Type Testing Of LiF:Mg,Cu,P Extremity TLD system at OPG

1. Introduction

Ontario Power Generation (OPG) is an electricity generation company whose principal business is the generation and sale of electricity in the province of Ontario. OPG is one of the largest power generators in North America, with a total capacity of over 22,000 megawatts (MW). OPG owns and operates a variety of generating stations including; several fossil stations, many hydroelectric stations, and two operating nuclear stations. The nuclear stations are located on the shores of Lake Ontario, and comprise the Pickering Nuclear Generating Station and the Darlington Nuclear Generating Station, with plans for new build at Darlington.

The Canadian Nuclear Safety Commission (CNSC) regulates the use of nuclear energy and materials to ensure safety, security, protection of health and the environment. The CNSC licenses OPG's nuclear facilities through the Nuclear Safety and Control Act (NSCA). The operation of nuclear power stations will result in the occupational radiation exposures to some OPG employees. These exposures could potentially lead to adverse biological effects, so a Radiation Protection Program is required to ensure doses received by the employees are controlled. An important part of the Radiation Protection Program is a radiation dosimetry program. OPG's dosimetry program measures both doses from sources outside of the body (external dosimetry) and doses from radioactive material taken into the body (internal dosimetry). Both dosimetry systems must be licensed by the CNSC. OPG operates its own dosimetry service primarily at the Whitby Health Physics Laboratory (HPL).

A personal thermoluminescent dosimeter (TLD) or TLD badge is used to measure the whole body dose from photon and beta radiation sources external to the body. Under circumstances where the employee may be expected to receive a large dose to the hands or feet, extremity TLDs are worn in addition to the whole body TLD to measure the extremity dose.

Technical requirements and quality assurance measures must be met for licensed dosimetry services in Canada. These requirements are specified in the regulatory standard, "Technical and Quality Assurance Standards for Dosimetry Services in Canada, S-106 Revision 1" [AECB, 1998]. An international standard from the International Electrotechnical Commission (IEC), "Thermoluminescence Dosimetry Systems for Personal and Environmental Monitoring, IEC 61066 Second edition" provides some specific guidance on how the type testing can be done [CEI/IEC 61006, 2006]. The guidelines given in IEC 61066 are guidelines for testing that do not have to be followed exactly, as long as the requirements set out by S-106 are met.

OPG's current extremity TLD chip system is barely able the meet the requirements set out by S-106 because of a poor beta response, and does not accurately measure the skin dose to the extremities. The new system being investigated uses a different kind of TLD

to measure extremity dose. These new TLD dosimeters are called EXTRADs and are based on a different type of TL material which has many advantages over the current system. Several advantages of the new system include: greater sensitivity, individually bar-coded dosimeter elements, negligible fading, and good response to beta radiation.

The purpose of this project is to perform, analyze and document type test for OPG's planned Extremity TLD (EXTRAD) system, and determine whether the system meets the accuracy and precision requirements specified in S-106. Although the research project was completed in cooperation with OPG, the results of these experiments have a broader impact. The EXTRAD program could be initiated in other nuclear facilities, such as Bruce Power, and Atomic Energy of Canada.

2. Extremity Dosimetry

Extremity dosimeters are used to estimate the surface dose to the hands and feet. The ICRP dose limit to the hands is 500 mSv/year (50 rem/year), while the whole body dose limit for a radiation worker is 20 mSv/year (2 rem/year) averaged over 5 years, with a maximum of 50 mSv in one year [ICRP, 2007]. The goal of extremity dosimetry is to accurately record doses to the extremities so that the total extremity dose does not exceed the limit.

For the extremity dosimeter to be effective, it must be securely attached to fingers and be protected from direct contact with the fingers and sweat. In the current extremity dosimeter system, white square in the following figure, the packaging consists of heat sealing the LiF:Mg,Ti crystal inside a plastic sachet which is then taped to an extremity using surgical tape. The chips are packed in an envelope with a bar code on it identify the extremity TLD pack number. To read each dosimeter is a labour intensive process that requires a lot of time for a large number of extremity dosimeters. The EXTRAD TLD chipstrate is composed of LiF: Mg, Cu, and P, crystalline powder with a density thickness of 7 mg/cm^2, in an area of 18 mm^2, located near one end of a thin Kapton™ film, along with a barcode and identification number, and is shown following figure 1. EXTRAD chips are loaded, two at a time referred to as Elements 2 and 3, into carrier cards. Up to 1400 of these carrier cards can be loaded into the automated reader, which heats the chipstrates, reads the signal, anneals the chipstrate, and unloads chipstrate without constant human input.

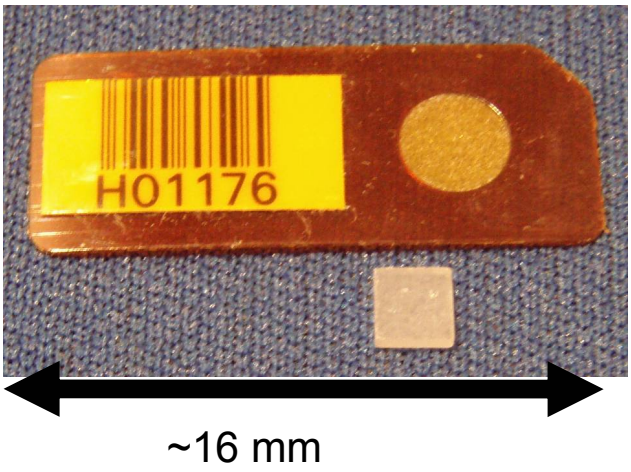

Figure 1 EXTRAD Chipstrate (above) and Current Extremity Chip (below)

The chipstrate dosimeters must also be protected by some sort of plastic pouch and have some mechanism of attachment to the finger. There were several different packaging designs considered for the EXTRAD dosimeters; the designs that underwent type testing are shown in the figure below. All of the designs involve sealing the chipstrate inside thin plastic to protect it from the environment but not thick enough to significantly attenuate beta radiation. Each packaging design has a slightly different mechanism to attach the dosimeter to the finger. The dosimeters shown in figure 2 are the dosimeter elements inside four modifications of the protective packaging. The decision on which type will be chosen depends on a number of factors, such as user acceptability, ruggedness, ease of handling by lab personnel, etc.

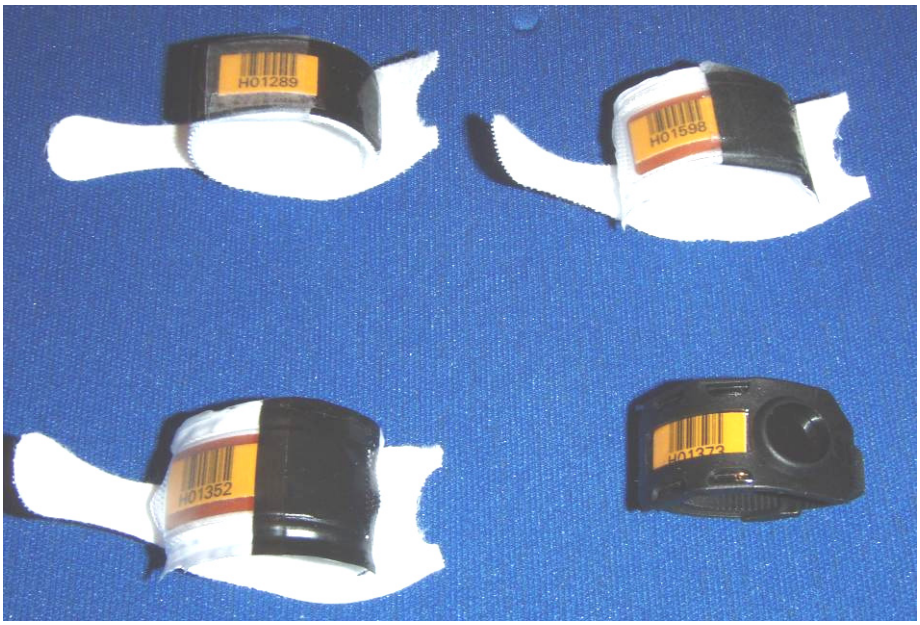

Figure 2 Chipstrate Packaging Designs

Top left is the TLD pouch taped to a Qwik-Tie Velcro strap, bottom left is the TLD sachet heat sealed to the same Qwik-Tie Velcro strap. Top right is the same TLD sachet and Qwik-Tie with tape over the TL portion, and the bottom right is the TLD pouch with the finger strap. The chipstrate together with packaging is referred to as an EXTRAD. Many other designs were considered in the early stages of EXT-RAD program but were rejected for various reasons.

3. Type Testing

Type testing is the thorough investigation of the characteristics of a type of instrument or dosimeter. The testing includes the dosimeter's responses to photons and beta particles for various energies, and angles of incidence as well as the dependence of the whole measurement system on other influence quantities [IRCU, 1988]. The purpose of type testing of a dosimetry system is to identify all potential sources of error and uncertainty in the dose measurement, and to quantify those error and uncertainties that may contribute significantly to the overall error or combined standard uncertainty [Hirning and Yuen, 1998].

Technical requirements and quality assurance measures must be met for licensed dosimetry services in Canada. These requirements are specified in the document, "Technical and Quality Assurance Standards for Dosimetry Services", CNSC regulatory standard S-106 Revision 1 [CNSC, 2006]. S-106 specifies the minimum requirements that must be met by the licensed dosimetry service before a system can be employed to test workers. S-106 specifies the requirements for three basic types of dosimetry: external dosimetry, internal dosimetry, and measurement of radioactive atmospheres. The purpose of the testing is to identify and quantify all the potential sources of error and uncertainty in the dose measurement and to ensure that the performance is within limits specified in S-106 Rev 1 [AECB, 1998].

The type tests are described in International Electrotechnical Commission (EIC) standard 61066, "Thermoluminescence dosimetry systems for personal and environmental monitoring" [EIC 2006]. This standard provides detailed guidelines and procedures to test all of the influence quantities that are known to affect the response and that are required by the CNSC regulations for the dosimetry system. EIC 61066 describes possible type testing procedures and gives limits for the test results, but the type tests in EIC 61006 are designed to test the dosimetry system performance and error limits for each test separately. However, S-106 allows the dosimetry service to have a very poor result with a low probability. What matters is that the overall accuracy and precision are acceptable. A summary of the influence quantities and system characteristics that were considered in this project are provided in the following tables 1 and 2.

Table 1 Influence Quantities

Influence Quantity	Description
Energy and angle of photon radiation	The dosimeter response to photon radiation should be measured as a function of energy as well as angle of radiation.
Energy and angle of beta radiation	The dosimeter response to beta radiation should be measured as a function of energy as well as angle of radiation.
Fading	Long-term and short-term fading should be considered with TLDs. If there is a significant time interval between irradiation and readout, signal fading could occur. There could also be pre-irradiation loss of sensitivity that occurs between annealing and irradiating TLD dosimeters.
Dose response linearity	The linearity of dose response is tested by irradiating dosimeters to different exposures (i.e., 10 mR to 1000 R). The response is expected to be linear over the range of occupational exposures.
Temperature and humidity	Environmental conditions such as heat and humidity could have a significant effect on the response of the dosimeter.
Light	The sensitivity of dosimeters to light should be measured in type testing.
Loss of Sensitivity	The sensitivity of the dosimeters should be tested at the beginning and then again later after multiple anneal, irradiate, and read cycles. The sensitivity should remain the same.
Water Immersion	The sensitivity of the dosimeter to immersion under water should be measure in type testing.
Mechanical Performance	The sensitivity of the dosimeter to dropping on a hard surface should be measured in type testing.
Self-irradiation	The irradiation of a dosimeter due to radioactive impurities in the dosimeter itself has been observed in TL materials. This effect should be tested.

Table 2 System Characteristics

System Characteristic	Description
Detection Limit	The detection limit should be calculated for the dosimetry system.
Reproducibility	This influence quantity is a measure of the stability of response of both the dosimeter and the reader. In type testing, dosimeters that have been prepared and read are prepared in the same way and read again many times to observe how well the measurements can be reproduced.
Batch homogeneity	The measured responses of a collection of dosimeters should be compared.
Homogeneity of calibration chips	The calibration uncertainty can be estimated using the distribution of calibration dosimeter readings.
Uncertainty in System Calibration	The uncertainties in the calibration of the NE Technology ionization chamber and Doseleader electrometer by the National Research Council Canada (NRCC), and the calibration of the exposure facility itself at the HPL.
Residual Signal	The residual signal remaining in the dosimeter should be tested after the dosimeters are irradiated to different exposures (i.e., 10 mR to 1000 R).

3.1. Accuracy and Precision Requirements Specified in S-106

The response, R, of the dosimeter is defined as the result of the dose measured under specified conditions, $H_m(d)$, divided by the conventionally true dose that would have been received under those conditions, $H_c(d)$. $H_m(d)$ is the measured value, usually the mean of a series of replicated values or repeated experiments.

$$R = \frac{H_m(d)}{H_c(d)}$$

The response is a product of the response under reference conditions, R_0, and the relative response to each influence quantity, r_i.

$$R = R_0 r_1 r_2 \mathrm{K}\ r_n = R_0 \prod_{i=1}^{n} r_i$$

The mean response of a dosimeter influence quantity is the product of the response for each influence quantity, $R(x_1, x_2, \ldots x_n)$, and the probability density function, $p(x_1, x_2, \ldots x_n)$, for the set of influence quantities. There are n influence quantities, r_1, r_2, and r_n, representing relative response values for each influence quantity.

$$\overline{R} = \int R(x_1, x_2, \mathrm{K}\ x_n)\, p(x_1, x_2, \mathrm{K}\ x_n)\, dx_1 dx_2 \mathrm{K}\, dx_n$$

Now the overall requirement for accuracy and precision is given in the S-106 document, and can be calculated using the following expression:

$$\frac{1}{\rho} \le \overline{R} \pm 2u_c \le \rho$$

where

$$\rho = 3 \ for\ d = 0.07 \quad and \quad 100\ mSv \le H_c(0.07) \le 10\ Sv$$
$$\rho = 3 \ for\ d = 0.07 \quad and \quad H_c(0.07) = 10\ mSv$$

where d is the depth in tissue which the dose is intended to measure.
For extremity dosimeters, all doses between 10 mSv and 10,000 mSv (1 rem to 1,000 rem), the limit on the response combined with the standard uncertainty is:

$\overline{R} - 2u_c \ge 0.33\ and\ \overline{R} + 2u_c \le 3$.

4. Results

Type Testing was performed for the new EXTRAD extremity TLD system at OPG. Experiments were performed to test the effect of various influence quantities on dosimeter response and the detection limit was calculated for both reading elements. System characteristics contributing to the standard uncertainty of the TLD system were also studied. Several other tests were also performed on the new TLD system. The

overall accuracy and precision of the new extremity TLD system at OPG was determined to see if meets the CNSC requirements specified in S-106.

The detection limit was calculated for Elements 2 and 3 separately, with different test, background, control, and calibration chipstrates used for each test. For each test the reader was calibrated to read 10 background chipstrates and 10 test chipstrates for each element. Irradiations were performed with either the Cs-137 HPL irradiation facility or the Sr-90 internal irradiator. The detection limit was found to be 0.931 and 1.22 mR for Elements 2 and 3, respectively. The determination limit was also calculated, with values of 2.41 and 3.33 mR for Elements 2 and 3, respectively.

For beta energy and angle of radiation, TLDs were irradiated with three sources of beta radiation Sr/Y-90, Kr-85, and Pm-147; and at five angles 0°, 30° vertical, 30° horizontal, 60° vertical, and 60° horizontal. The chipstrates were packaged into one of the four holders and irradiated on a finger phantom. The response decreased significantly with decreasing beta energy; this was most evident with the TLD Sachet with the tape. The response also decreased with increasing angle, with the TLD Pouch on the Strap showing the greatest decrease. The mean relative responses calculated are 1.03 ± 0.09, 1.01 ± 0.18, 1.09 ± 0.07, and 1.10 ± 0.14, for the TLD Sachet without tape, TLD Sachet with tape, TLD Pouch on Velcro, and the TLD Pouch with Strap, respectively.

The linearity test was performed with irradiations at the Whitby HPL and at the Darlington irradiation facility. The test confirmed the current literature that the LiF:Mg,Cu,P chipstrates have a flat response up to exposures of 200 R. Superlinearity was seen at the higher exposures but this was most likely due to over-response in the PMTs. The mean relative response was calculated to be 0.992 ± 0.002.

The effect of self irradiation was tested by placing the chipstrates in the TLD Pouch, TLD sachet, and bare carrier cards, into a lead safe with an EPD for 30 days. The mean relative response was calculated to be 0.958 ± 0.08 and 1.009 ± 0.02 for the TLD sachet and TLD Pouch.

The effect of pre-irradiation and post-irradiation fading was tested on the chipstrates by varying the time between chipstrate annealing, irradiation, and reading. The duration of fading was varied from one hour in short term fading to four months in the long term fading. The mean relative response was calculated to be 1.027 ± 0.016 for the chipstrates.

The residual signal was tested on the chipstrates to examine the signal remaining on the chipstrates after they have been readout. This effect had been observed early on in the type testing process, which is why the chipstrates were routinely annealed three times before testing. It was determined that for exposures of 10 R and above the chipstrates would have to be retired from use due to the signal remaining on the chipstrate.

Chipstrates were read over one hundred times and irradiated ten times to see if there would be any loss of sensitivity of the chipstrates. After the hundred read and irradiation

cycles, a small reduction of 3.0 and 2.0%, was observed for Elements 2 and 3, respectively. However, the element correction coefficient (ECC) values are used to account for the differences between chipstrates, so by generating new ECC values for the chipstrates the readings will remain accurate. In normal situations, aside from type testing, the chipstrates are unlikely to be read a hundred times in a short period of time. So if the chipstrates receive new ECC values every few years, the loss of sensitivity will not contribute significantly to the doses measured.

The combined mean response and combined standard uncertainty were calculated to determine the performance of the new extremity TLD system at OPG. The IEC 61066 standard lists several other type tests that can be done, including the effect of electromagnetic fields however, our past operating experience and the design of the readers have identified that this is unimportant, and are not required by the S-106 regulations.

The greatest contributors to the combined standard uncertainty were the influence quantities of beta energy and angle response, with and 18%. Beta energy and angle response were also the greatest contributors to the combined mean response being different from 1.0. The mean relative responses were calculated for the beta energy and angle response for the four packaging types. The rest of the influence factors that were considered had very little significance to the overall calculation of the mean response and combined standard uncertainty. The uncertainty due to random errors was measured in the tests for batch homogeneity, calibration chipstrate homogeneity, and reproducibility.

5. Conclusions

The uncertainty for the system characteristics was combined with the estimated system uncertainty to result in the combined standard coefficient of variation. The calculated responses are; $1.12 \pm 15\%$, $1.09 \pm 21\%$, $1.21 \pm 11\%$, and $1.22 \pm 15\%$, for the beta energy and angle response in the TLD Sachet without tape, the TLD Sachet with tape, the TLD pouch on Velcro, and the TLD Pouch in the Strap, respectively. The overall response for the beta meets the requirement specified in the S-106 because the combined mean response falls between the range 1/3 and 3. All of the packaging types tested meet the S-106 requirements.

6. References

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ICRU, 1988. Determination of Dose Equivalents from External Radiation Sources – Part 2, International Commission on Radiation Units and Measurements Report 43, ICRU, Bethesda.

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Atomic Energy Control Board, Regulatory Standard S106, Technical and Quality Assurance Standard for Dosimetry Service in Canada, 1998