20 years of the life of the reactor. In order to more accurately determine the adjuster rod's positions from the measured γ-ray profile, it was necessary to perform a series of MCNP5, Monte Carlo simulations to better understand its features.

## 5. MCNP5 Simulations

The geometric model of the PLGS reactor in Figure 6 was created in MNCP5. This model included the concrete and light water shielding surrounding the calandria, the calandria walls, the SUI guide tube and Adjuster Rods 15 and 16. A vertical, 1-dimensional lattice of cylindrical, silicon cells was created for the tally scoring cells. This lattice was placed within the SUI guide tube geometry, and was created to simulate the Si diode, its sampling positions and the dose rates it received. The tallies produced were for the γ-ray energy (MeV/g) deposited in each silicon tally cell.

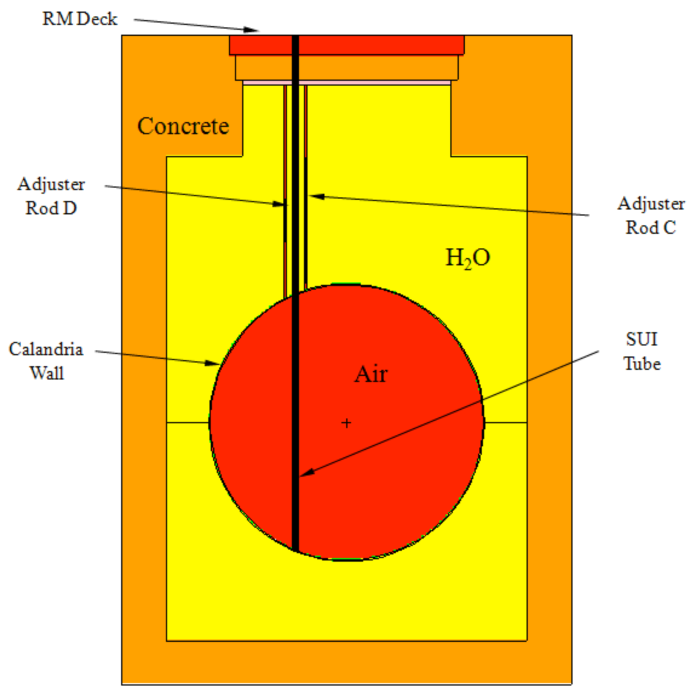


Figure 6 A visualization of the MCNP5 geometry used for the PLGS γ-ray profile simulations.

Separate MCNP5 input files were created for each γ-ray source definition. These files fell into five different groups as shown in Figure 7: 1) the calandria end-shield, 2) the calandria midsection (the larger diameter section between the two end-shields), 3) the calandria discs, (the inner faces of the end-shields) 4) Adjuster Rod 15 and 5) Adjuster Rod 16.

Figure 7 provides a diagram of the calandria's end-shields, midsection and discs. Since the steel walls of the calandria are very thick (~3 cm), the flux of neutrons that bombarded them decreased with the penetration depth within the walls. This is because many of the isotopes in the steel, such as Fe-56, Cr-53, Ni-58, etc., capture neutrons as they pass through it. To approximate the effect of the attenuation of the neutron flux within the calandria walls, the source definitions were created so that five slices (0.6 to 0.7515 cm thick) were sampled for each calandria part. Thus, 5 different source definitions were created for each calandria part. This resulted in a total of 15 input files for the calandria's contribution to the dose rate.

The decrease in Co-60 source strength with slice depth in each part of the calandria wall was then approximated by

$$f = 10^{-idr} \tag{1}$$

where f, i and dr are the attenuation factor, the slice number and the slice thickness respectively. The value of i ran from 0 to 4. Thus, for example, the dose tally of each slice of the calandria midsection was scaled by its respective f-value. Each silicon tally cell received γ-ray doses from the calandria walls and Adjuster Rods 15 and 16. The average γ-ray dose, $D_{calandria}$, per source γ-ray due to the calandria walls, was calculated via

$$D_{calandria} = \frac{1}{V_{calandria}} \sum_{parts} \sum_{i=0}^{4} f_{i,part} D_{i,part} V_{part} \tag{2}$$

The sum over parts is merely the sum over the end-shields, middle section and discs of the calandria. $D_{i,part}$ is the array tally data for slice i of a given part of the calandria. $V_{part}$ is the volume of the steel in the part of the calandria, and $V_{calandria}$ is the total volume of the steel in the calandria walls. The method used to convert the tally doses to real dose rates is described in Chapter 5.

Eight simulations were performed (eight input files) to simulate the dose contributions due to Adjuster Rods 15 and 16. The first two simulations placed the adjuster rods at their expected (based on the commissioning data) positions of 14872 mm during refurbishment. The second pair of simulations placed the adjuster rods at their estimated positions, based on our measurements, of 14390 mm. The third and fourth pairs of simulations placed the adjuster rods 1 cm above and 1 cm below the estimated positions, respectively. Four of these eight input files simulated the γ-ray dose due to Adjuster Rod 15. The other four files simulated the γ-ray dose due to Adjuster Rod 16.

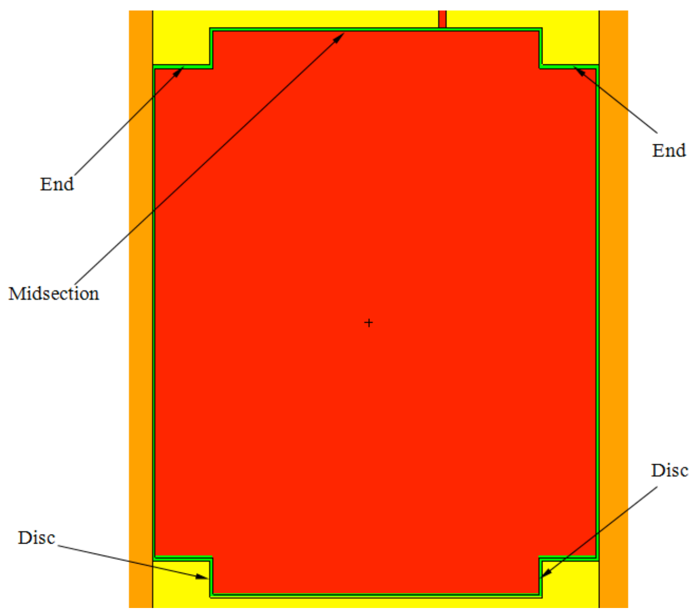


Figure 7 An MCNP5 visualization of the calandria midsection, ends and discs.

## 6. The MCNP5 simulations' results

After running the 23 input files through MNCP5, the tallies and their associated errors were extracted from the 23 output files, and processed in Microsoft Excel. The total calandria dose tallies were then calculated from the calandria source output files via Equation (2. A dose tally to real dose rate scale factor was then calculated for the total calandria tallies by taking the ratio of the maximum measured dose rate to the maximum total calandria dose tally value. We calculated the calandria tally dose to real dose conversion factor to be $1.69\times10^{12}$. The total calandria dose tallies were then converted to dose rates via multiplication by this conversion factor.

For all four simulated adjuster rod positions, the sums of the tally dose contributions, $D_{rods}$, due to both Adjuster Rods 15 and 16 were calculated via the following formula:

$$D_{rods} = D_{15} + 3.34D_{16} \tag{3}$$

D15 and D16 are the tally doses due to Adjuster Rods 15 and 16, respectively. The factor of 3.34 in front of D16, the tally dose due to Adjuster Rod 16, is the ratio of Adjuster Rods 16's steel volume to the steel volume of Adjuster Rod 15. The tally dose to real dose conversion factors for the dose tallies due to the two adjuster rods were then calculated by taking the ratio of the measured dose rate peak between 12500 mm and 17000 mm to the peak values of $D_{rods}$ in the same position region. The peak value of the measured dose rate between 12500 mm and 17000 mm was estimated to be 11500 Rad/h. The tally dose rate to real dose rate conversion factors were found to be between $1.08\times10^{10}$ and $1.09\times10^{10}$ for the four adjuster rod positions that we simulated. The total adjuster rod tallies for each simulated position case were then multiplied by these conversion factors to convert them to real dose rates for comparison with the measured data.

### 6.1 A Comparison between the Measured and Simulated Dose Rates due to the Calandria Walls

As one can see from Figure 8, between ~16660 mm and ~17020 mm, the agreement between the measured dose rate and the dose rate simulated in MCNP5 is excellent. This is the region outside and above the calandria wall, and below the bottom of the longer adjuster rod, Adjuster Rod C. This was a particularly simple region to model, since the top of the calandria was essentially the only γ-ray source in this region. The maximum MCNP5 quoted error for this region was about 2%.

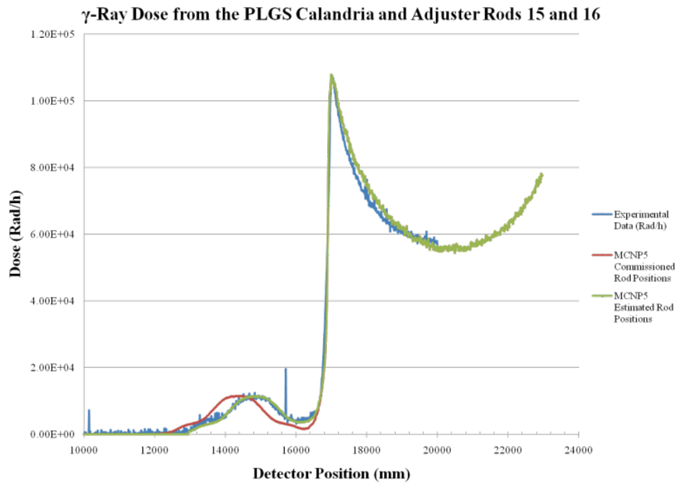


Figure 8 Overlaid plots of the measured dose rate and the simulated dose rates for the adjuster rods at their estimated positions and their expected positions during refurbishment.

The agreement between the simulated and the measured dose rates is not as good for the region inside the calandria vessel. The simulated data suggest that the dose rate decays more slowly with distance from the calandria edge than the measured data. Nonetheless, the greatest discrepancy between the measured and simulated dose rates in this region is 7.6% (the mean difference is 2.5%). The maximum MCNP5 quoted error for this region is about 0.9%. An improvement in the agreement between the simulated and measured dose rates might be obtained by simulating 10 or more γ-ray source slices rather than 5 for each part of the calandria wall.

## 6.2 A Comparison between the Measured and Simulated Dose Rates due to Adjuster Rods 15 and 16

As one can see from Figure 8, the peak in the simulated dose rate for the case in which the adjuster rods were at their expected positions is shifted to a position about 500 mm higher than that for the measured data. On the other hand, the peak obtained by simulating the adjuster rods at their estimated positions is closely aligned with the measured peak.

Figure 9 is an overlaid plot of the measured and simulated dose rates for the adjuster rods for the cases in which the rods were at their estimated positions. By weighting the vertical positions in Figure 9 by the measured and simulated doses, one can obtain the means and standard deviations of the central peaks associated with Adjuster Rods 15 and 16. Based on these calculations, the mean of the simulated peak for the rods at their estimated positions was about 5 mm away from that of the measured peak.

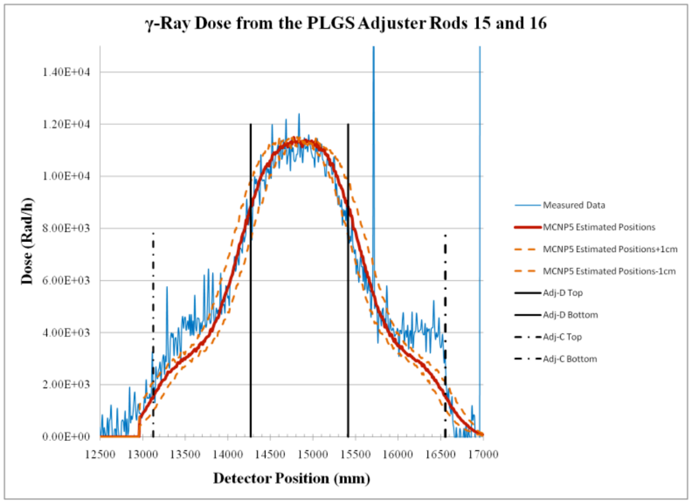


Figure 9 Overlaid plots of the measured and simulated dose rates due to Adjuster Rods 15 and 16. The adjuster rods were at their estimated locations, 10 cm above them and 10 cm below them.

Figure 9 also contains overlaid plots of the simulated dose rate for the cases in which the adjuster rod positions were 10 cm above and below their estimated positions. The left edge of the +10 cm dose rate curve and the right edge of the -10 cm dose rate curve overlap with the measured dose rate curve. Taking into account these overlaps, we can determine the position of the adjuster rods to within an error of ±10 cm (±100 mm), based on the measured γ-ray dose rate profile and our MCNP5 simulations.

## 7. Conclusions

For the first time ever, an experiment was performed to measure the vertical, γ-radiation profile inside a shut-down CANDU reactor. With the exception of the region of the adjuster rods, the shape of the measured γ-radiation profile closely followed the features of the reactor. Based on the calibrated sensitivity factor of 28.3 pA/(Gy/hr), the maximum measured dose rate, which occurred at the calandria edge, was 1080 Gy/hr. This value provided the PLGS staff with important dose rate information.

The shape of the dose rate profile that we measured deviated from the shape that we expected. In essence, the dose rate peak due to the adjuster rods appeared at a position 482 mm lower than the expected peak position. This discrepancy was well outside of the 70 mm error within which the adjuster rod positions were known at the time the reactor was first commissioned. Based on the measured centre of the dose rate peak due to the adjuster rods, we estimated that their positions were 14390 mm. The results of this measurement imply that the adjuster rods had shifted to positions 482 mm lower than their original locations.

In an effort to better understand the measured dose rate profile, and to properly determine the positions of the adjuster rods, we performed MCNP5 simulations of the shut-down reactor. These MCNP5 simulations modelled the calandria walls, SUI guide tube, silicon diode sensor, and Adjuster Rods 15 and 16. The simulated dose rates for the calandria regions and the adjuster rods regions agreed well with the measured data for the simulations in which the adjuster rods were at or within 10 cm of their estimated locations. Based on our simulations and our measured γ-ray profile data, we determined that the positions of the adjuster rods were 482 mm lower than their expected locations within an error of ±10 cm. We thus demonstrated the fact that it is possible to measure the vertical locations of the features in a nuclear reactor by combining measurements of its γ-ray dose rate profile with simulations.

The ultimate result of these measurements and simulations is the demonstration of the fact that one can use a silicon diode sensor to accurately measure the positions of a reactor's γ-ray emitting features, such as its adjuster rods.

## 8. References

[1] Knoll, G.F., 1989. Radiation Detection and Measurement, 2nd Edition, John Wiley & Sons.

[2] Sur, B., Yue, S., and Jonkmans, G., 2009. "A Detector System for Measuring High Radiation Fields", Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies NPIC&HMIT 2009, Knoxville, Tennessee, April 5-9, 2009, on CD-ROM, American Nuclear Society, LaGrange Park, IL.