Development of the Mini-Ionization Chamber for High-Dose Real-Time Monitoring Inside a Gamma Irradiation Facility

Ary de A. Rodrigues, Jose M. Vieira, and Margarida M. Hamada

***Abstract*—A cylindrical ionization chamber of 0.9 cm^3 has been developed for high-doses real-time monitoring during the sample irradiation at a static position in a ^{60}Co gamma industrial plant, with about 25.9 PBq (700 kCi). Nitrogen gas at pressure of 1 bar was utilized to fill the ionization chamber for which an appropriate configuration was determined, to be used as a detector for high-dose measurements. The first detector tests were carried out using a ^{60}Co Gammacell with about 0.26PBq (7 kCi) and dose rates of 0.6, 1.8, and 2.6 kGy/h. These dose rates were reached with lead absorbers. A good linearity of the detector was found between dose and accumulated charge, independently of the different dose rates. The developed ionization chamber was suitable to be used as a real-time dosimeter for dose rates between 0.6 to 2.6 kGy/h at a ^{60}Co gammacell, independently of the spectrum degradation caused by absorbers between 50%–90%.**

***Index Terms*—Dose-rate monitor, high dose, ionization chamber, real-time monitoring.**

I. Introduction

GAMMA irradiation facilities are designed for processing large amounts of products, which are exposed to large dose of a gamma radiation, on an industrial plant [1], [2]. The irradiation, in industrial scale, is usually carried out in dynamic form, where the products are put inside containers and pass around a gamma source with activity of TBq to PBq (kCi to MCi). The dose is estimated as being directly proportional to the time that the products spend to go past the source. Fig. 1 shows an example of industrial gamma irradiator.

However, in some situations, mainly for research and process validation purposes, it is required to irradiate small samples, in the static position, with lower and more accurate doses than those used in dynamic irradiation. At the EMBRARAD Company, Cotia, Brazil, most of the irradiation in the static position are of products from health care companies, which need to validate their sterilization process according to ISO 11 137 international standard [3]. This norm recommends three validation methods, classified as: method 1, method 2A, and method 2B. Method 1 requires a verification dose not higher than 10% or at least 90% of the target dose. Method 2A requires the irradiation of samples in series of not less than nine doses, increasing in nominal increments of 2 kGy. The doses shall be delivered independently and may vary at random from the nominal dose by ± 1.0 kGy or $\pm 10\%$, whichever is greater. The method 2B is the strictest, requiring to irradiate samples in a series of at least eight doses with nominal increments of 1 kGy. The doses shall be delivered independently and may vary at random from the nominal dose by ± 0.5 kGy or $\pm 10\%$, whichever is greater, with exception that at 1.0 kGy the dose may vary by only ± 0.2 kGy [3]. These doses can be delivered by irradiating samples at a static position inside the irradiation room of a panoramic gamma irradiator.

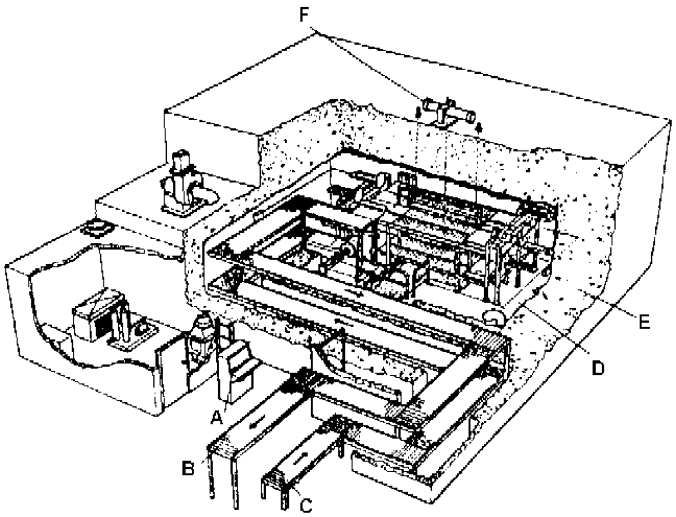

Fig. 1. JS 7500 MDS Nordion gamma irradiator. A: control panel. B: outlet conveyor. C: inlet conveyor. D: irradiation room. E: biological shield. F: source hoist mechanism.

Nowadays, for static position irradiation, the samples are put inside the irradiation room at a fixed distance from the source and the dose is usually determined using dosimeters [2]. The exposure time for a sample in these conditions can be estimated dividing the target dose by the average dose rate in that position [2], [4]–[7]. The dose is only known after the irradiation, reading the dosimeter. However, containers usually with different kinds of products and different densities cross the sample in the static irradiation position and the radioactive source, as shown in Fig. 2. So, the dose rate varies in function of the product density that passes between the static position samples and the source.

At least two dosimeters are used for the static irradiation. One dosimeter is read when the exposure time calculated is finished.

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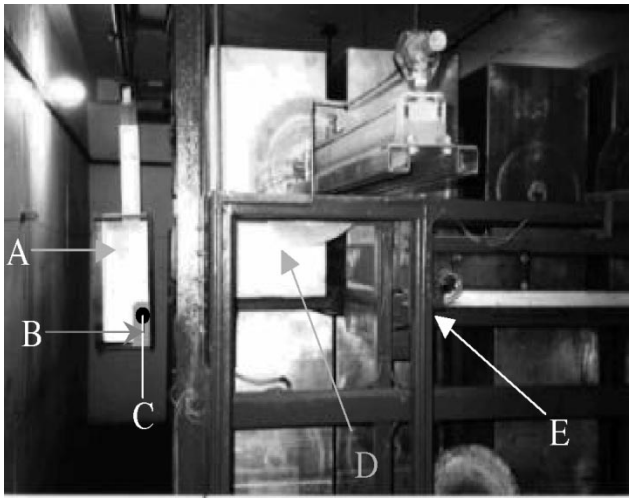

Fig. 2. JS 7500 irradiator static irradiation position. A: sample holder. B: hypotetic ionization chamber. C: sample. D: containers. E: ^{60}Co source irradiation position.

However, if the target dose is not reached, a new irradiation is carried out. The new exposure time (T_{NE}) will be the result of the target dose value (D_T) minus the last dosimeter dose (D_L) divided by the last dose value (D_L) divided by its exposure time (T_E), as shown in $T_{NE} = (D_T - D_L)/D_L/T_E$. It is repeated until the target dose is reached. Sometimes, the dose rate can increase unexpectedly and the delivery dose will be higher than the target dose. A suitable methodology would be to monitor the dose in real-time, measuring the dose on line with a radiation detector, which would improve the dose accuracy and avoid that the required dose be exceeded.

Typical dose rate monitors are devices that produce an electrical current proportional to the applied dose rate. For medical applications such as radiotherapy, where the total accumulated dose is low, semiconductor detectors are commonly used for dose rate measurements. However, radiation damages, both transient and permanent, preclude their use in industrial applications, where lifetime doses of several megagray may be received [1], [2], [8], [9]. For this kind of application, self-powder gamma detectors (SPGD) and ionization chambers with central cathode are potentially more resistant to radiation damage and they are attractive alternatives to be used as a real-time dosimeter due to their no directional dependence [8]–[11].

The SPGD consists of two concentric electrodes separated by a layer of insulating material, where external gamma-rays induce a net of electron flow that can be measured externally and which is proportional to the gamma fluence rate [11]. The SPGD had its application limited probably due to its low output signal. More recently, this limitation has been overcome, due to the substantial improvement of electronic system quality for current measurements. Van Nieuwenhove and Verneeren [11] have reinvestigated the use of the SPGD to measure the dose rate in a ^{60}Co gamma irradiation facilities and they obtained precise relative measurements of the gamma dose rate in the range 0.5–2.0 kGy/h.

The ionization chamber has as basic operation principle the ionizing radiation entering the chamber. This causes the ionization of the gas and the resultant electron/ion flow to the charged electrodes is a measure of the gamma dose rate [2], [4], [11]. Ionization chambers present the advantage of having a high sensitivity (current per unit dose rate) and a relatively low cost compared to SPGD. However, the commercially available small ionization chambers are more suitable to low radiation level measurements. Sephton *et al.* [9] tested five commercial ionization chambers to measure high-dose rates of at least 160 kGy/h, at industrial irradiation plants. In this study, only two chambers survived irradiation up to 6.2 MGy without sustaining damage, apart from some stiffening of the cables. The chambers had an active volume of 7 cm^3 along an active length of 2.5 cm [9]. Chambers with large size are not appropriated for very localized measurements [8]–[11]. In this work, a small ionization chamber of 0.9 cm^3 was developed and tested as a gamma-ray detector inside a gammacell chamber, where the static position irradiation conditions were simulated. The ionization chamber response was studied, for doses between 1 and 7 kGy, under saturation current conditions and under dose rate variation caused by ^{60}Co spectrum degradation. The degradation is expected due to the absorption of the ^{60}Co photons in the material under dynamic irradiation that goes through the source [4]–[6].

II. Ionization Chamber Design

In the ionization chamber project the requirements below were considered [2], [4]–[7]:

- to be small enough not to disturb the medium electronic equilibrium;
- resistance to high-doses and dose rates;
- reproducibility;
- it should produce an ionization current high enough to give a good signal-to-noise ratio (SNR) and to be transmitted to an electrometer, far about 20 m from the detector, because the measurements will be monitored from the control panel placed in the operation room at the industrial plant.

Fig. 3 shows the schematic drawing of the developed ionization chamber. The vessel of the ionization chamber was constructed in cylindrical shape with 11.3 mm of length and 10.2 mm of diameter. It was made with 1 mm thickness stainless steel that is enough for establishing the ^{60}Co γ rays electronic equilibrium [2], [4]–[7]. The overall volume of the detector is 0.9 cm^3.

To transmit the signal generated in the ionization chamber to the associated electronic and processing unit a mineral insulated cable (ECIL S.A) was used. The cable is constituted externally of stainless steel (AISI 304L), the insulator of $\mathrm{Al_2O_3}$ and the inner wire also of the stainless steel (AISI 304L), the details shown in Fig. 3(c). A pair of these cables was welded directly to the ionization chamber body, without requiring the use of a connector as in the coaxial cable, due to the small diameter of the mineral insulated cable as shown in Fig. 3(a). The inner wires of the cables were used as a cathode and a anode. The anode must not be a closed circle because if there is a high radio frequency source nearby it may induce a current inside the anode. The outer stainless steel structure of the cables was used as ground to avoid electromagnetic interference in the detector. No displacement of the anode wire was observed when

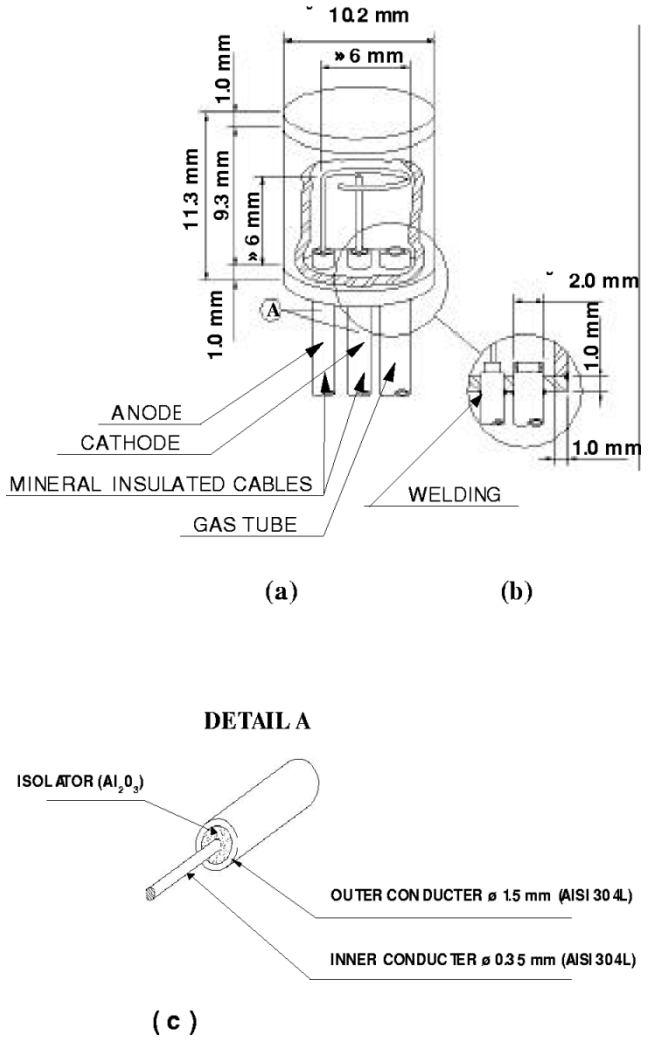

Fig. 3. (a) Schematic drawing of the developed chamber. (b) Expanded view of the cables and gas tube welding. (c) Mineral insulated cable detail.

submitted to mechanical shocks. The diminished diameter of the anode loop (6.0 mm) made with wire of 0.35 mm must be provided the mechanical stability.

The coaxial cable used in commercial ionization chambers are commonly made of polymeric material, which deteriorates with high-dose rates in a short time due to its low radiation resistance. Additionally, this kind of cable is about 5 mm in diameter, which is large for the ionization chamber of 10.2 mm in diameter, making the connection between them very difficult. Both problems were overcome in this work using mineral insulated cables that are only 1.5 mm thick and are resistant to radiation [12], [13], Fig. 3(c).

A gas with low value of the energy loss per ion pair (W-value) produces higher saturation currents than the high W gas, generating high saturation current. So, for low dose measurement application the low W gases should be used to fill the chamber. For the proposed applications, as the ionization chamber will work under high-dose rates (about kGy/h), a high W gas can be used. Therefore, in this work, the gas chosen to fill the ionization chamber was the nitrogen, whose W-value for electrons is 34.8 eV/ion pair. The detector was filled with Nitrogen at pressure of 1.0 bar, because at this pressure it is technically simpler to fill the chamber and on the other hand, the generated saturation current was suitable to carry out the proposed experiment. A stainless steel gas tube of 2.0 mm diameter was welded in the body of the chamber to fill it (Fig. 3(b)). The chamber was evacuated and washed with nitrogen, at least three times, before of sealing the chamber filled with nitrogen, in order to avoid the ionization chamber contamination by oxygen (electronegative gas). The chamber was filled inside the gammacell at 35°C.

For an ideal performance of the ionization chamber detector as real-time dosimeter for static position irradiation, the collected charge should have the same correlation with the dose, independently of the dose rate variation caused by the ^{60}Co spectrum degradation.

III. Experimental Procedure

In order to test the developed detector, measurements of current versus voltage and accumulated charge versus dose were carried out, at different dose rates, using an irradiator type ^{60}Co gammacell (model 220 of the AECL—Atomic Energy of Canada Limited, Kanata, Canada, with 0.26PBq (7 kCi)). The dose rate variation by ^{60}Co spectrum degradation that occurs at the static position irradiation inside a gamma irradiation facility was simulated as closely as possible. The dose rates used were: 0.6, 1.8, 2.6, and 5.7 kGy/h, which were obtained with lead absorbers of 90%, 70%, and 50% and without absorber, respectively.

Each dose was determined using an Amber 3042 perspex dosimeter (Harwell), for each absorber. The calibration of this dosimeter was obtained by irradiation of dosimeters sets inside the gammacell from 1 to 30 kGy, within the uncertainties of 2% (1σ or 68.3% confidence level) The gammacell is calibrated twice a year with alanine dosimeter from International Dose Assurance Service (IDAS) program of the International Atomic Energy Agency (IAEA).

The ionization chamber in saturation current conditions was irradiated together with the dosimeters to verify the linearity between the accumulated charge and the dose for each absorber.

The charges and currents were measured using the electrometer Keithley model 610C and high voltage, ranging from 0 to 500 V, was supplied by a Keithley source model 247. The maximum charge the electrometer can record is 10 μC. The irradiation temperature was 35 °C.

IV. Results and Discussion

Fig. 4 shows the picture of the developed ionization chamber detector at a nitrogen pressure of 1.0 bar, welded with 20 m of the mineral insulated cable.

The SNR produced by the detector, simulating the static irradiation conditions in the industrial irradiator, was enough to be transmitted to the electrometer placed 20 m far from the detector. The ratio between signal and noise was about 1000.

Fig. 5 shows the variation of the current with chamber voltage using absorbers at 50%, 70%, and 90% and without absorbers. At least three current versus voltage curve measurements were made with the ionization chamber for each lead absorber, varying the voltage from 0 to 500 V. The difference among curves of a same absorber was less than 1%. Very flat

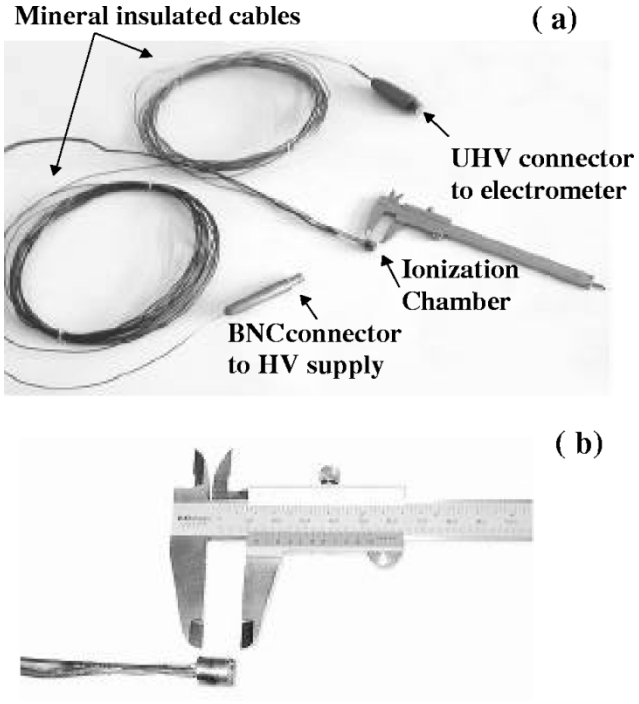

Fig. 4. (a) Ionization chamber welded with mineral insulated cables of 20 m length. (b) Expanded ionization chamber picture.

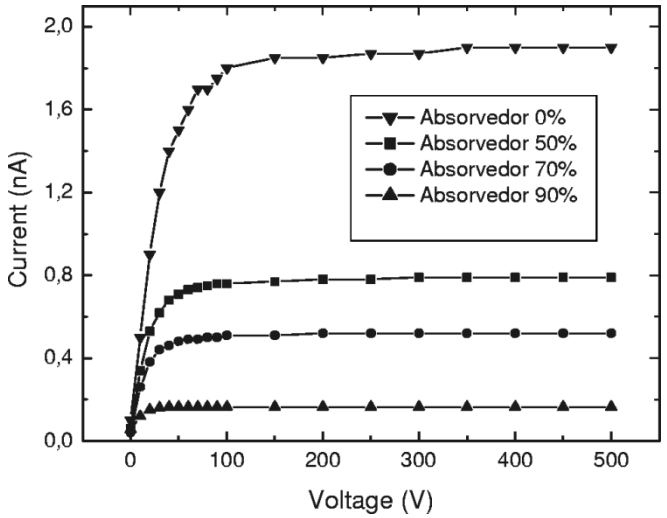

Fig. 5. Ionization chamber saturation current at 1 bar of nitrogen gas in function of the voltage under different dose rates.

chamber plateaus were observed for all dose rates, as shown in Fig. 5. For 90% lead absorber the saturation current of 0.165 nA was obtained with a minimum voltage of 50 V, while a minimum voltage of 350 V was required to reach the saturation current of 1.90 nA, when measured without absorber. Table I summarizes the results of the saturation current measurements and the required minimum voltages for different absorbers.

To ensure the saturation current stabilization, the accumulated charge measurements in function of dose were performed at 400 V for all lead absorbers. Fig. 6 shows the variation of the charge with the dose, at dose rate of 0.6, 1.8, 2.6, and 5.7 kGy/h, in the dose range from 1 to 7 kGy. The doses were measured by

TABLE I
SATURATION CURRENTS AND THEIR MINIMUM VOLTAGE FOR EACH LEAD ABSORBER

Lead absorber	Saturation current	Minimum voltage
90 %	0.165 nA	50 V
70 %	0.520 nA	200 V
50 %	0.790 nA	300 V
Without	1.900 nA	350 V

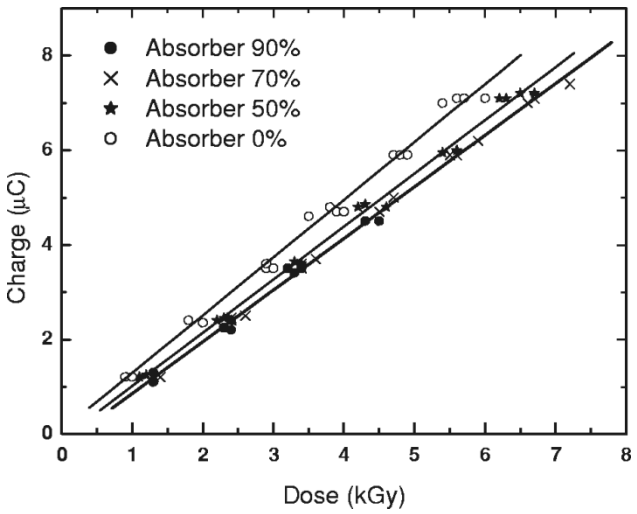

Fig. 6. Dose against charge curve measured by ionization chamber with 1 bar of nitrogen gas and under different dose rates.

Amber 3042 Perspex dosimeters and the dose rates were determined dividing the measured higher dose by its exposure time for each experiment and for each absorber.

As it can be observed in Fig. 6, all curves exhibit linearity between doses and collected charge. A slight variation among the curves using absorbers at 50%, 70%, and 90% was observed. This is due to the ^{60}Co spectrum degradation from 90% to 50% lead absorbers. The thicker the lead absorber, the larger the spectrum degradation [4]–[6].

For curves without absorber a significant difference of about 17% was observed compared to curves with absorbers, because of the higher number of uncollided photons. This condition means that there is no material crossing between the sample in the static irradiation position and the source, however, it is a rather unrealistic situation to occur in an irradiation industrial plant.

In spite of the slight ^{60}Co spectrum degradation by using absorbers, the ionization chamber accuracy was well within that recommended by the ISO 11 137. For 7 μC the dose obtained at dose rate of 0.6, 1.8 and 2.6 kGy/h was 6.8, 6.6, and 6.3 kGy, respectively, which corresponds to a maximum difference of ± 0.3 kGy or $\pm 5\%$. For 1.2 μC dose of (1.3 ± 0.1) kGy or $\pm 8\%$ was obtained and for 3.6 μC the obtained dose was of (3.4 ± 0.1) kGy or $\pm 3\%$. Plotting all points on a same figure, except those without the absorber, an average calibration curve can be determined for all absorbers and, consequently, for the dose rates, as shown in Fig. 7. The linear correlation between the

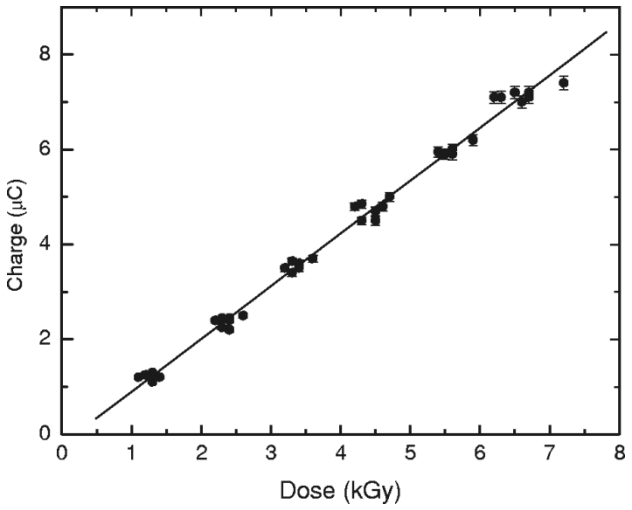

Fig. 7. Ionization chamber calibration curve for 90%, 70%, and 50% absorbers, using different dose rates of 0.6, 1.8, and 2.6 kGy/h.

dose versus the accumulated charge of the ionization chamber detector showed the coefficient $r = 99.94$. Therefore, there was a good correlation of the accumulated charge for the dose.

The ^{60}Co spectrum degradation in the ionization chamber is an important phenomenon that should be considered for the proposed application. It means that this detector has to be calibrated and operated within a degradation spectrum range due to the photons absorption in the dynamic irradiation material that going past the ^{60}Co source. In the EMBRARAD JS 7500 irradiator, the material density that passes between the source and the static irradiation material varies from 0.1 to 0.3 $\mathrm{g/cm^3}$, with a maximum thickness of 1 m. It means an absorption range of about 42% to 81%. This absorption range is close to that studied in the ionization chamber tests in gammacell. In an industrial irradiator, the irradiation room is very large compared to the gammacell chamber, so the scattered beams will be less intense than inside a gammacell irradiator. Then, the accuracy between the accumulated charge and dose is expected to be improved in the industrial plant.

V. Conclusion

The ionization chamber showed to be suitable for using as a real-time dosimeter to measure the dose range studied, from 1 to 7 kGy. A good correlation between the dose versus accumulated charge was found, independently of the spectrum degradation for absorption ranging from 50 to 90%. The accuracy was of 0.1 kGy or 8% for 1.3 kGy and 0.3 kGy or 5% for 6.6 kGy, thus meeting the ISO 11 137 requirements.

VI. Future Work

The detector test under a real industrial condition will be carried out in static irradiation position with a ^{60}Co irradiator, of about 25.9 PBq (700kCi), model JS 7500, from MDS Nordion, at EMBRARAD Ltd.

Acknowledgment

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