# EXTREMITY TLD MONITORING AT OPG: CALIBRATION, QUALITY ASSURANCE, AND TYPE TESTING

# EXTREMITY TLD MONITORING AT OPG: CALIBRATION, QUALITY ASSURANCE, AND TYPE TESTING

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# Abstract

At Ontario Power Generation (OPG), extremity doses are measured using Thermoluminescent Dosimeter (TLD) chips. These chips are lithium fluoride crystals doped with magnesium and titanium (LiF:Mg,Ti). In order to accurately measure the dose received by a worker, it is essential to understand and quantify all potential influencing factors relating to the extremity dosimetry system. These factors include the way the system is calibrated, the response of the TLD chips to different types and energies of radiation, the effects of the different chip holders used for chip irradiations, and environmental factors.

A special investigation was undertaken to identify and quantify the source of a long-standing bias in quality assurance (QA) test results between the Whitby Health Physics Laboratory (HPL) and the National Research Council - Canada (NRCC). The four major factors contributing to the bias were determined to be:

1) The response of LiF:Mg,Ti to the different irradiation sources used at the Whitby HPL ($^{137}Cs$) and at the NRCC ($^{60}Co$).
2) A difference in sensitivity between the field chips and the chips used to calibrate the readers at the Whitby HPL.
3) Differences in exposure rate standards used at the NRCC and at the Whitby HPL.
4) Different chip holders, used to hold the chips during an irradiation, at the NRCC and at the Whitby HPL.

Experimental tests and Monte Carlo simulations have been performed to determine the relative response between various chip holders used at the Whitby HPL and at the NRCC. The experimental results were found to be in close agreement with the results generated by Monte Carlo N-Particle (MCNP). Monte Carlo simulations have also been used to determine the effects of adding different thicknesses of material in front, behind, and around a single TLD chip. The properties of a new bulk chip holder are also examined with the intention of replacing the current bulk chip holder. After making an individual sensitivity correction, it was determined that the response across the new holder was uniform. This implies that two chips placed anywhere in the holder will receive the same dose.

The remaining part of the project focused on the identification and quantification of several factors which can influence TLD results. These tests included a measurement of the repeatability of the TLD process, the minimum time required between the annealing and the irradiation, and a 7-day fade test. For the first type test, sets of measurements were repeated under identical conditions to examine how repeatable a given measurement may be. The average relative standard deviation of the TLD readings from the chips was measured to be 1.7%. A second type test was conducted to identify the minimum amount of time required between the annealing period and the irradiation. This minimum time required for an accurate measurement was determined to be about 24 hours, but only about 6 hours are required for a relative measurement. A 7-day fade test was conducted to determine the amount of signal lost in the first week. Using the equation of the trend-line, a fade rate of 1.5% per week was calculated for the first week.

# Acknowledgements

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# Chapter 1

# Introduction

Ontario Power Generation (OPG) is an Ontario-based company whose principal business is the generation and sale of electricity in Ontario and its interconnected markets. OPG generates approximately 75% of Ontario's power through the use of 6 fossil-fuel stations, 35 hydroelectric stations, 32 green power stations, and 3 nuclear stations. The 3 nuclear stations, (comprised of 4 units at Darlington, 4 units at Pickering A, and 4 units at Pickering B) account for about a quarter of OPG's total electrical generating capacity. The actual electrical output for the nuclear stations is often a larger percentage because it is preferred to use nuclear over coal stations. Because of the presence of radioactive sources and the operation of radiation devices, OPG requires a Radiation Protection (RP) Program to protect workers and visitors to OPG facilities from ionizing radiation. The RP Program is designed to ensure the radiation dose limits set out by the Canadian Nuclear Safety Commission (CNSC) are not exceeded. These dose limits are designed to eliminate deterministic effects caused by exposure to ionizing radiation, while reducing stochastic effects to a tolerable level. The Canadian dose limits are generally consistent with the recommendations of the International Commission on Radiological Protection (ICRP). Contained within the RP Program is the radiation dosimetry program, whose purpose is to detect, interpret, assign, and record all significant doses received by, and committed to, individuals over a known period of time. OPG's radiation dosimetry program can be generally divided into external dosimetry, for radioactive sources outside the body, and internal dosimetry, for radioactive material taken into the body. To evaluate external dose to the whole body, workers are required to wear a dose recording device (usually a TLD badge) on their upper torso. Often, however, situations arise where this does not provide the worker with adequate dosimetry. Depending on the nature of the job, it is possible for a worker to receive an extremity dose which significantly exceeds the whole-body dose measured by the TLD badge. Extremity doses are measured by attaching a pair of extremity TLD chips to the left and right extremities. Often these will be the left and right hands, but sometimes may be the left and right feet. In some cases, extremity TLDs may be attached to both the hands and feet. The scope of this project is to evaluate OPG's current extremity dosimetry program with a focus on system calibration, quality assurance, and the quantification of several influencing factors.

# Chapter 2

# Fundamentals of OPG's Extremity TLD System

## 2.1 Thermoluminescent Dosimetry

The basis for OPG's extremity dosimetry program is the thermoluminescent dosimeter (TLD). OPG uses chips of the standard TLD material, lithium fluoride, doped with magnesium and titanium, and written as LiF:Mg,Ti. On exposure to ionizing radiation, electrons in the LiF crystal are excited from the valence band to the conduction band. The electrons and holes can then become trapped in various trapping centers, created by the impurities in the crystal. Following exposure to ionizing radiation, the crystal is heated, which provides enough energy for the electrons and holes to escape their respective traps, recombine, and emit a photon. This process is illustrated in Figure 2.1.1. The number of photons released during this process is directly proportional to the amount of energy deposited into the crystal by the ionizing radiation. The intensity of luminescence as a function of temperature, which exhibits several maxima, is called the thermoluminescence glow curve and will be discussed in the following sections. By using the appropriate conversion factor, it is then possible to evaluate the dose delivered to the chip.

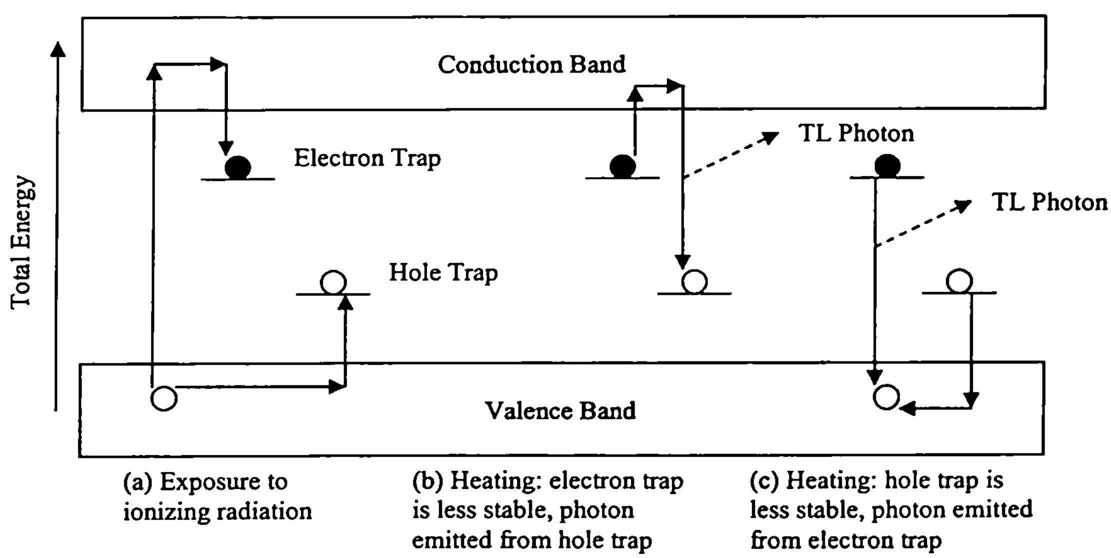


**Figure 2.1.1: Schematic Energy-level Diagram of a TL Material.**

## 2.2 TLD Readers and Annealing Protocol

TLD chips are read, one at a time, in one of two Harshaw 3500 TLD readers (manufactured by Thermo Electron). In the readers, a chip is placed in a heater pan, which is then slid into a drawer and blanketed with $N_2$ gas. The photons, emitted as the chip is heated, are detected using a photomultiplier tube (PMT). The light output from the PMT is usually displayed as a glow curve, a plot of the light output versus temperature or time. The heating temperature as a function of time is known as the time-temperature profile (TTP), and can be programmed over a range of values. The standard TTP used at OPG for LiF:Mg,Ti extremity chips is:

| | | |
|---|---|---|
| Preheat temperature | 50°C | (reached in under 2 s) |
| Preheat Time | 0 s | (not held) |
| Ramp Rate | 25°C $s^{-1}$ | |
| Maximum Temperature | 300°C | (reached in 10 s from the start of acquisition) |
| Acquisition time | 16.67 s | (maximum temperature held for 6.67 s) |
| Anneal Time | 0 s | (no further reader anneal past acquisition) |

A schematic of the TLD reader set-up is shown in Figure 2.2.1.

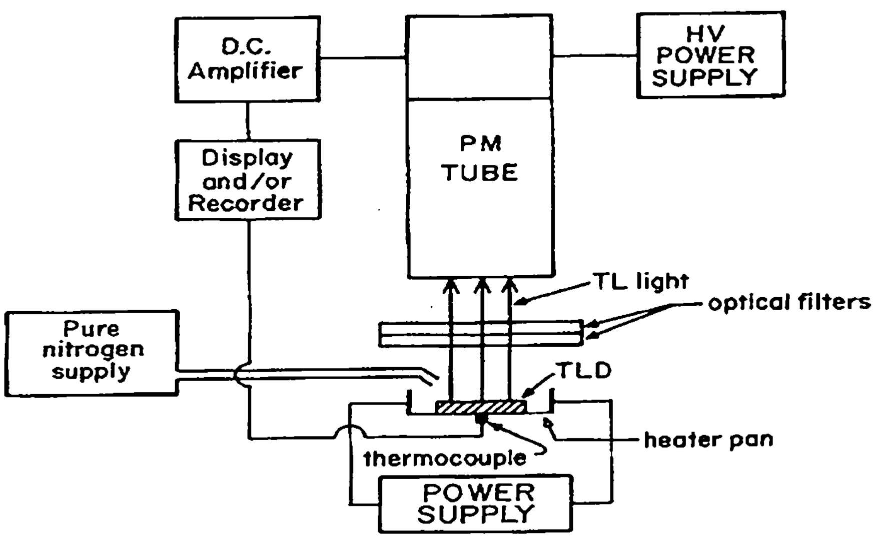


**Figure 2.2.1: Diagram of a TLD Reader.**

To remove any residual signal from the TLD chips, and to restore the material to its pre-irradiation condition, the chips are annealed in an oven at the Whitby Health Physics Laboratory (HPL). The TLD chips are annealed at specific times in the reading process, under specific conditions. Before irradiation, all chips are annealed at 400°C for 1 hour to remove any residual signal remaining on the chip. Following this high temperature anneal, the chips are allowed to cool, and then are annealed at 80°C for 16 hours. This low temperature anneal reduces the sensitivity of the low-temperature glow-curve peaks, which has the effect of reducing the rate at which low energy traps combine (known as the fade rate). In addition, there is normally a delay of about 24 hours between irradiation and reading, to further reduce the effect of short-term fading on the results.

A test was performed at the Whitby HPL to test the effects of both the high and low temperature anneal. Four sets of 5 chips were exposed to four different combinations of high and low temperature anneals, before being exposed to 500 mR. The first set received neither a high or low temperature anneal. The second set received only the high temperature anneal, while the third set received only the low temperature anneal. The fourth set received both the high temperature anneal and the low temperature anneal, which is the standard practice for annealing chips at the Whitby HPL. The results from this test are displayed in Figure 2.2.2.

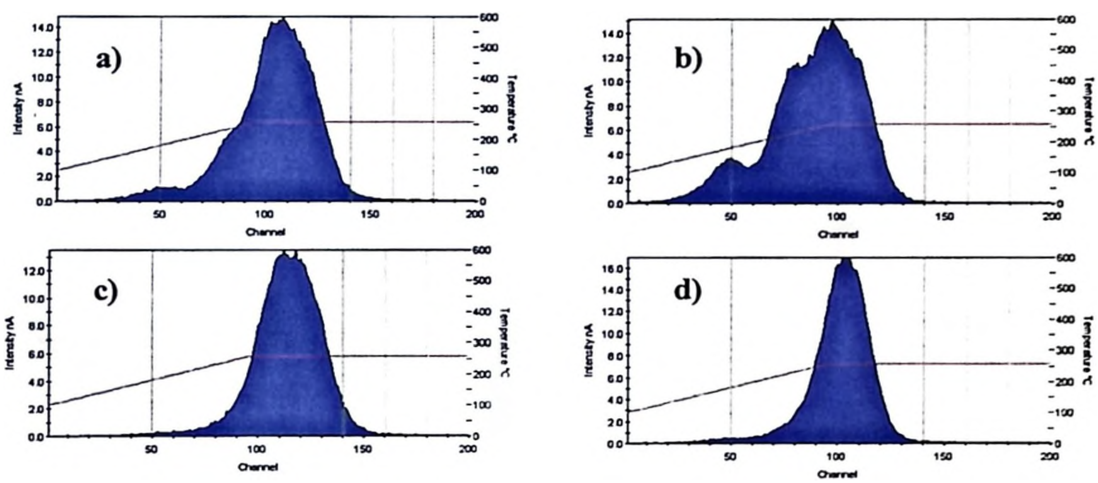


**Figure 2.2.2: Effects of High and Low Temperature Anneal on the TLD Glow Curve.** a) No Anneal, b) High-Temp Anneal only, c) Low-Temp Anneal only, d) High and Low Temperature Anneal

The low-temperature peaks are evident in curves a) and b), both of which did not receive a low-temperature anneal. Glow curve c), which received only the low-temperature anneal, has a wider peak than that of glow curve d). This test shows that the high and low temperature anneals together provide the optimal glow curve. The low temperature anneal has the effect of getting rid of the low temperature peaks, while the high temperature anneal is intended to restore or standardize the TLD characteristics by erasing accumulated radiation damage and dispersing the impurity ions to their original configuration (Horowitz, 1990).

## 2.3 OPG's Current Extremity TLD System

Extremities are defined as any part of the hands, wrists, forearms, and elbows (for hands) and feet, ankles, lower legs, and knees (for feet). Extremity doses are measured by attaching a TLD chip, distributed and used in pairs, to the extremity or extremities expected to receive the highest dose. Since most significant extremity doses result from handling a source or a contaminated piece of equipment, TLD chips are most commonly attached to the fingertip of the working hand. According to the OPG standard, Radiation Dosimetry Program – External Dosimetry (RPD-ED), extremity TLDs are issued when it is likely that a worker will receive an extremity dose which significantly exceeds the whole-body dose recorded by the worker's TLD badge and the worker will receive 60 mrem (0.6 mSv) extremity dose in one day or 100 mrem (1 mSv) for longer wearing periods (Chase 2005a). Figure 2.3.1 shows extremity TLD use, for both the hands and the feet, at Pickering Nuclear Station during 2003. The high use periods usually occur during a reactor outage, with an increased workload in high hazard areas.

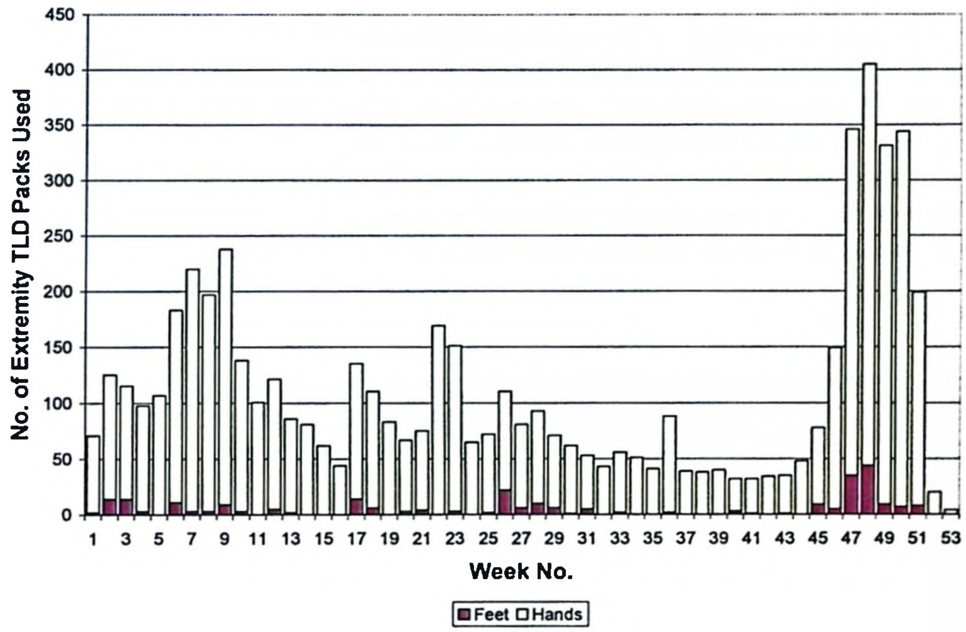


**Figure 2.3.1: Extremity TLD Packs Issued at Pickering Nuclear Station, for the Hands and Feet, During 2003.**

Extremity dosimeters are made by enclosing chips of LiF:Mg,Ti in heat-sealed plastic sachets. The chips are a standard Thermo Electron product TLD-700, enriched in $^{7}Li$ to make them insensitive to thermal neutrons. The chips are 3.2 mm x 3.2 mm x 0.89 mm thick (240 mg $cm^{-2}$). The plastic sachet is 9-10 mg $cm^{-2}$ thick, and is colour-coded: red for left, green for right, and clear for control. A set of three chips (one of each colour) are put into a paper envelope, and sent to the station. There, the user removes the red and green sachets and tapes them to left and right extremities with surgical tape. The envelope is labeled with the employee's name, Dose Information System Number (DISN), current date, and the extremity (hands or feet) being monitored. After use, the sachets are monitored for contamination, put back into the envelope, and sent back to the dosimetry laboratory in Whitby.

The chips are read out on one of two readers at the Whitby HPL. A computer program, known as *WinREMS*, plots the light intensity output (as current in the PMT) and temperature against time, and is known as a Glow Curve. Figure 2.3.2 shows a glow curve for a delivered exposure of 500 mR, while Figure 2.3.3 shows a glow curve from a Field chip which received about 15 mrem. Integrating the area under the calibration region (the Calibration Region Integral-CRI) of the Glow Curve yields the total charge created in the PMT. This is converted to an exposure by using a reader calibration factor (RCF), determined from the results for a set of calibration chips irradiated to 500 mR, and a set of control chips. The charge created in the control chips is subtracted from the charge created by the calibration chips and divided by 500 mR, producing a nC-to-mR conversion factor. The system is usually calibrated using 5 calibration chips (Cal) chips, irradiated to 500 mR, and 5 control chips. Typically, the Cal chips have been selected from the field population, but have also been part of a special calibration set.

Typically, an exposure of 1 Roentgen corresponds to a dose of 1 rem (0.01 Sv). For OPG's extremity TLD system, however, the reading in mR is multiplied by a dose conversion factor of 2 to obtain the skin dose in mrem. This correction factor of 2 is the inverse of the beta response factor, and is considered conservative because most significant extremity doses are due to high–energy beta fields, which have a correction factor less than 2, and because the extremity dose from gamma rays will always be overestimated (by 100%, since the response factor for gamma rays is 1.0) (Chase 2005a).

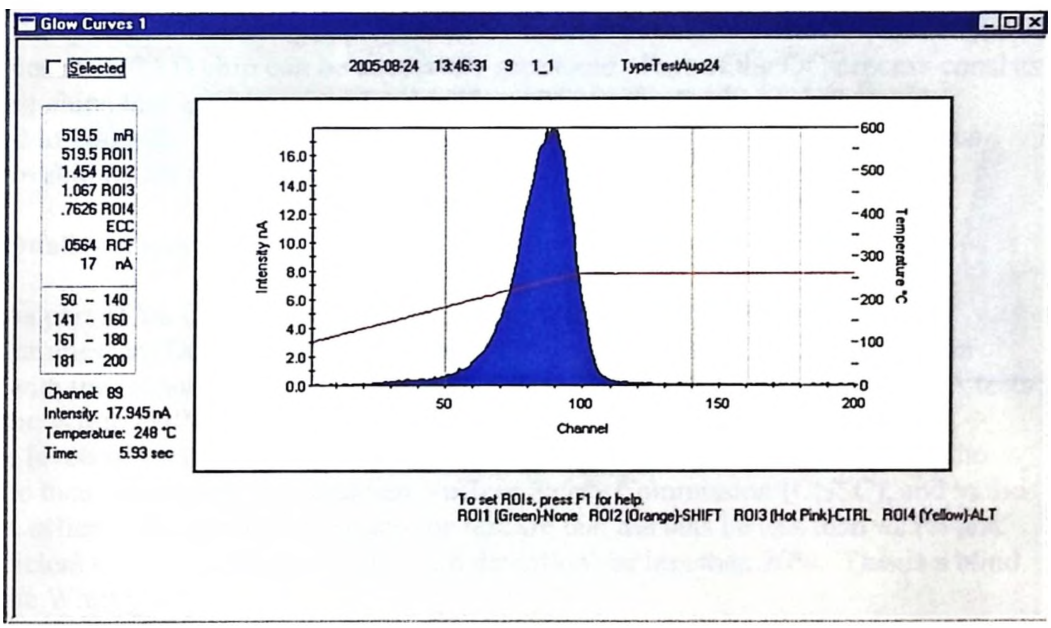


**Figure 2.3.2: Glow Curve for a Delivered Exposure of 500 mR.**

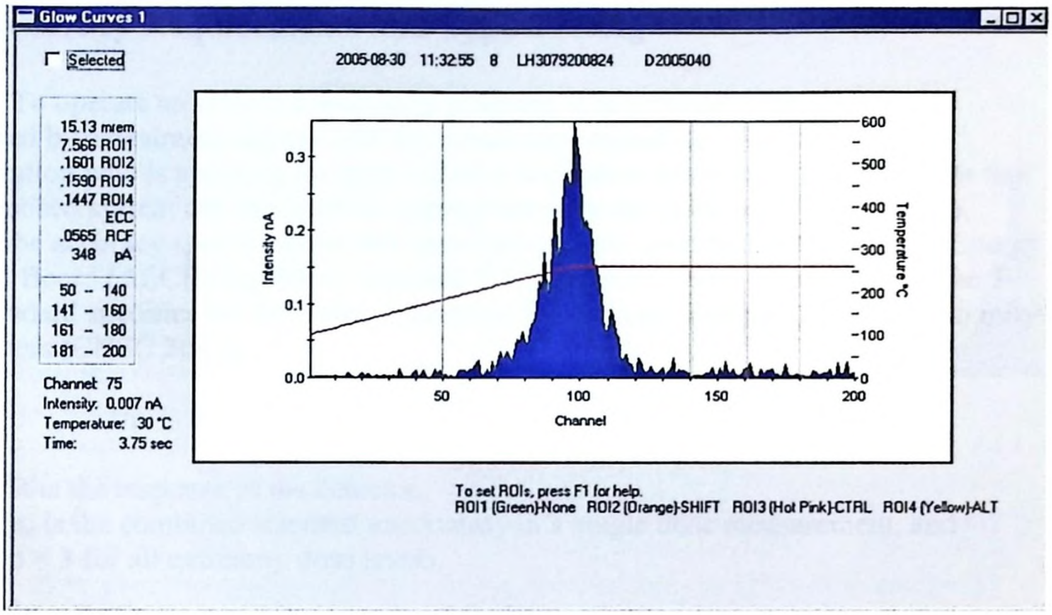


**Figure 2.3.3: Glow Curve for a Field Chip Which Received Approximately 15 mrem.**

### 2.3.1 Quality Control (QC)

The Quality Control (QC) process at OPG is an internal verification that ensures that the dose to a TLD chip can be accurately measured. Part of the QC process consists of reading chips that have been randomly selected from the field population and irradiated to 100 mR. The results must be within a certain range, and if not, various corrective actions are required.

### 2.3.2 Quality Assurance (QA)

As part of the Quality Assurance (QA) program for OPG's extremity Thermoluminescent Dosimetry (TLD) system, OPG participates in a QA verification process with the National Research Council – Canada (NRCC). These quarterly QA tests require the Whitby HPL to read sets of 5 chips, irradiated at the NRCC to unknown exposure levels of between 30 and 9000 mR, and return the results to the NRCC. The results are then reported to the Canadian Nuclear Safety Commission (CNSC), and to the HPD QA officer. The limits for passing the test are that the bias be less than ±25% and the coefficient of variation (relative standard deviation) be less than 20%. This is a blind test for the Whitby HPL.

## 2.4 Accuracy Requirements and Type Testing

To operate an effective dosimetry program, it is imperative that the dose measured by a dosimeter agrees with the actual delivered dose. A person or organization who is applying for approval of a dosimetry service must demonstrate that the proposed system can measure the appropriate personal dose equivalent, $H_p'(d)$, within the accuracy specifications and uncertainty limits specified in the Atomic Energy Control Board (AECB) regulatory standard S-106 (AECB 1998). Revision 1 of the S-106 standard specifies the following conditions for accuracy and precision for extremity dosimeters (CNSC 2005):

$$1/\rho \leq R \pm 2\mu_s \leq \rho$$

where R is the response of the detector,
$\mu_s$ is the combined standard uncertainty in a single dose measurement, and
$\rho = 3$ for all extremity dose levels.

The S-106 regulatory standard also specifies that a dosimetry service must undergo extensive type testing. Type testing involves a series of experimental tests for a type of dosimeter that are performed to identify all potential sources of error and uncertainty in the dose measurement, and to quantify those errors that may contribute significantly to the overall error or combined standard uncertainty. These sources of error and uncertainty are often known as influence quantities. The goal of a Type Test report is to identify and quantify all influence quantities.

# Chapter 3

# Calibration and Quality Assurance of OPG's Extremity TLD System

This chapter deals with the way that the extremity TLD system is calibrated and how OPG undergoes both internal and external tests to verify that it can accurately assess a dose to a worker. About 4000 new chips were added to increase the size of the field population. The addition of new chips has the effect of changing the mean sensitivity of the field population. The first section of this chapter deals with the addition of these new chips, and selecting a set of calibration chips which are representative of the new field population. Quality control (QC) tests are performed internally at the Whitby HPL to ensure that the dose deposited within a TLD chip can be measured accurately. Past QC results have indicated that the calibration chips were more sensitive than the field chips. For its external verification, OPG participates in quarterly quality assurance (QA) tests with the NRCC. These QA tests have shown a persistent negative bias of -5 to -15% for the last several years. Section 3.2 details the results of several special tests which were performed to identify the bias. The final two sections of chapter 3 deal with the various chip holders used to irradiate chips at the Whitby HPL and at the NRCC. The use of different chip holders was identified to be one source of bias leading to the discrepancy between the Whitby and NRCC QA test results, and thus required special attention. The current bulk chip holder used at the Whitby HPL is in poor condition and needs to be replaced. Section 3.3 deals with the introduction of a new bulk chip holder. In this section, the new holder is tested to make sure that the response is uniform across the holder. The final section contains a quantitative comparison between the four holders used at the Whitby HPL and at the NRCC. The relative amount of scattering in each holder is quantified using both experimental tests and Monte Carlo particle simulations.

## 3.1 Selection of Calibration and Test Chips

The TLD chips used for extremity TLDs have a range of sensitivities. In order to properly calibrate the system, it is necessary to select a set of calibration chips which have similar sensitivities and which are representative of all of the chips used in the field. A preliminary measurement showed that the average sensitivity of the field chips was 96.3% of the calibration chips, before the addition of a batch of new chips. The addition of new chips into the field population should increase the mean of the field population. To better understand the effect of introducing the new field chips and to obtain chips with specified sensitivities for further testing, the sensitivities of a large number of field and new chips were measured. Seven batches of chips, totaling about 1000 field and 900 new chips, were irradiated to 500 mR and read out on one of the readers. This allowed the chips to be separated by their differing sensitivities. The chips were put into vials corresponding to intervals of 10 mrem out of a nominal 1000 mrem (e.g., 970-979, 980-989, etc.). The distribution of both the new and field chips is illustrated in Figure 3.1.1.

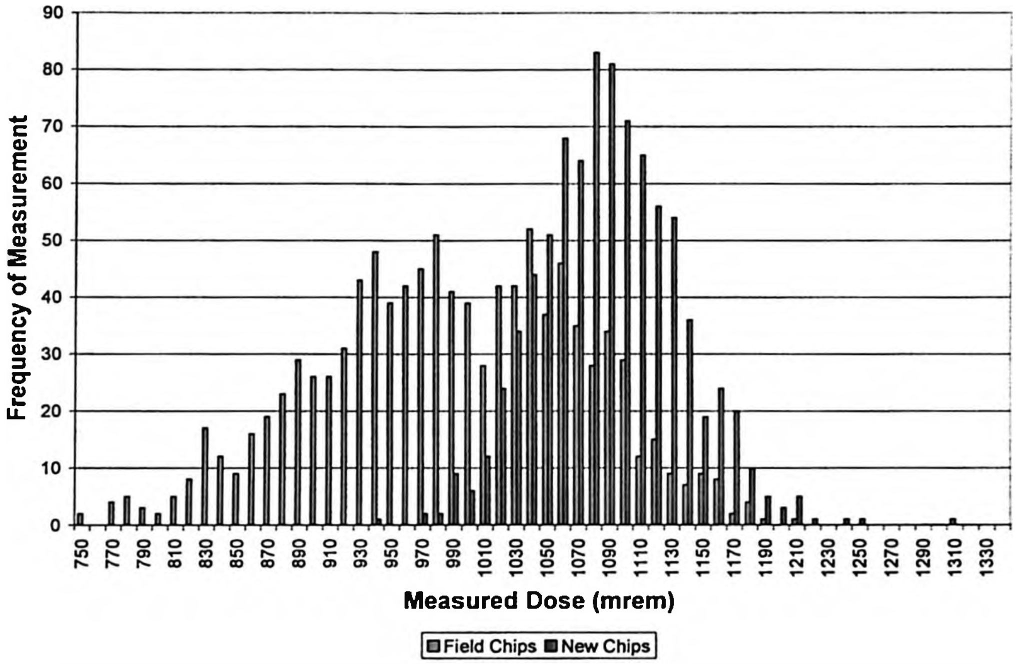


**Figure 3.1.1: Distribution of Measured Doses of Field and New Chips, for Batches 1-7 After an Exposure of 500 mR.**

To confirm the relative sensitivities between the 7 batches, the chips from the 1000-1009 mrem vials were annealed, re-irradiated to 500 mR and read on one of the readers. Although these chips should have had similar sensitivities, it was found that chips from batches 4, 5, 6, and 7 were of higher sensitivity. This suggested that the RCF did not remain constant over the several weeks in which the chips were read out. The RCF was indeed found to have changed over this several week period and a correction factor based on the RCF at the time of the reading was applied to each batch. Figure 3.1.2 shows both the uncorrected and RCF-corrected doses of the chips from the 1000-1009 mrem vials for batches 1 to 7.

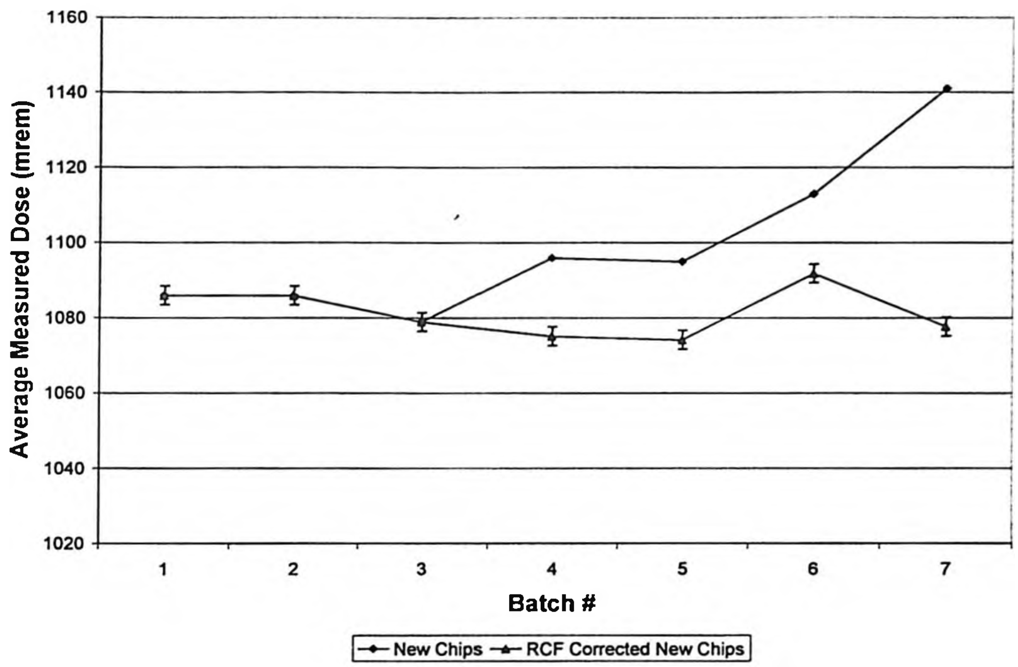


**Figure 3.1.2: Uncorrected and RCF Corrected Doses for Batches 1 to 7.**

The vials contained in batches 4, 5, 6, and 7 were re-labeled according to a correction factor based on the RCF, normalized to batch 1, used during the time when each batch was read out. Vials 4, 5, and 6 were relabeled as 20 mrem lower than their original dose, while vial 7 was relabeled as 50 mrem lower than its original dose. This correction assisted in making the average measured doses for batches 1 to 7 more consistent. Table 3.1.1 gives the mean and standard deviation for field and new chips before and after the correction. It shows a slight reduction in the standard deviation of both the field and new chips, as well as a slight convergence between the two means.

**Table 3.1.1: Mean and Standard Deviation for both New and Field Chips Before and After RCF Correction.**

| | | Uncorrected | RCF Corrected |
|---|---|---|---|
| Field Chips | Mean | 977.6 | 973.1 |
| | Standard Deviation | 81.5 | 80.8 |
| New Chips | Mean | 1094.8 | 1082.8 |
| | Standard Deviation | 44.6 | 42.5 |

Figure 3.1.3 is a revised histogram for batches 1 to 7, using the correction factors obtained from the RCF comparison.

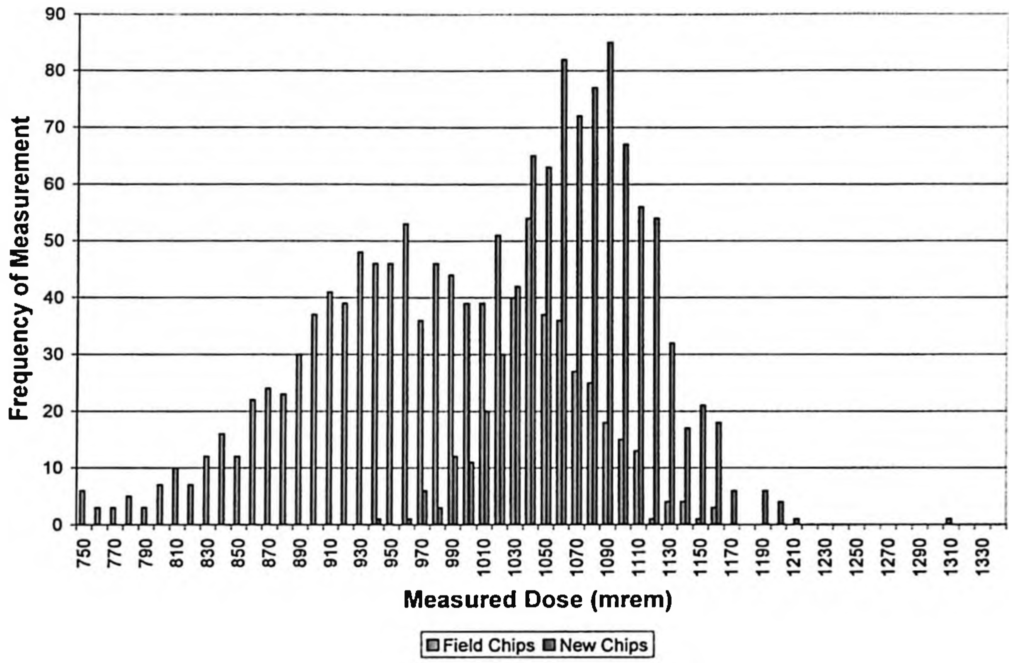


**Figure 3.1.3: Revised Distribution of Measured Doses of both Field and New Chips, for Batches 1-7 After an Exposure of 500 mR.**

The purpose of measuring the sensitivity of a large number of chips was to select a set which matched the average sensitivity of the field chips. Because the sensitivity of the field chips was less than that of the calibration chips, a proposed cal set was selected from the 960-969 mrem vials. This was done to try and match the sensitivities between the field chips and the calibration chips. This proposed cal set (50 chips), along with the current "golden" Cal (50 chips) and 100 randomly selected field chips, were irradiated to 500 mR and read out. The results are shown in Table 3.1.2.

**Table 3.1.2: Sensitivity Comparison Between "Golden" Cal Chips, Proposed Cal Chips, and Field Chips.**

| | Field Chips | Golden Cal Chips | Proposed Cal Chips |
|---|---|---|---|
| Sensitivity Compared to Golden Cal Chips | 0.989 | 1.000 | 0.969 |
| Sensitivity Compared to Field Chips | 1.000 | 1.011 | 0.980 |

Based on these results, the current "Golden Cal" set can continue to be used, but should be augmented with the chips from the 970-979, 980-989, and 990-999 vials. This should lower the sensitivity of the "Golden Cal" set and bring it into closer agreement with the sensitivity of the field population.

## 3.2 Quality Assurance Tests

Quality Assurance (QA) tests, conducted each quarter and in conjunction with the NRCC, have shown a negative bias in the range of -5 to -15% for almost all results for as far back as the first quarter of 1997. This longstanding bias triggered a series of special tests to identify the apparent cause of the bias. The results of this investigation were outlined in a memorandum to the dosimetry section manager (Counter 2005).

The first of two tests, performed in November 2004, confirmed the negative bias but only partially accounted for it. The QA chips are irradiated at the NRCC with a $^{60}$Co source, while the chips used for reader calibration at the Whitby HPL are irradiated with a $^{137}$Cs source. For this special test, the NRCC used $^{60}$Co to irradiate one set of chips and $^{137}$Cs to irradiate another, while a third set was irradiated with $^{137}$Cs at Whitby in the same holder that the calibration chips are irradiated in. The test chips were read, and then annealed, irradiated, and re-read to obtain relative sensitivities that were used to correct the results for each group of test chips. The measured doses were compared to the calculated delivered doses. It was found that the chips irradiated with $^{60}$Co at the NRCC read 2.4% lower than those chips irradiated with $^{137}$Cs at the NRCC, an effect documented by Shortt et al. (1996, 1997). However, the chips irradiated with $^{137}$Cs at the NRCC had a measured result that was 7.6% less than those exposed to $^{137}$Cs at Whitby.

This prompted a second special test to identify other factors that might contribute to the bias. It was postulated that the different chip holders used at Whitby and at the NRCC were contributing to the bias. The NRCC uses a 1.4% correction factor to covert their free-in-air exposure to an exposure in the lollipop holder, while Whitby uses a 1% correction factor for their 280-chip holder. The larger size of the Whitby 280-chip holder suggested that the 1% correction factor underestimates the amount of scattering created. Schematics of Whitby's bulk holder and of the NRCC's lollipop are shown in Figures 3.4.1 and 3.4.2, respectively. The main difference incorporated into the April 2005 test was that the Whitby irradiations were done in both of the two different chip holders. This allowed the effect of the different holders on the delivered dose to be examined. A further difference was in the group sensitivity correction, which instead of correcting each group by the average of all groups, corrected each group by the average of a set of calibration chips. This was found to improve the relative response of the chips in the bulk holder. In order to determine the extra scattering created by the larger bulk holder, the Whitby free-in-air exposures were compared to the NRCC free-in-air exposures. For irradiations performed at Whitby, the relative responses (i.e., measured dose/delivered dose) for the holder and the lollipop were found to be 100.0% and 97.7%, respectively. This 2.3% difference reflects the greater amount of scatter created in the holder versus that created in the lollipop. After incorporating all the known correction factors, the NRCC $^{137}$Cs lollipop exposure and the Whitby $^{137}$Cs lollipop exposure were within 1% of each other.

It was also determined that up until February 2005, the NRCC exposure rate standard had been revised while the Whitby exposure rate standard had not. This contributed about 2.3% of the negative bias up to February 2004 when the exposure rate calculation used for extremity TLDs was changed at Whitby. Following the first quarter

2005 QA test, the Whitby exposure rate standard was revised to match the NRCC exposure rate standard.

To summarize, the test program found the following four factors to be the major contributors to the QA bias.

1) The TLD material, LiF:Mg,Ti, is less sensitive to the $^{60}Co$ source used for the NRCC test irradiations than to the $^{137}Cs$ source used for calibrating the extremity TLD readers at Whitby, contributing about 2.4% to the negative bias.

2) The field chips for the NRCC test are less sensitive than the calibration chips. A preliminary measurement showed the calibration chips to be about 3.7% less sensitive than the field chips.

3) Up to and including the Q1 2005 QA test, the exposure rate standard for Extremity TLDs had been updated at the NRCC, but not at the Whitby HPL. This contributed a negative bias of about -2.3% up to February 2004, when the standard used for extremity TLD exposures was changed and the bias decreased to -0.3%.

4) Irradiations done at the NRCC and at the Whitby HPL use different chip holders. The holder affects the amount of dose absorbed by the chips, because of attenuation in the front wall and scattering from material around the chips. The scatter correction factor used for the 280-chip holder at Whitby underestimates the actual exposure delivered to the calibration chips by about 3%.

The results from these two special tests were then applied to the NRCC QA results from both the first and second quarters of 2005. Four main corrections were made to the data from the first and second quarter 2005 QA tests. A 2.5% correction was used to account for the fact that the NRCC uses a $^{60}Co$ source, while Whitby HPL uses a $^{137}Cs$ source. A 2.3% correction was used to account for the different holders used at the NRCC and at Whitby. A factor of 1.014/1.01 was used because the NRCC corrects their free-in-air exposure by 1.4%, while reader calibration at the Whitby HPL is done using a 1% correction factor. A group sensitivity correction was also applied to each of the tests, although somewhat differently for the first and second quarter. These factors were applied as follows:

Corrected Measured Dose = Measured Dose x 1.025 x 1.023 x 1.014/1.01 x group sensitivity

The Q1 reanalysis used a 96.3% correction factor for group sensitivity, because the field chips had previously been shown to have 96.3% of the calibration chip sensitivity. The Q2 test corrected each group for its own group sensitivity, which was calculated using a set of calibration chips. Only the first quarter QA test required a correction to account for the exposure rate standard which had not yet been updated. For the first quarter test, the average relative response was improved from 0.85 to 0.94. Although a significant improvement, a -6% bias still remains, and was believed to be partially the result of several bad test chips. For the second quarter test, performed for each of two readers, the average relative response for readers 1 and 2 were improved from 0.963 and 0.956 to 1.032 and 1.013, respectively. Applying these corrections should decrease this longstanding bias, as well as result in future QA tests falling equally above and below the nominal relative response of 100%. The results of the two special tests, the analysis of the Q1 2005 QA results, and the analysis of the Q2 2005 QA results are summarized in Table 3.2.1.

**Table 3.2.1: Summary of Special Tests, Q1 Analysis, and Q2 Analysis.**

| Correction Factor | Special Test-November 2004 | Special Test –April 2005 | Corrected Q1 2005 QA Test | Corrected Q2 2005 QA Test (Reader 1) | Corrected Q2 2005 QA Test (Reader 2) |
|---|---|---|---|---|---|
| Sensitivity Correction | group (using field chips) | group (using cal chips) | 3.7% (1/0.96) | group (using cal chips) | group (using cal chips) |
| $^{60}Co$ vs. $^{137}Cs$ Correction | 2.5% | 1.6% | 2.5% | 2.5% | 2.5% |
| Free-in-air corrections | N/A | 1.4%/1% | 1.4%/1% | 1.4%/1% | 1.4%/1% |
| Lollipop vs. Holder Correction | N/A | 2.3% | 2.3% | 2.3% | 2.3% |
| Remaining Bias | -7.6% | -0.9% | -6% | 3.2% | 1.3% |

## 3.3 Introduction of a New Bulk Chip Holder

The current OPG bulk chip holder is in somewhat poor condition and it is desired that it be replaced with a new holder, whose scattering properties are accurately determined. The current bulk holder holds 280 chips in 4 columns. The chips are placed 5 across each column and are stacked 14 rows high. The chips in any one of the columns are placed directly next to, or directly above, each other, increasing the chance of mixing up the chips. Mixing up chips is a potential concern for both QA tests and type testing. The new proposed holder holds 300 chips in 10 separated rows. Along each row the chips are placed adjacent to one another, but are labeled from 1 to 30. This greatly reduces the possibility of mixing up any of the chips. The 300-chip holder is shown in Figure 3.3.1. Before the new chip holder can be put into service, its properties must be accurately determined. The primary concern is that there be a uniform response across the holder, meaning that chips lying on the periphery receive the same dose as chips lying closer to the centre, and that the effect of holder scatter is quantified.

Three hundred chips were selected from the 1000-1009, 1010-1019, 1020-1029, 1030-1039, and 1040-1049 vials. These chips were pre-selected to have similar sensitivities and to have relative responses close to 100%. All chips were annealed and put randomly into the 300-chip holder. The chips were irradiated to 500 mR and read on one of the readers. The rows were read out in a pseudo-random order (row 1, then row 10, then row 4, etc.) to ensure that the results were not influenced by a time-varying reader sensitivity. Figure 3.3.2 shows the measured dose along each of the rows. Aside from a few outliers, the response appears uniform across each of the rows. To confirm that there are no trends with the horizontal and vertical position, the average measured dose across each row and down each column are plotted in Figures 3.3.3 and 3.3.4.

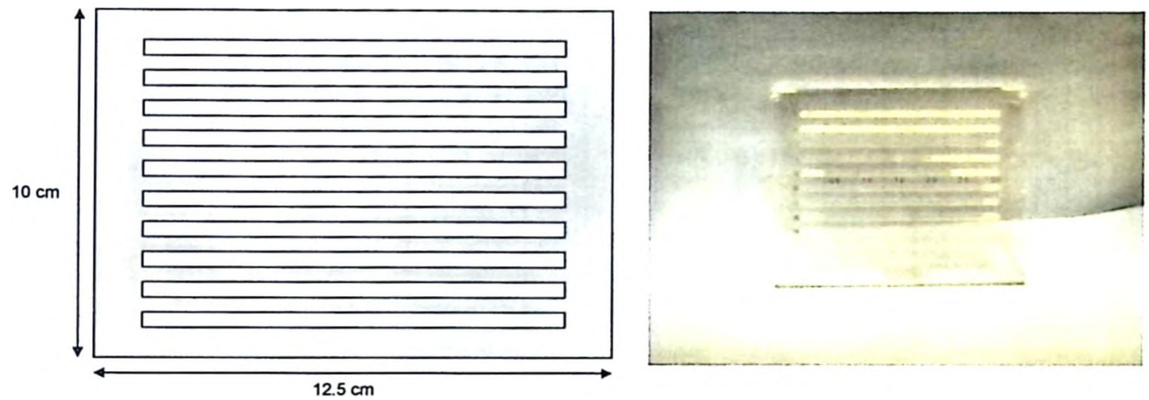


**Figure 3.3.1: Schematic and Picture of 300-chip Holder.** The front wall is 2.95 mm and the back wall is 2.20 mm.

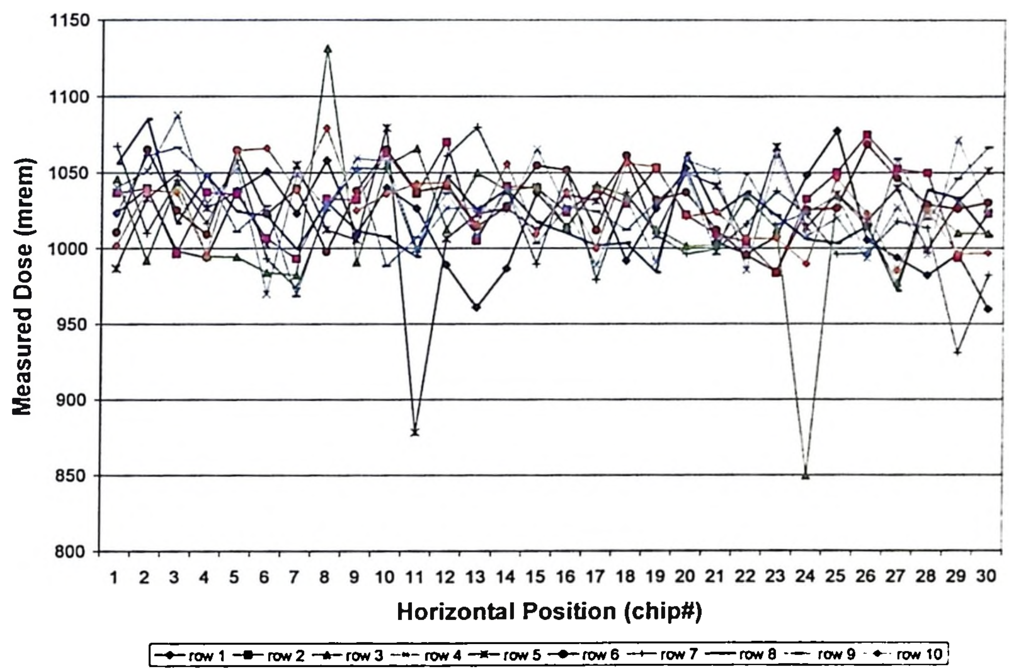


**Figure 3.3.2: Measured Dose vs. Horizontal Position for the 10 Rows of the New OPG Bulk Chip Holder**

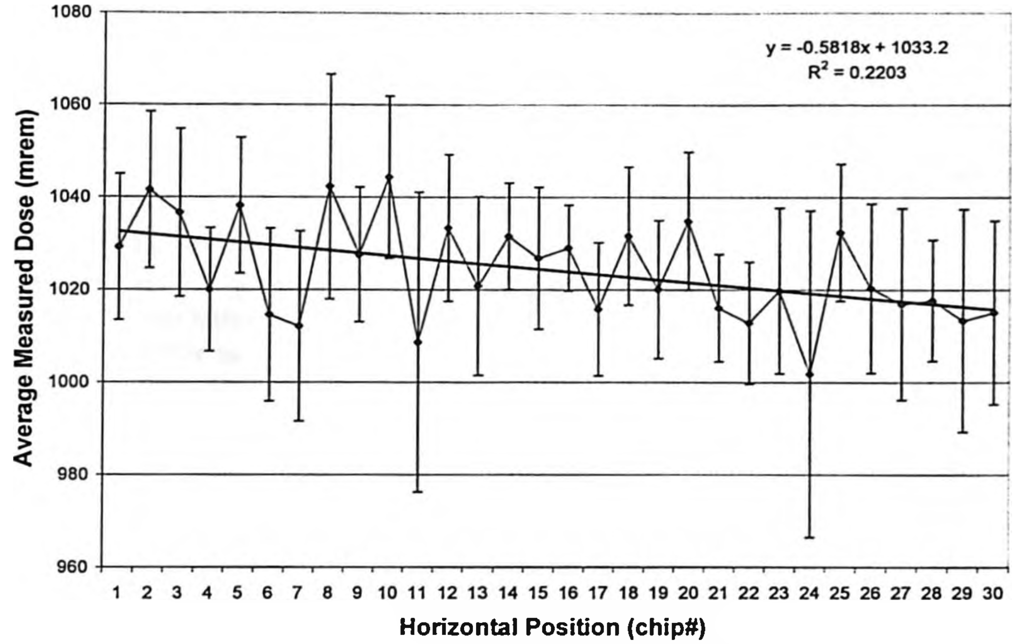


**Figure 3.3.3: Average Measured Dose vs. Horizontal Position for the New Whitby Bulk Chip Holder.**

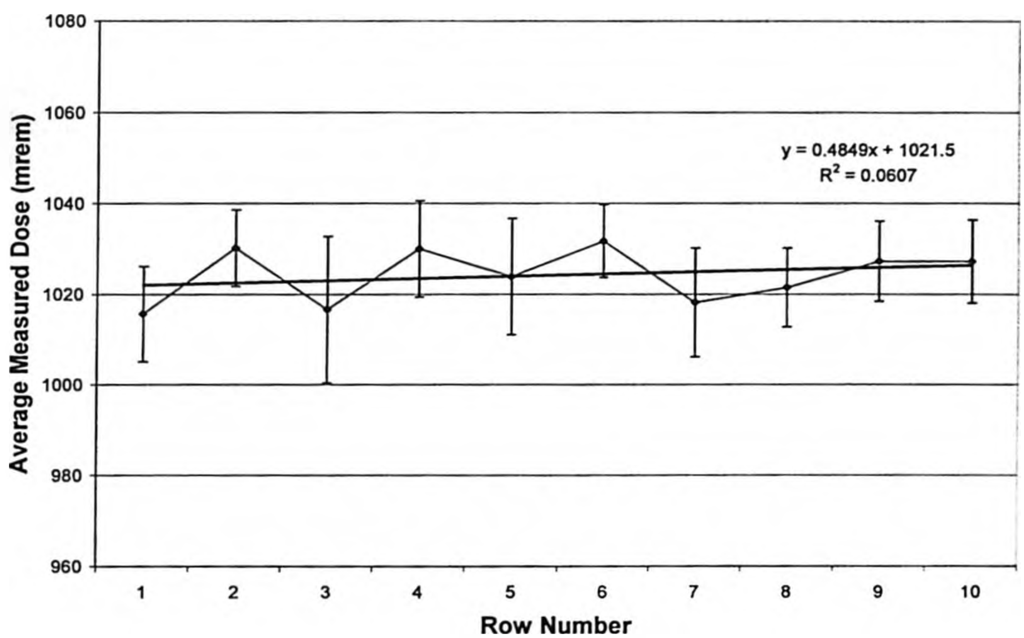


**Figure 3.3.4: Average Measured Dose vs. Row Number for the New OPG Bulk Chip Holder.**

Using linear regression techniques, the negative slope of Figure 3.3.3 was found to be statistically different from 0. The slope of the trend-line in Figure 3.3.4, however, was determined to not be statistically different from 0. The average measured dose was also plotted against the order in which the rows were read (not shown) and there was no trend. This means that a time-varying reader sensitivity was not significantly affecting the results. These results confirm that there is no difference in absorbed dose for chips positioned in different rows.

The statistically significant negative slope found in Figure 3.3.3 was a cause for concern. This triggered an investigation to determine the cause of this trend. Possible explanations are that either the holder was positioned in a way that a greater dose was delivered to the left side, or that the chips, picked at random, happened to have a decreasing sensitivity going from left to right, or that the source delivers a slightly higher exposure to one side. From the equation of the best-fit line in Figure 3.3.3, it was calculated that the left edge (column 1) of the holder would have to have received about 1.66% more exposure than the right edge (column 30) to account for the difference. Using the inverse square law, this corresponds to the left edge being 0.83% closer than the right. At 3 metres, this translates into a distance of about 2.5 cm, which was too large an error to have gone unnoticed.

This prompted another test to correct the results by the individual sensitivity of each chip. Chips were selected from various locations in the 300-chip holder, as shown in Figure 3.3.5. The chips, 85 in all, were selected to be representative of several rows (1, 5/6, and 10), several columns (1, 15/16, and 30), the four corners, the centre, and any outlying chips. The chips were annealed, placed in the centre of the 300-chip holder (in a semi-random fashion), and surrounded with other chips. They were then irradiated to 500 mR, and read out on one of the readers. Special care was taken to retain the identity of each chip. An individual chip sensitivity correction was obtained by dividing each individual chip reading by the mean reading, and was used to correct the original data across rows 1, 5/6, and 10. This was done in an attempt to explain the decreasing trend observed across the holder from left to right. For rows 1 and 10 the individual chip sensitivity corrections were found to improve the results by making the slope closer to zero. Applying the individual chip sensitivity corrections to row 5/6 was found to make the results worse, by making the slope even more negative. The corrected and uncorrected data for rows 1, 5/6, and 10 are illustrated in Figures 3.3.6, 3.3.7, and 3.3.8, respectively.

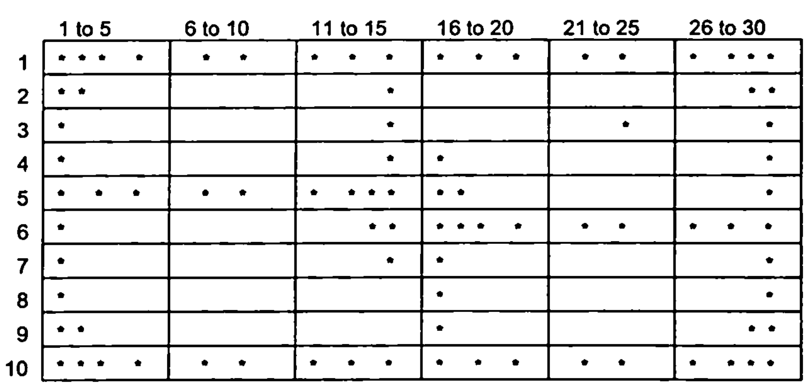


**Figure 3.3.5: Schematic of the 300-chip Holder, Showing the 85 Chips Selected to Correct the Results from Figure 3.3.2.** The chips were selected to be representative of several rows and columns, the four corners, the centre, and any outlying chips.

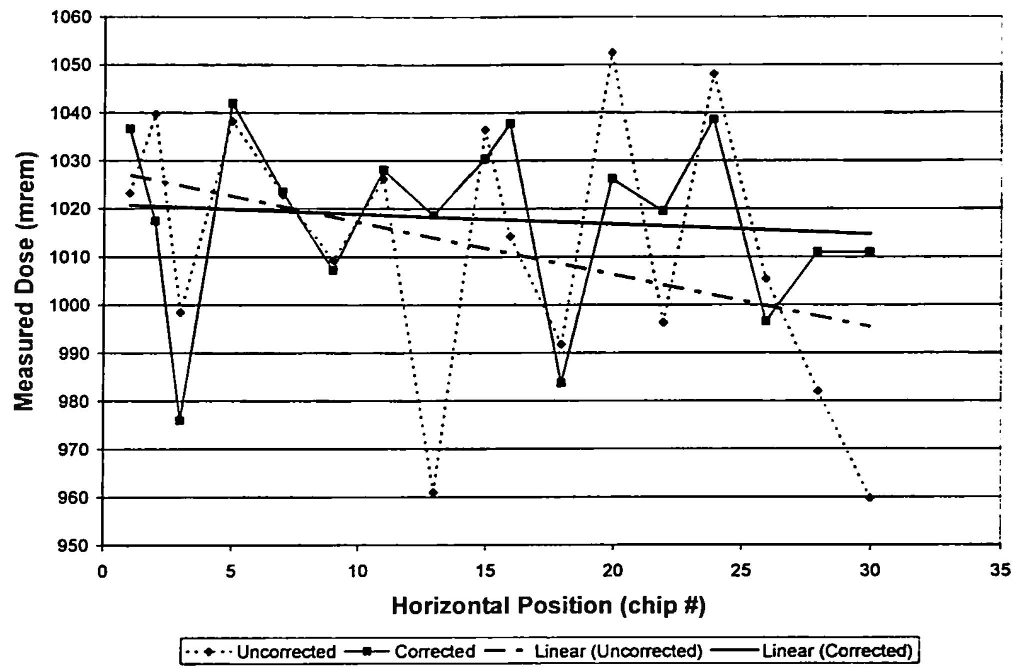


**Figure 3.3.6: Corrected and Uncorrected Data for Row 1 of the 300-chip Holder.** Correcting by individual chip sensitivity serves to lessen the decreasing response from left to right.

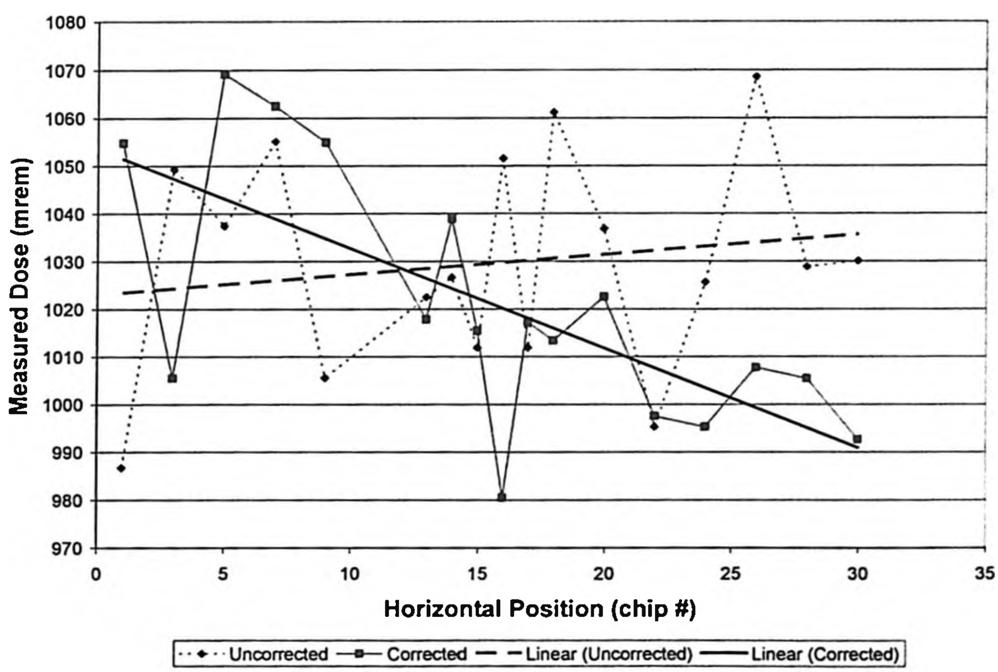


**Figure 3.3.7: Corrected and Uncorrected Data for Row 5/6 of the 300-chip Holder.** Correcting by individual chip sensitivity was found to make the left-to-right trend even more pronounced.

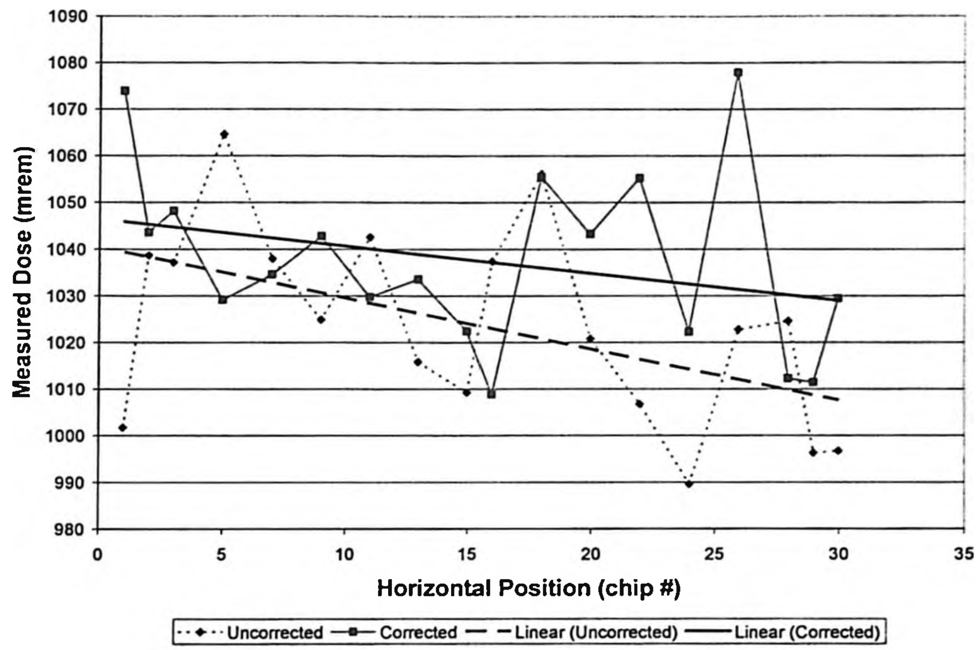


**Figure 3.3.8: Corrected and Uncorrected Data for Row 10 of the 300-chip Holder.** Correcting by individual chip sensitivity serves to lessen the decreasing response from left to right.

While Figures 3.3.6 and 3.3.8 show an improvement to the data, Figure 3.3.7 shows an even more pronounced negative slope from left to right. With the average standard deviation for repeatability of 1.7%, changes of up to about 35 mR in individual chip results are expected and it could be a statistical fluke that the slope in rows 5/6 became so negative. This individual sensitivity correction still served to improve the overall results of this new holder test. The average measured exposure in different sections of the holder is shown in Figure 3.3.9. Any section of the holder is in agreement with any other section to within two standard errors. This is an improvement over the original data where chips from various sections were not found to overlap within two standard errors (not shown).

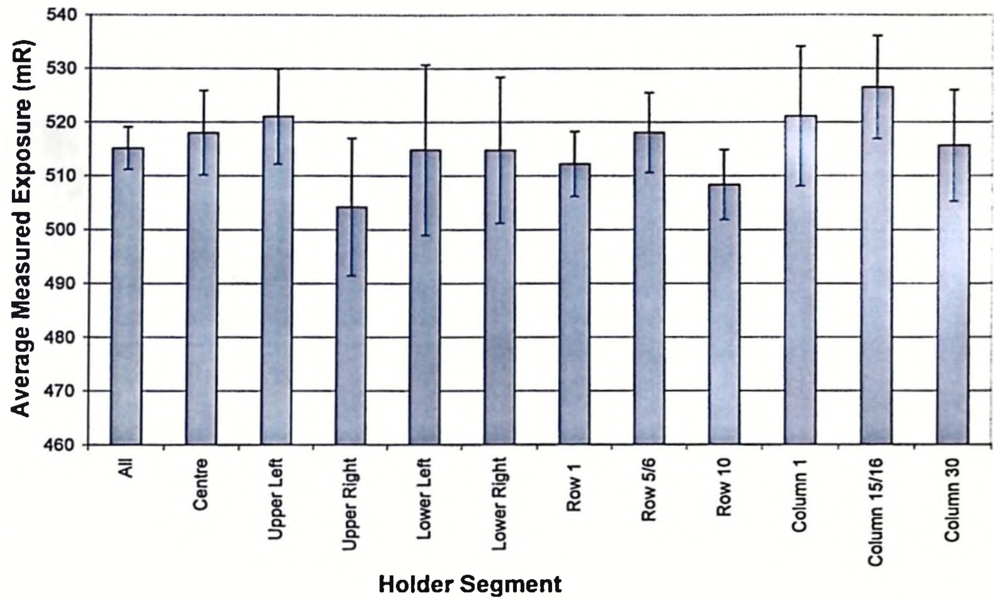


**Figure 3.3.9: Average Measured Exposure for Various Segments of the Holder.** The data is shown with two standard errors, at the 95% confidence level.

These findings allow us to conclude that when irradiating chips in new 300-chip holder, the dose received by a chip is independent of its position in the holder. This is essential for interpreting the results of various tests where a large number of chips are irradiated together in the new bulk holder.

## 3.4 Effect of Chip Holder on TLD Results

To deliver an accurate dose to any set of TLD chips, it is essential to quantify the scattering effects of the chip holder being used. A certain thickness of material is required in front of the chips to produce charged particle equilibrium (CPE), and is dependent on the source of radiation. OPG typically irradiates chips using $^{137}Cs$, which requires less material for electronic equilibrium than $^{60}Co$, which the NRCC uses for QA irradiations. The effects of increasing both the front and back wall thicknesses were documented by Shortt et al. (1996, 1997). As the front wall thickness is increased beyond the thickness required for CPE, the response decreases. This is because the extra material serves to increase the attenuation. Increasing the back wall thickness leads to an increase in the relative response, and was attributed to an increase in backscatter. The effect of the back wall thickness was less significant than that of the front wall. Davis et al. (2003) investigated the response of the TLD chip as a function of the radial size of a holder. His findings included an increased response as the radius of the chip holder was increased, and was also attributed to an increase in scattering. Chips are not always irradiated in the same chip holders, and it is therefore necessary to quantify the amount of scattering created by each holder. Currently at OPG, chips are irradiated in a bulk holder, which holds 280 chips, and is shown in Figure 3.4.1.

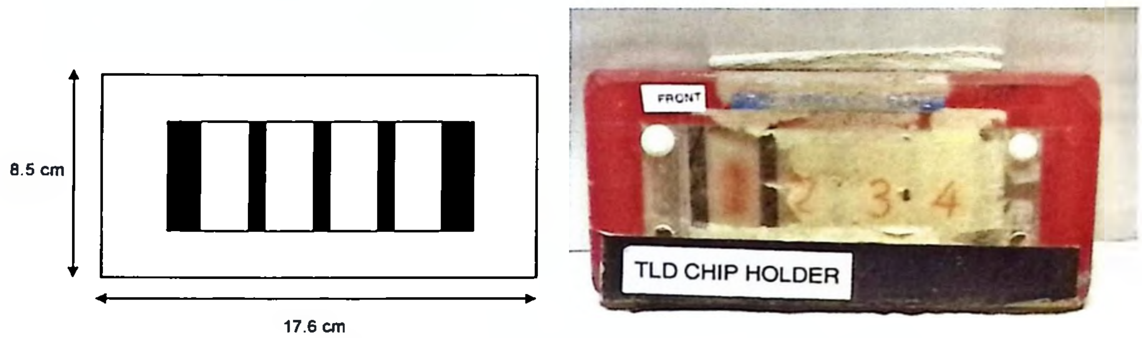


**Figure 3.4.1: Schematic and Picture of OPG's 280-chip Holder.** The front and back walls are 3 mm and 6 mm, respectively.

The NRCC irradiates chips for their quarterly QA tests in a "lollipop" holder. The NRCC "lollipop" holds 5 chips and is shown in Figure 3.4.2. A similar holder with a capacity of 25 chips is shown in Figure 3.4.3. Using both experimental tests and a Monte Carlo particle simulation (MCNP5), the relative amounts of scattering between the various holders can be quantified.

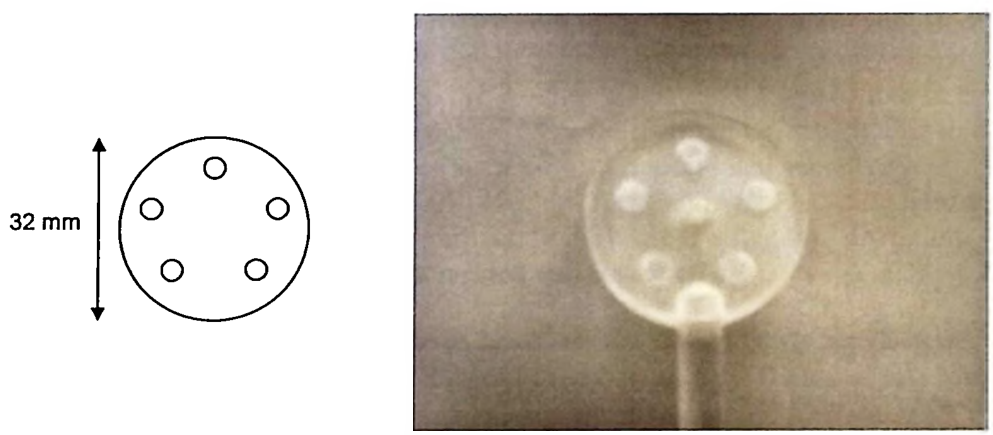


**Figure 3.4.2: Schematic and Picture of NRCC Lollipop Holder.** The front wall is 4 mm and the back wall is 4 mm.

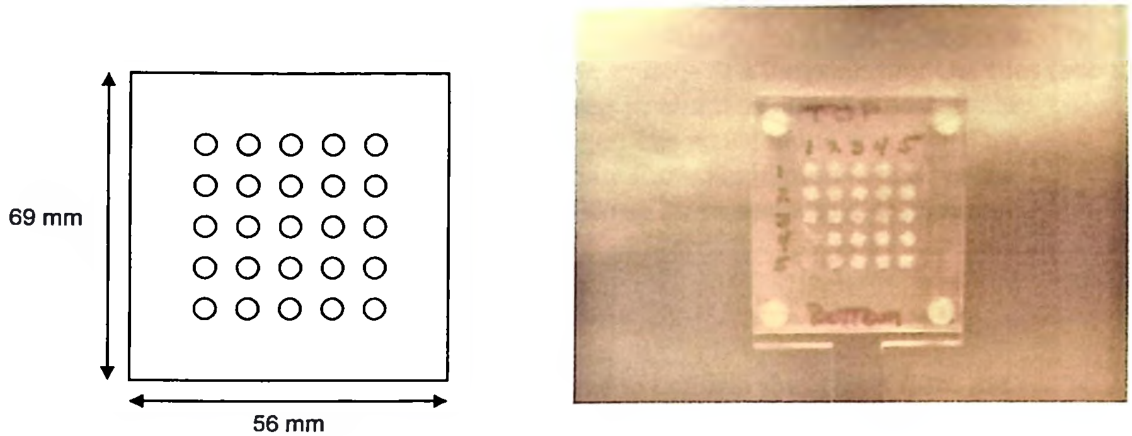


**Figure 3.4.3: Schematic and Picture of the 25-chip Holder.** The front and the back walls are both 6 mm.

### 3.4.1 Experimental Results

At OPG, TLD chips are irradiated in several different chip holders. This test was conducted to quantify the scattering characteristics of each holder. The four holders used in this test were the NRCC's lollipop, the 25-chip holder, OPG's current bulk holder (280-chips), and OPG's new bulk holder (300-chips), which are shown in Figures 3.4.2, 3.4.3, 3.4.1, and 3.3.1, respectively. This test used 140 chips taken from the 1000-1009, 1010-1019, 1020-1029, and 1030-1039 mrem vials. The chips were annealed together and then irradiated to 500 mR in one of the holders. Fifty chips were irradiated in each of the bulk holders, twenty-five in the 25-chip holder, and 3 sets of five in the lollipop. All results were normalized to the NRCC's lollipop holder, which, due to its smaller size, produced the least amount of scattering. An individual sensitivity correction was performed by irradiating all 140 chips together in the 300 chip holder. Applying this correction was found to significantly decrease the standard deviation. Table 3.4.1 shows the results for the uncorrected and corrected data.

**Table 3.4.1: Corrected and Uncorrected Results for the Various OPG Chip Holders.**

| | | Lollipop | 25-Chip Holder | 280-Chip Holder | 300-Chip Holder |
|---|---|---|---|---|---|
| | **Chips Used** | 3 x 5 | 25 | 50 | 50 |
| **Uncorrected** | **Mean** | 485.9 | 497.7 | 502.6 | 496.7 |
| | **Standard Deviation** | 11.8 | 12.4 | 15.3 | 14.6 |
| | **Relative to Lollipop** | 100.0% | 102.4% | 103.4% | 102.2% |
| **Corrected** | **Mean** | 486.4 | 493.9 | 502.5 | 495.4 |
| | **Standard Deviation** | 6.1 | 8.9 | 14.8 | 8.3 |
| | **Relative to Lollipop** | 100.0% | 101.5% | 103.3% | 101.9% |

The difference between the 280-chip holder and the lollipop was found to be 3.3%. The April 2005 special test, performed to identify the sources of a longstanding QA bias (see Section 3.2), identified a 2.3% difference between irradiations done in the 280-chip holder and irradiations done in the NRCC lollipop. The actual value was therefore estimated to be between 2.3% and 3.3%. A Monte Carlo simulation is used in the following section to determine a third and potentially more accurate measurement.

### 3.4.2 Monte Carlo Results

A Monte Carlo particle simulation was used to confirm the effects from the previous section and those documented by Shortt et al. (1996, 1997) and Davis et al. (2003). Monte Carlo N-Particle version 5 (MCNP5) was used to investigate the effects of varying the front, rear, and radial wall thicknesses of Lucite around a single chip. A mono-energetic $^{137}$Cs source, having a solid angle approximately equal to that of the Whitby HPL irradiation facility, was positioned at 1 meter from the target. TLD chips were modeled as cylinders, having a surface area equal to that of the usual square shape, and surrounded by 2 mm of Lucite to provide charged particle equilibrium. The front, rear, and radial walls were then increased separately in increments of 1 mm, and compared to the initial case of 2 mm. MCNP was set up to produce absorbed dose results in units of rads/starting particle. Results for a given solid angle were normalized to the isotropic case by multiplying them by the fraction of solid angle. When normalized to the isotropic case, all values were found to agree with the calculated theoretical values. The response of the chips as a function of front, rear, and radial wall thickness is shown in Figure 3.4.4. The results are in close agreement with those reported by Shortt et al. (1996, 1997) and Davis et al. (2003).

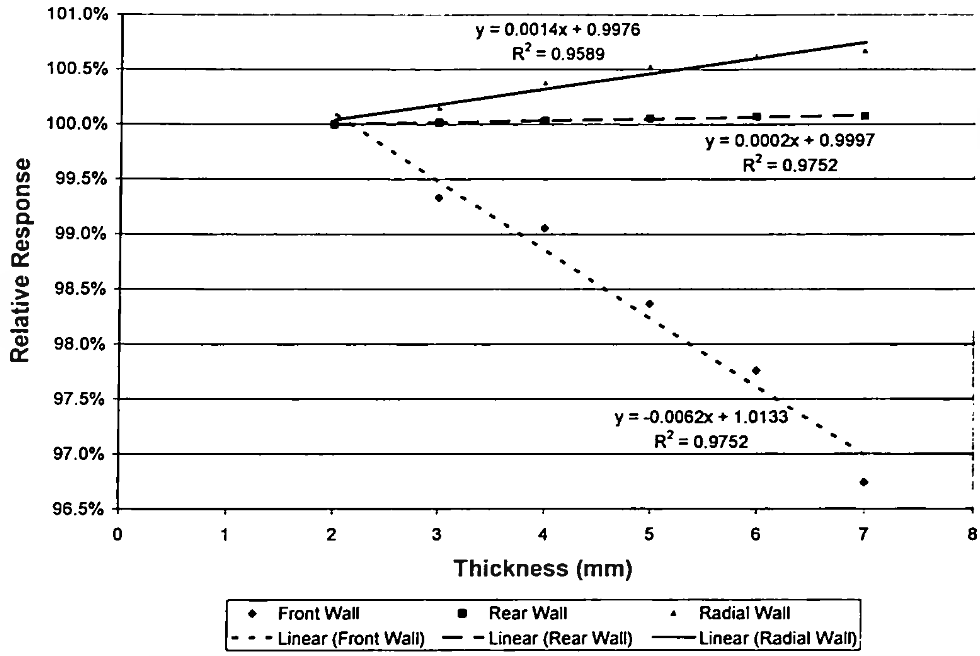


**Figure 3.4.4: Monte Carlo Simulation of Relative Response as a Function of Front, Rear, and Radial Wall Thickness.** Each parameter was increased separately, while leaving the other two at 2 mm.

A second Monte Carlo particle simulation was performed to test the response of the various chip holders used by OPG and by the NRCC. Results were normalized to the single chip case, which was surrounded by 2 mm of Lucite for charged particle equilibrium, and to the NRCC lollipop. Four different chip holders were modeled into MCNP, and are shown in Figures 3.3.1, 3.4.1, 3.4.2, and 3.4.3. Results for the simulations are shown in Table 3.4.2. The Monte Carlo results are in good agreement with the experimental results from Section 3.4.1. The biggest discrepancy arises for the 280-chip holder. The Monte Carlo results are much closer to the 2.3% found during the April 2004 special test, suggesting that the relative scattering between the 280-chip holder and the lollipop holder is closer to 2.3% than it is to 3.3%.

**Table 3.4.2: Monte Carlo Results for Various Chip Holders.**

| | Single Chip | Lollipop | 25-Chip Holder | 280-Chip Holder | 300-Chip Holder |
|---|---|---|---|---|---|
| **Average (rads/part.)** | 2.907E-13 | 2.911E-13 | 2.954E-13 | 2.984E-13 | 2.958E-13 |
| **Error** | 0.98% | 0.98% | 0.98% | 0.98% | 0.98% |
| **Relative To Single Chip** | 100.0% | 100.1% | 101.6% | 102.7% | 101.7% |
| **Relative To Lollipop** | 99.9% | 100.0% | 101.5% | 102.5% | 101.6% |

**Table 3.4.3: Comparison Between Experimental Results and Monte Carlo Results.**

| | Lollipop | 25-Chip Holder | 280-Chip Holder | 300-Chip Holder |
|---|---|---|---|---|
| **Corrected Experimental Results –Relative to Lollipop** | 100.0% | 101.5% | 103.3% | 101.9% |
| **Monte Carlo Results –Relative to Lollipop** | 100.0% | 101.5% | 102.5% | 101.6% |

Another set of calculations was performed to determine the point at which both the radial and rear wall thicknesses no longer contribute to the dose absorbed by the chip. This was done by increasing the radius and rear wall thickness separately by increments of 5 mm, for the single chip geometry. The results from this simulation are found in Figures 3.4.5 and 3.4.6.

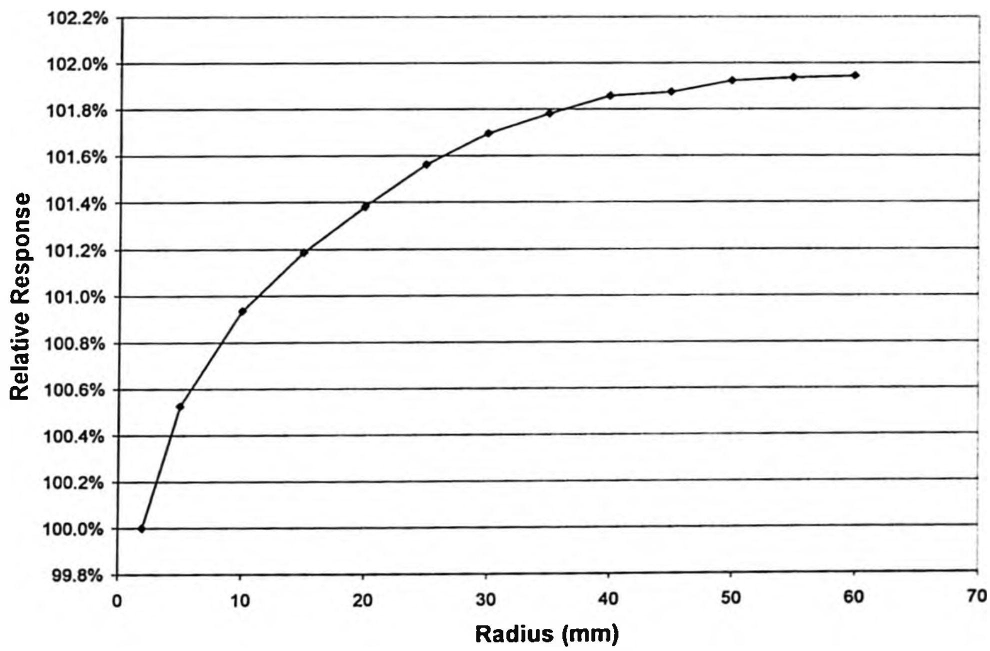


**Figure 3.4.5: Monte Carlo Particle Simulation of Relative Response as a Function of Radius.** The front and back walls are both 2 mm.

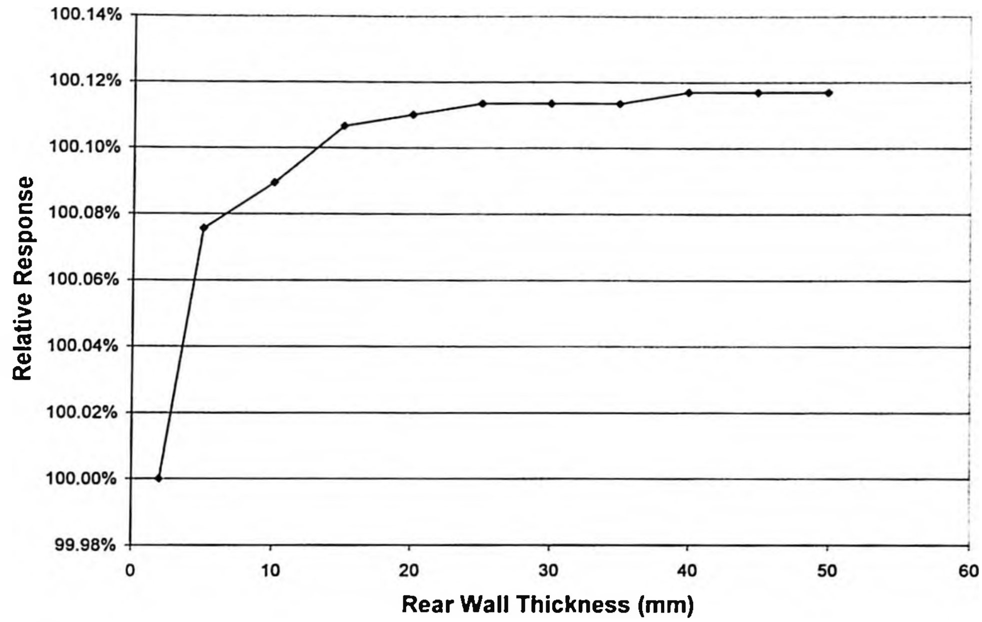


**Figure 3.4.6: Monte Carlo Particle Simulation of Relative Response as a Function of Rear Wall Thickness.** The front wall and radius are both 2 mm.

From Figure 3.4.5, the maximum response is obtained for a radius of about 60 mm. Beyond this radius, the addition of more material around the chip does not contribute significantly to absorbed dose. From Figure 3.4.6, the maximum response is obtained for a rear wall thickness of about 25 mm. Adding more material behind the chip was found to have little to no effect on the response of the chip. The vertical scale of Figure 3.4.6 has a very small range and the difference between data points is in the least significant figure. The Monte Carlo results themselves contain about 1% error, which is greater than the variations among the data points. The results are significant, however, because MCNP starts with the same random number seed.

Figure 3.4.7 shows the results from another simulation where the response was determined for increasing rear wall thickness at three different radii. This test used radii of 2 mm (as in Figure 3.4.4), 5 mm, and 7 mm, surrounding a single chip. From the figure, it can be concluded that a larger radius will amplify the response of the chip as the rear wall thickness is increased. This was because the extra material surrounding the chip serves to scatter more of the backscattered photons, which would otherwise miss the chip, towards the chip.

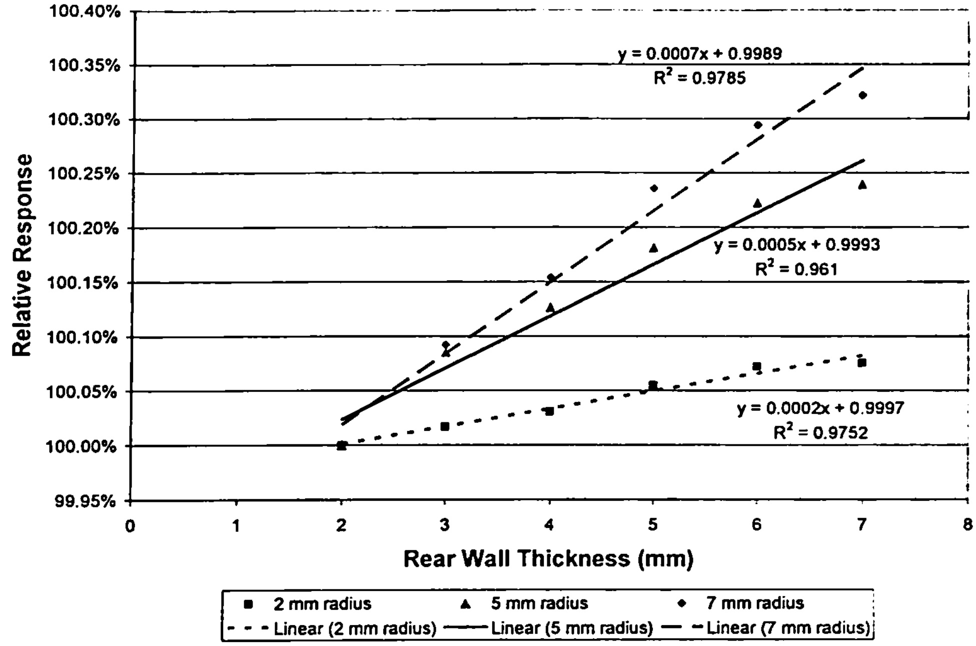


**Figure 3.4.7: Monte Carlo Particle Simulation of Relative Response as a Function of Rear Wall Thickness for Radii of 2, 5, and 7 mm.**

# Chapter 4

# Type Testing of OPG's Extremity TLD System

## 4.1 Repeatability Test

The first of several type tests conducted dealt with how repeatable a set of TLD readings are. A set of 25 chips, selected to have similar sensitivities, were repeatedly annealed, irradiated to 500 mR in the 25-chip holder, and read on one of the readers. Because only the relative sensitivity of the 25 chips was of importance, the chips were selected from the 1100-1109 mrem vials. They were therefore of greater sensitivity than the field population. Each run was conducted over a three day period, where the chips were annealed over the first night, irradiated the second day, and read out on the third. Using this method, it was possible to conduct a maximum of two runs per week. Special care was taken to ensure that the identity of each individual chip was retained during the annealing period. This test determines the overall precision of the whole TLD process. Several chips were cracked and broken while being loaded into the holder. This was attributed to the design of the holder, which had chip slots that were slightly shallower then the thickness of the chips. Tightening the front face of the holder too much was found to crack and break the chips. The results from this type test, shown in Table 4.1.1, contain data for the broken chips up to the point when they were removed. Data for runs 1 to 10 are plotted in Figure 4.1.1.

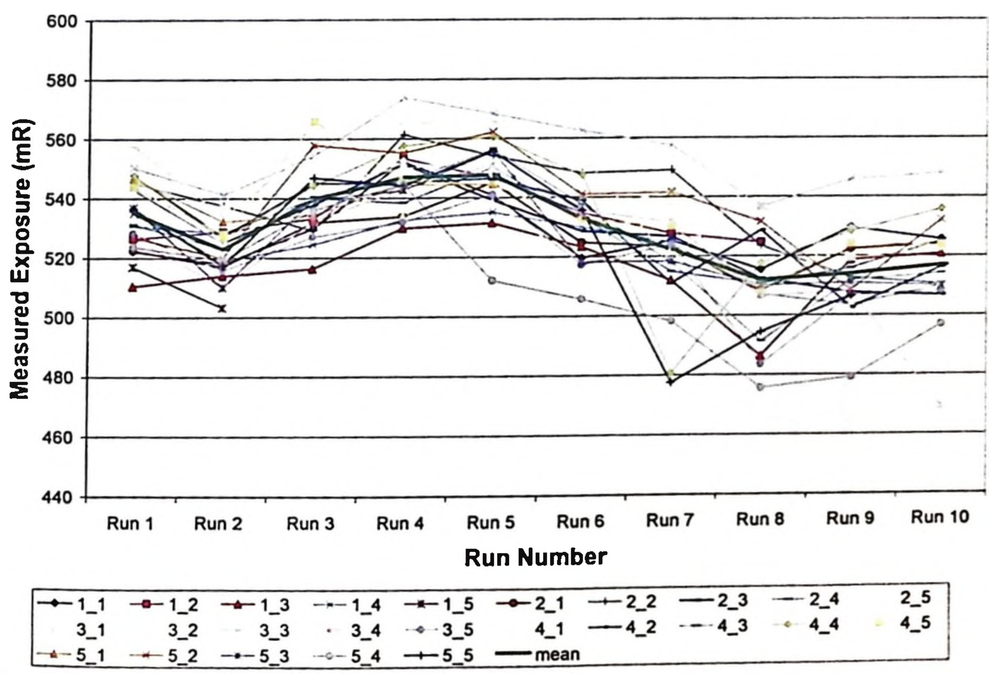


**Figure 4.1.1: Measured Exposures for Runs 1-10 of Repeatability Test.**

**Table 4.1.1 Repeatability Test – Measured Exposures (mR) for Runs 1-10.**

| Chip* | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Run 7 | Run 8 | Run 9 | Run 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1-1 | 522.19 | 517.95 | 529.86 | 552.16 | 540.88 | 519.53 | 525.27 | 515.35 | 529.50 | 525.49 |
| 1-2 | 526.45 | 528.76 | 533.23 | 553.44 | 546.69 | 534.87 | 527.77 | 524.54 | | |
| 1-3 | 510.44 | 513.92 | 516.30 | 529.86 | 531.54 | 523.32 | 511.84 | 486.21 | 518.53 | 520.62 |
| 1-4 | 534.96 | 518.90 | 524.47 | 532.61 | 535.17 | 529.97 | 524.66 | 507.12 | 503.45 | 509.70 |
| 1-5 | 516.95 | 503.18 | | | | | | | | |
| 2-1 | 522.51 | 516.96 | 531.91 | 533.76 | 545.16 | 524.77 | 523.32 | 508.19 | 522.29 | 524.03 |
| 2-2 | 545.18 | 537.62 | 529.14 | 561.44 | 554.15 | 548.23 | 549.05 | 523.41 | 512.70 | 510.42 |
| 2-3 | 543.04 | 525.15 | 537.96 | 551.59 | 539.11 | 528.57 | 526.75 | 512.31 | 507.66 | 506.63 |
| 2-4 | 530.67 | 528.27 | 540.15 | 538.47 | 550.34 | 533.27 | 514.88 | 510.61 | 515.90 | 524.96 |
| 2-5 | 543.22 | 525.23 | 540.08 | 552.56 | 547.91 | 535.30 | 536.95 | 505.40 | 529.15 | 528.28 |
| 3-1 | 545.47 | 536.47 | 545.39 | 550.27 | 551.45 | 536.44 | 541.62 | 536.60 | 519.09 | 522.65 |
| 3-2 | 533.23 | 517.06 | 545.90 | 534.04 | 538.40 | 517.74 | 522.05 | 510.40 | 503.78 | 510.74 |
| 3-3 | 550.33 | 541.17 | 554.45 | 573.94 | 568.38 | 562.54 | 557.49 | 536.70 | 545.81 | 547.95 |
| 3-4 | 526.87 | 510.24 | 532.33 | 543.18 | 551.14 | 535.71 | 531.50 | 506.32 | 508.13 | 469.13 |
| 3-5 | 528.32 | 515.65 | 527.09 | 531.95 | 541.25 | 517.19 | 523.92 | 483.48 | 506.57 | 507.98 |
| 4-1 | 557.64 | 533.92 | 557.50 | 565.18 | 565.82 | 554.02 | 518.17 | 547.86 | | |
| 4-2 | 547.63 | 527.21 | 545.11 | 545.21 | 546.53 | 539.01 | 510.81 | 528.71 | 502.40 | 516.08 |
| 4-3 | 531.29 | 523.08 | 540.48 | 545.46 | 556.35 | 537.71 | 517.91 | 491.29 | 511.75 | 514.03 |
| 4-4 | 547.76 | 526.21 | 544.27 | 557.68 | 560.64 | 547.49 | 480.58 | 517.48 | 528.13 | 535.73 |
| 4-5 | 543.91 | 527.98 | 565.94 | 545.99 | 544.34 | 532.27 | 530.24 | 508.41 | 524.00 | 523.47 |
| 5-1 | 546.69 | 532.16 | 534.41 | 544.44 | 544.45 | | | | | |
| 5-2 | 526.85 | 520.02 | 557.86 | 555.31 | 562.18 | 541.01 | 541.63 | 531.59 | 508.26 | 532.03 |
| 5-3 | 536.82 | 509.83 | 539.71 | 542.55 | 555.81 | 518.12 | 518.33 | 510.09 | 510.88 | 509.90 |
| 5-4 | 523.71 | 519.16 | 536.07 | 544.76 | 512.13 | 505.75 | 498.22 | 475.55 | 479.10 | 496.73 |
| 5-5 | 536.64 | 517.41 | 546.94 | 544.19 | 555.62 | 535.64 | 477.49 | 494.33 | 506.47 | |
| mean† | 534.72 | 522.90 | 539.22 | 546.14 | 546.64 | 531.70 | 524.35 | 510.26 | 514.35 | 516.83 |

* The first number corresponds to the row number, while the second corresponds to the column number. Therefore, chip 2-4 was located in the 4th column of row 2.

† Only the 20 chips that survived all 10 runs are included in the mean values

For each run, the average exposure value was calculated using only those chips that survived all 10 runs. Each individual chip measurement was then compared to the average measurement for that run. The standard deviation was then calculated for each chip. To obtain a measure of chip repeatability, the mean of the standard deviations for each chip was calculated. These results are found in Table 4.1.2. The average standard deviation for all of the chips was found to be about 1.7%. This implies that if one were to repeatedly anneal, irradiate, and readout the same chip under controlled conditions, a standard deviation smaller than 1.7% could not be expected. It was also noted that over the course of the 10 runs, that the standard deviation of each run was found to increase by about 1%.

Table 4.1.2 Repeatability Test – Percent of Average Measured Exposure*.

| Chip | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Run 7 | Run 8 | Run 9 | Run 10 | Standard Deviation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1-1 | 0.9766 | 0.9905 | 0.9826 | 1.0110 | 0.9895 | 0.9771 | 1.0018 | 1.0100 | 1.0294 | 1.0168 | 1.80% |
| 1-2 | 0.9845 | 1.0112 | 0.9889 | 1.0134 | 1.0001 | 1.0060 | 1.0065 | 1.0280 | | | |
| 1-3 | 0.9546 | 0.9828 | 0.9575 | 0.9702 | 0.9724 | 0.9842 | 0.9761 | 0.9529 | 1.0081 | 1.0073 | 1.97% |
| 1-4 | 1.0004 | 0.9923 | 0.9726 | 0.9752 | 0.9790 | 0.9967 | 1.0006 | 0.9938 | 0.9788 | 0.9862 | 1.06% |
| 1-5 | 0.9668 | 0.9623 | | | | | | | | | |
| 2-1 | 0.9772 | 0.9886 | 0.9864 | 0.9773 | 0.9973 | 0.9870 | 0.9980 | 0.9959 | 1.0154 | 1.0139 | 1.33% |
| 2-2 | 1.0196 | 1.0281 | 0.9813 | 1.0280 | 1.0137 | 1.0311 | 1.0471 | 1.0258 | 0.9968 | 0.9876 | 2.10% |
| 2-3 | 1.0156 | 1.0043 | 0.9977 | 1.0100 | 0.9862 | 0.9941 | 1.0046 | 1.0040 | 0.9870 | 0.9803 | 1.13% |
| 2-4 | 0.9924 | 1.0103 | 1.0017 | 0.9860 | 1.0068 | 1.0030 | 0.9819 | 1.0007 | 1.0030 | 1.0157 | 1.05% |
| 2-5 | 1.0159 | 1.0045 | 1.0016 | 1.0118 | 1.0023 | 1.0068 | 1.0240 | 0.9905 | 1.0288 | 1.0222 | 1.19% |
| 3-1 | 1.0201 | 1.0259 | 1.0114 | 1.0076 | 1.0088 | 1.0089 | 1.0329 | 1.0516 | 1.0092 | 1.0113 | 1.44% |
| 3-2 | 0.9972 | 0.9888 | 1.0124 | 0.9779 | 0.9849 | 0.9738 | 0.9956 | 1.0003 | 0.9794 | 0.9882 | 1.18% |
| 3-3 | 1.0292 | 1.0349 | 1.0282 | 1.0509 | 1.0398 | 1.0580 | 1.0632 | 1.0518 | 1.0612 | 1.0602 | 1.36% |
| 3-4 | 0.9853 | 0.9758 | 0.9872 | 0.9946 | 1.0082 | 1.0075 | 1.0136 | 0.9923 | 0.9879 | 0.9077 | 3.00% |
| 3-5 | 0.9880 | 0.9861 | 0.9775 | 0.9740 | 0.9901 | 0.9727 | 0.9992 | 0.9475 | 0.9849 | 0.9829 | 1.40% |
| 4-1 | 1.0429 | 1.0211 | 1.0339 | 1.0349 | 1.0351 | 1.0420 | 0.9882 | 1.0737 | | | |
| 4-2 | 1.0241 | 1.0082 | 1.0109 | 0.9983 | 0.9998 | 1.0138 | 0.9742 | 1.0362 | 0.9768 | 0.9986 | 1.92% |
| 4-3 | 0.9936 | 1.0003 | 1.0023 | 0.9987 | 1.0178 | 1.0113 | 0.9877 | 0.9628 | 0.9949 | 0.9946 | 1.47% |
| 4-4 | 1.0244 | 1.0063 | 1.0094 | 1.0211 | 1.0256 | 1.0297 | 0.9165 | 1.0141 | 1.0268 | 1.0366 | 3.45% |
| 4-5 | 1.0172 | 1.0097 | 1.0495 | 0.9997 | 0.9958 | 1.0011 | 1.0112 | 0.9964 | 1.0188 | 1.0129 | 1.58% |
| 5-1 | 1.0224 | 1.0177 | 0.9911 | 0.9969 | 0.9960 | | | | | | |
| 5-2 | 0.9853 | 0.9945 | 1.0346 | 1.0168 | 1.0284 | 1.0175 | 1.0330 | 1.0418 | 0.9882 | 1.0294 | 2.06% |
| 5-3 | 1.0039 | 0.9750 | 1.0009 | 0.9934 | 1.0168 | 0.9745 | 0.9885 | 0.9997 | 0.9932 | 0.9866 | 1.30% |
| 5-4 | 0.9794 | 0.9928 | 0.9941 | 0.9975 | 0.9369 | 0.9512 | 0.9502 | 0.9320 | 0.9315 | 0.9611 | 2.64% |
| 5-5 | 1.0036 | 0.9895 | 1.0143 | 0.9964 | 1.0164 | 1.0074 | 0.9106 | 0.9688 | 0.9847 | | |
| average | | | | | | | | | | | 1.72% |
| St. Dev. | 2.03% | 1.66% | 2.18% | 2.05% | 2.28% | 2.46% | 3.29% | 3.29% | 2.69% | 3.15% | |

*The average measured exposure was calculated for each run and does not include chips that were broken any time during the 10 runs

## 4.2 Time between Anneal and Irradiation

A second type test was conducted to determine the effect of waiting different lengths of time between the annealing procedure and the irradiation. This test was performed at the Whitby HPL over the period of 5 working days. Twenty-five test chips were selected from the 1110-1119 mrem vials, and annealed. They were then irradiated in sets of 5, to 500 mR, at approximately 1, 2, 3, 6, and 25 hours following the annealing period. The chips were all read out approximately 24 hours after the final irradiation at 25 hours. A group sensitivity correction was applied by irradiating all groups together in the 300-chip holder and comparing the average of each group to the average of all the groups. The results are found in Table 4.2.1. Figure 4.2.1 shows the average measured exposure as a function of the time between the annealing period and the irradiations.

**Table 4.2.1: Time Between Anneal and Irradiation – Run 1 Results.**

| Time Between Anneal & Irradiation (hrs) | Uncorrected Average Measured Exposure (mR) | 2*Standard Error (mR) | Group Correction Factor | Corrected Average Measured Exposure (mR) |
|---|---|---|---|---|
| 1 | 539.62 | 6.08 | 0.994 | 542.77 |
| 2 | 551.04 | 10.48 | 1.004 | 548.87 |
| 3 | 554.22 | 7.08 | 0.981 | 564.75 |
| 6 | 556.11 | 13.85 | 1.011 | 550.12 |
| 25 | 527.72 | 17.78 | 1.010 | 522.70 |

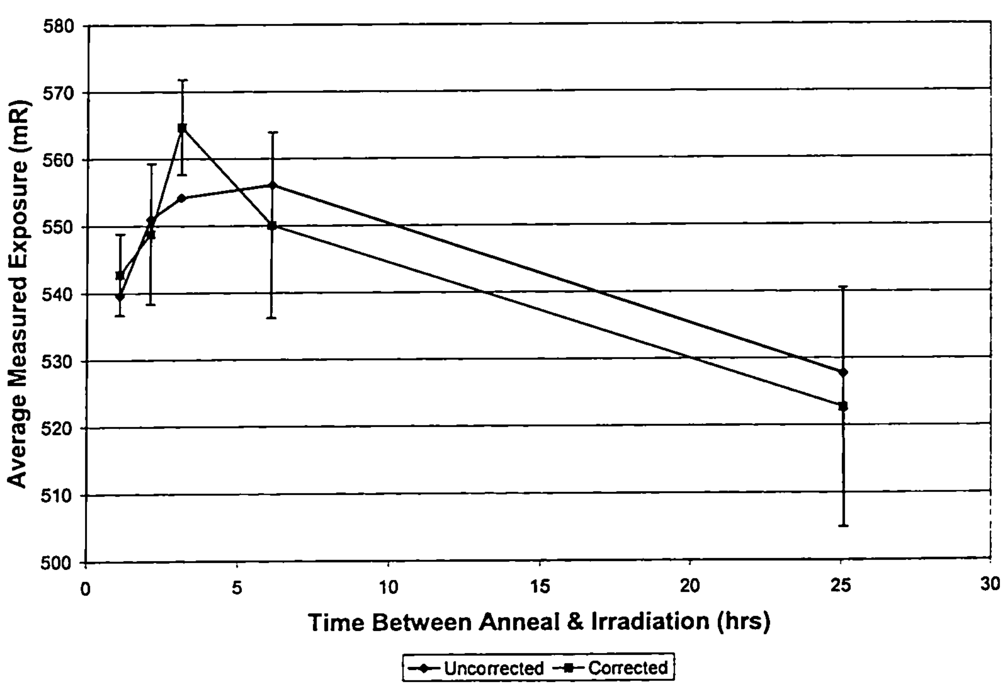


**Figure 4.2.1: Average Measured Exposure as a Function of the Time Elapsed Between the Annealing Period and the Irradiations – Run 1.**

Figure 4.2.1 failed to show the average measured exposure leveling off to a constant value. Since the goal of this test was to determine the minimum waiting time following the annealing period, the test was repeated. The test was repeated using an additional group irradiated at 49 hours after the annealing period. The results from the second run are shown in Table 4.2.2. Instead of a group sensitivity correction, as in run 1, each chip was corrected by its individual sensitivity. Figure 4.2.2 shows the average measured exposure as a function of the time between the annealing period and the irradiation. Just as in Figure 4.2.1, each corrected exposure is shown with 2 standard error bars, the 95% confidence level.

**Table 4.2.2: Time Between Anneal and Irradiation (including 49 hours) – Run 2 Results.**

| Time Between Anneal & Irradiation (hrs) | Uncorrected Average Measured Exposure (mR) | 2*Standard Error (mR) | Corrected Average Measured Exposure (mR) | 2*Standard Error (mR) |
|---|---|---|---|---|
| 1 | 475.11 | 6.52 | 470.99 | 11.23 |
| 2 | 482.85 | 11.82 | 477.27 | 15.11 |
| 3 | 475.64 | 10.11 | 486.20 | 14.14 |
| 6 | 478.19 | 23.35 | 477.37 | 24.73 |
| 25 | 476.42 | 14.79 | 467.92 | 5.53 |
| 49 | 466.33 | 13.33 | 476.25 | 7.45 |

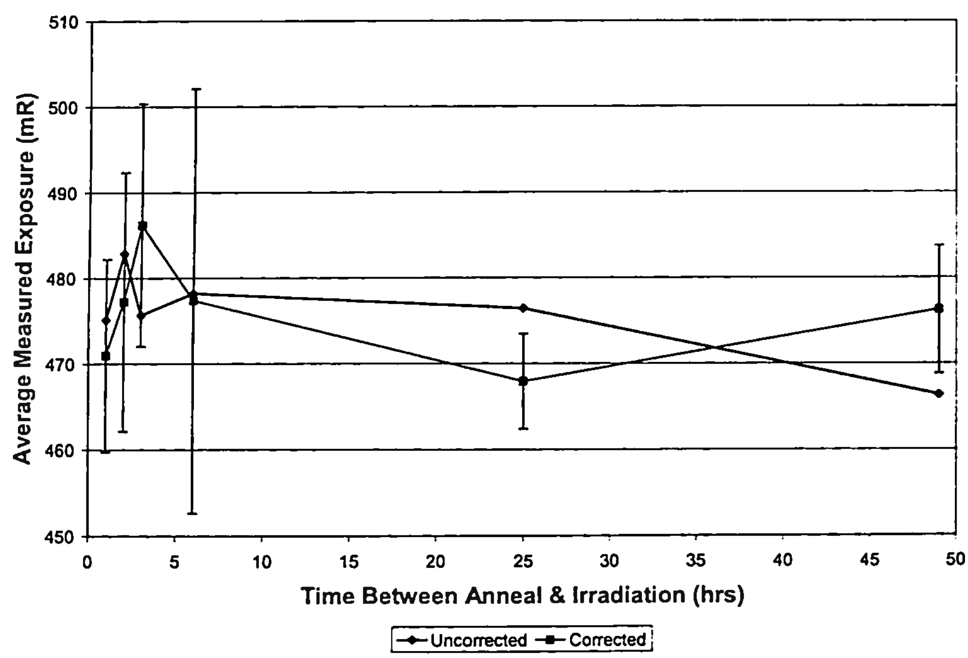


**Figure 4.2.2: Average Measured Exposure as a Function of the Time Elapsed Between the Annealing Period and the Irradiations – Run 2.**

The data from both the first and second run of this test is shown in Figure 4.2.3. Although the chips were chosen from different sensitivity groups, they exhibit a similar pattern up to 25 hours. Figure 4.2.2 shows that irradiations at 25 and 49 hours following the annealing period are in close agreement. This suggests that chips irradiated too soon after being annealed will experience erratic sensitivity variations. This is supported by the fact that chips irradiated within the first several hours following the anneal have a relatively large standard deviation. It is therefore recommended that a minimum period of 24 hours should elapse between the anneal and the irradiation. However, if only relative readings are required, as in the repeatability test, then this waiting time can be shortened to 6 hours.

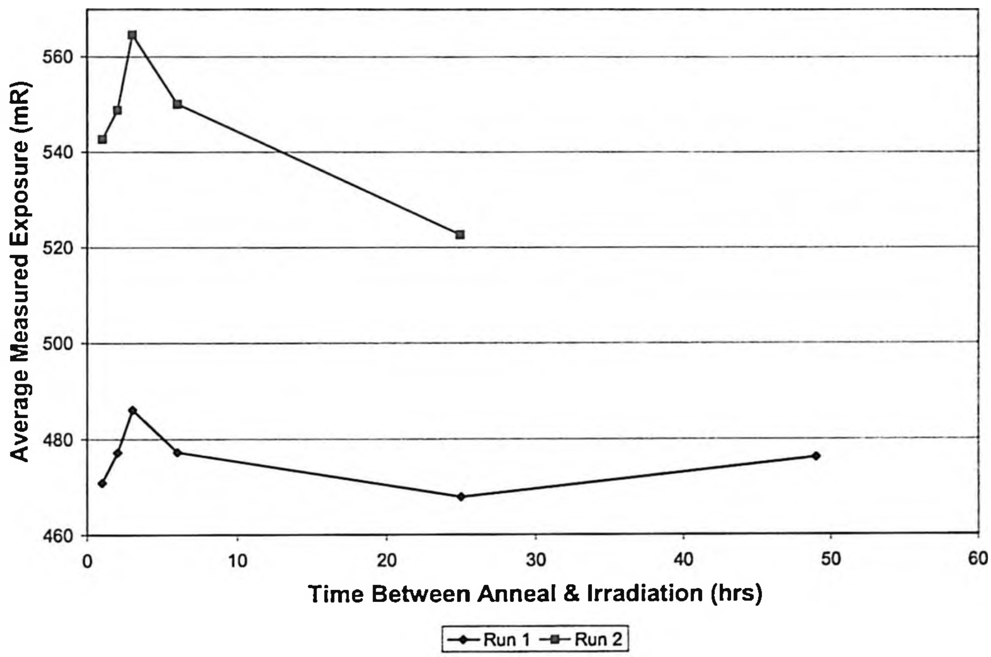


**Figure 4.2.3: Average Measured Exposure as a Function of the Time Elapsed Between the Annealing Period and the Irradiations – Both Runs.** Run 1 and run 2, chosen from different sensitivity groups, show the same trend.

## 4.3 7-Day Fade Test

The 7-day fade test was performed to determine how different lengths of time between the irradiation and the readout will affect the chip results. During a given period of time there is a certain probability of electrons and holes combining to release a photon. If this occurs between the irradiation and the readout, the photon will not be observed, and its contribution to the dose deposited in the chip will not be recorded. This effect is known as fading, and is critical for determining the appropriate length of time required between an irradiation and readout. Nine sets of five chips, pre-selected to have similar sensitivities, were irradiated at approximately 1, 2, 3, 6, 24, 48, 74, 145, and 168 hours prior to being read out. These chips were selected from the 1120-1129 mrem vials. The sets of 5 chips were annealed at 400°C for 1 hour, and then low-temperature annealed overnight. They were left for 24 hours, and then irradiated to 500 mR at the appropriate time prior to the readout. The results from this test are summarized in Table 4.3.1.

**Table 4.3.1: Time between Irradiation and Readout - Results.**

| Time Between Irradiation & Readout (Hrs) | Uncorrected Average Measured Exposure (mR) | Standard Deviation (mR) | Average Relative Response (Uncorrected) | Corrected Average Measured Exposure (mR) | Average Relative Response (Corrected) |
|---|---|---|---|---|---|
| 1 | 561.91 | 12.43 | 1.124 | 564.56 | 1.129 |
| 2 | 572.48 | 10.13 | 1.145 | 571.60 | 1.143 |
| 3 | 567.03 | 10.59 | 1.134 | 563.30 | 1.127 |
| 6 | 553.91 | 13.44 | 1.108 | 567.36 | 1.135 |
| 24 | 570.31 | 9.07 | 1.141 | 567.45 | 1.135 |
| 48 | 557.25 | 9.11 | 1.114 | 564.64 | 1.129 |
| 74 | 568.64 | 14.18 | 1.137 | 558.68 | 1.117 |
| 145 | 564.61 | 5.21 | 1.129 | 563.55 | 1.127 |
| 168 | 560.82 | 21.25 | 1.122 | 556.06 | 1.112 |

The average measured exposure as a function of the time between the irradiation and the readout is shown in Figure 4.3.1. A correction based on group sensitivity was obtained by irradiating each of the groups to 500 mR (in the 300-chip holder) and comparing the average of each group to the average for all the groups. This group correction factor was found to improve the value of $R^2$ significantly. Error bars are included with the corrected data and consist of two standard errors, the 95% confidence level.

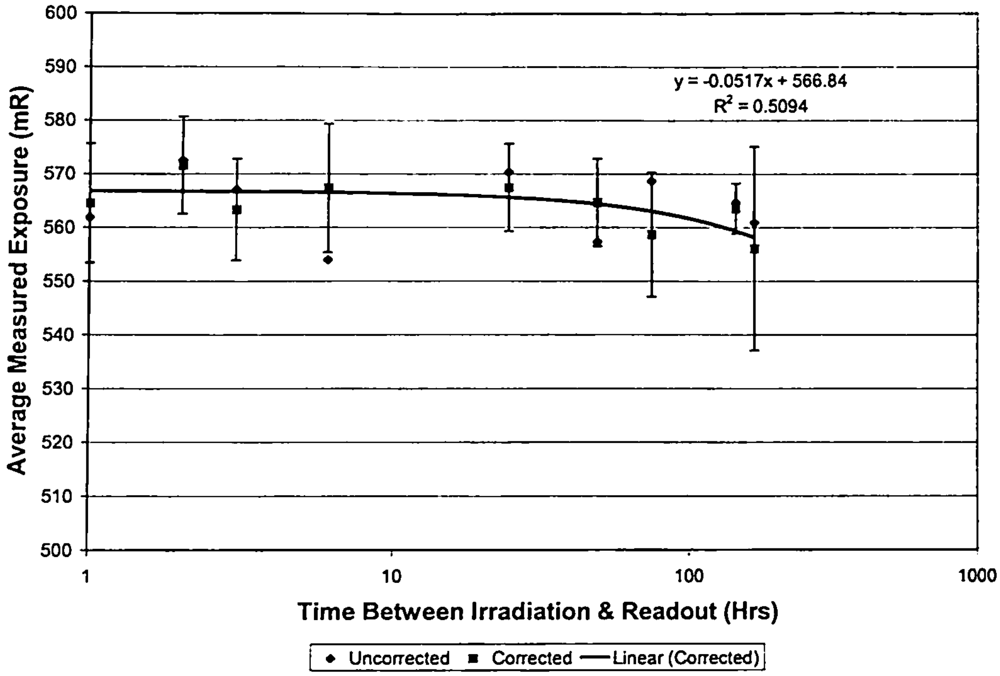


**Figure 4.3.1: Average Measured Exposure as a Function of the Time Elapsed Between the Irradiation and the Readout.** The curve in the linear trend line is caused by the use of a logarithmic scale for the x-axis.

The average relative response, plotted as a function of time between the irradiation and the readout, is illustrated in Figure 4.3.2. Although the two figures show the same trend, Figure 4.3.2 uses a linear x-axis as opposed to a logarithmic axis. Again, error bars have been included on the corrected data.

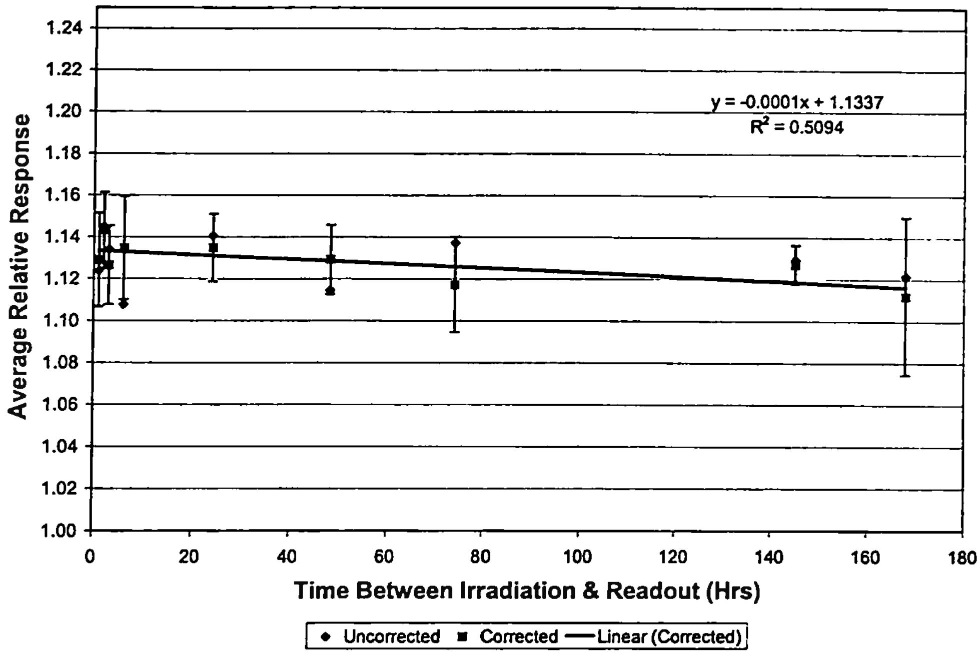


**Figure 4.3.2: Average Relative Response as a Function of the Time Elapsed Between the Irradiation and the Readout**

From the two figures, a slight fading effect is apparent. Using linear regression techniques, the slope of the trend-line was determined to be statistically different from 0. Using the equation of the best-fit line the fading rate was calculated to be 1.5% per week. This illustrates how over time, some of the trapped electrons/holes will recombine and release an unobserved photon. This could lead to a small underestimate of the dose received by the worker if the calibration chips were exposed after the worker was exposed. The results of this test indicate that in order to reduce fading, chips should not be left for an extended period of time before being read out.

# Chapter 5

# Summary & Conclusions

About 1000 field chips and 900 new chips were irradiated to 500 mR in 7 batches. The chips were put into vials corresponding to intervals of 10 mrem out of a nominal 1000 mrem (eg. 970-979, 980-989, etc.). It was found that the average measured dose did not remain constant over the 7 batches, and this was attributed to a time-varying RCF (reader calibration factor). Correcting each batch by the RCF at the time it was read out was found to correct this problem, and the vials from batches 4 -7 were consequently relabeled. The goal of this sensitivity separation was to obtain a set of chips whose sensitivity matched the average sensitivity of the field chips, and which will be used in the future to calibrate the reader. Chips found to have a higher or lower than average sensitivity were kept aside and used for various tests where only a matching relative sensitivity was of importance.

QA tests have been consistently low (-5 to -15%) since about the first quarter of 1997. This persistently low bias triggered a special investigation to identify the sources of the bias. The first special test, performed in November 2004, identified one factor which was contributing to the bias, but did not entirely account for it. A second special test, performed in April 2005, identified several other factors contributing to the bias. The test program found the following four factors to be the major contributors to the QA bias.

1) The TLD material, LiF:Mg,Ti, is less sensitive to the $^{60}$Co source used for the NRCC test irradiations than to the $^{137}$Cs source used for calibrating the extremity TLD readers at Whitby, contributing about 2.4% to the negative bias.

2) The field chips for the NRCC test are less sensitive than the calibration chips. A preliminary measurement showed the calibration chips to be about 3.7% less sensitive than the field chips.

3) Up to and including the Q1 2005 QA test, the exposure rate standard for Extremity TLDs had been updated at the NRCC, but not at the Whitby HPL. Before February 12, 2004, this contributed a negative bias of about -2.3%, and from this time on a negative bias of 0.3%.

4) Irradiations done at the NRCC and at the Whitby HPL use different chip holders. The holder affects the amount of dose absorbed by the chips, because of attenuation in the front wall and scattering from material around the chips. The scatter correction factor used for the 280-chip holder at Whitby understates the actual exposure delivered to the calibration chips by about 3%.

Due to the somewhat poor condition of OPG's current bulk holder (280-chips), it was desired that a new chip holder be introduced for use in quality assurance and type testing. Before entering a new chip holder into service, its response and scattering characteristics must be determined. The prospective new holder, holding 10 rows of 30 chips, was filled with chips and irradiated to 500 mR. The chips were chosen to have similar sensitivities. The average measured dose across each row and down each column were both plotted and revealed what appeared to be a decreasing response across the holder from left to right. It was determined that the trend was not due to an error in the positioning of the holder, and therefore was attributed to differing chip sensitivities. An individual chip sensitivity correction was performed to correct this left to right trend across the holder. This correction was found to significantly flatten the response across row 1 and row 10, which were therefore thought to be the source of the left to right trend. The tests performed on this holder show that a chip positioned anywhere in the holder will agree with any other chip to within 2 standard errors at the 95% confidence level.

At OPG and the NRCC, chips are irradiated in various chips holders. Chip holders of different size and shape create various amounts of scattering, which must be quantified in order to accurately evaluate the delivered dose. Shortt et al. (1996, 1997) and Davis et al. (2003) investigated the effects of front, rear, and radial wall thickness. The Monte Carlo N-Particle (MCNP) program was used to confirm the results reported by Shortt and Davis. MCNP was also used, along with experimental tests, to determine the relative amounts of scattering between the various holders. A single chip, positioned at 1 m from the source and surrounded by 2 mm of Lucite to obtain charged particle equilibrium, was used to test the effects of separately increasing the front, rear, and radial wall thickness. The results are found in Figure 3.4.3, and agree very well with the results reported by Shortt and Davis. Another MCNP simulation was performed to determine the rear and radial wall thicknesses where the addition of more material has no effect. A maximum response was produced for rear and radial wall thicknesses of 25 mm and 60 mm, respectively. Increasing the rear wall was found to have a much smaller effect on the chip response than increasing the radial wall. MCNP was also used to determine the relative response of the various chip holders. A final Monte Carlo simulation was conducted to determine the effect of increasing rear wall thickness on response for 3 different radii. It was already determined that increasing the rear wall thickness increased the response of the chip, and this effect became more pronounced as the radius around the chip was increased. This effect was again due to increased scattering. More material around the chip served to scatter the already backscattered photons towards the chip, which would otherwise miss the target.

Experimental tests, performed at the Whitby HPL, compared the response of the 4 different chip holders: the NRCC's lollipop, the 25-chip holder, OPG's old bulk holder (280-chips), and OPG's new bulk holder (300-chips). Experimental results were obtained by filling the holders with chips and comparing the average measured exposures for each holder. These results were then compared to the results that were generated using MCNP (Table 3.4.3). It was found that the experimental results agreed very well with the results obtained using MCNP. The biggest discrepancy was noted in the old bulk holder (280-chips). Compared to the lollipop holder, the 280-holder was found to have a 2.5% increase using MCNP, and a 3.3% increase determined experimentally. Section 3.2, however, identified this factor to be 2.3%, which is in much closer agreement to the Monte Carlo results. Because the two experimental tests yielded results of 2.3 and 3.3%, the Monte Carlo result, which falls within this range, should be used to account for the extra scattering created by the 280-chip holder.

The remainder of the report focused on the type testing of the current extremity TLD system. These type tests examined the repeatability of the TLD process, the waiting time required following the annealing period, and the 7-day fade rate.

The repeatability test was performed to determine how close two measurements of the same chip can be made under identical conditions. Twenty-five chips were repeatedly annealed, irradiated, and read out. The average relative standard deviation for all the chips over the 10 runs was found to be 1.7%.

The goal of the second type test was to identify the minimum waiting time following the annealing period. Chips irradiated too soon after being annealed experience an unpredictable sensitivity variation. This test was repeated twice, because the first run failed to identify the minimum waiting period. The second run extended the time for another 24 hours, and it was found that the reading at 48 hours was in close agreement to the reading at 24 hours. This served to identify the minimum waiting period following the annealing period as 24 hours. However, for tests only concerned with a relative reading, only a 6 hour waiting period was deemed necessary.

The third type test looked at the fade rate over a 7-day period. Groups of chips were irradiated at various times prior to being read out. A plot of the average measured exposure as a function of time between the irradiation and the readout showed a decreasing average measured exposure with time. This decrease in the average measured exposure over time represents the fading of a signal from the chip, and is a result of the recombination of electrons and holes. Using the equation of the trend-line, the fade rate was calculated to be 1.5% per week for the first week. Due to time constraints a longer fade test was not performed, but is strongly recommended.

# Glossary

**Absorbed Dose (D)** The energy imparted per unit mass by ionizing radiation to matter at a specific point. The SI unit of absorbed dose is joule per kilogram (J/Kg). The special unit of absorbed dose is gray (Gy). The previously used special unit of absorbed dose, the rad, was defined to be an energy absorption of 100 erg/g. Thus, 1 Gy = 100 rad.

**Committed Dose** The effective dose in an individual that will be accumulated during the fifty years following an intake of radioactive material into the body.

**Charged Particle Equilibrium** The condition existing at a point within a medium under irradiation, when, for every charged particle leaving a volume element surrounding the point, another particle of the same kind and energy enters.

**Effective Dose (E)** The radiation dose allowing for the fact that some types of radiation are more damaging than others and some parts of the body are more sensitive to radiation than others. It is defined as the sum over specified tissues of the products of the equivalent dose in a tissue and the weighting factor for that tissue.

**Equivalent Dose (H)** A quantity used for radiation-protection purposes that takes into account the different probability of effects which occur with the same absorbed dose delivered by radiations with different radiation weighting factors. It is defined as the product of the average absorbed dose in a specified organ or tissue and the radiation weighting values. If dose is in grays, equivalent dose is in sieverts (Sv).

**Kerma** The sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles per unit mass of a specified material. Kerma is measured in the same unit as absorbed dose. The SI unit of kerma is joule per kilogram, and its special name is gray (Gy). Kerma can be quoted for any specified material at a point in free space or in an absorbing medium.

**Personal Dose Equivalent $H_p(d)$** The dose equivalent in soft tissue, at an appropriate depth, d, below a specified point on the body, measured in sieverts (Sv). The reference depths, specified in millimeters, are 0.07 mm for weakly penetrating radiation and 10 mm for strongly penetrating radiations.

**Thermoluminescence** The process where electron/hole pairs are formed by exposure to ionizing radiation and become trapped at specific trapping centers, created by impurities in the crystal. When the crystal is heated, the electron and holes are provided with enough energy to escape their respective traps, recombine, and emit a photon.

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