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TWO-FACES STATIONARY IRRADIATION METHOD AND DOSIMETRIC CONSIDERATIONS FOR RADIATION PROCESSING AT THE MULTIPURPOSE GAMMA IRRADIATION FACILITY / IPEN-CNEN

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ABSTRACT

Over the last ten years, the Multipurpose Gamma Irradiation Facility of the Nuclear and Energy Research Institute – IPEN/CNEN located inside the São Paulo University campus has been providing services on radiation processing, especially for sterilization of health care and disposable medical products as well as support to research studies on modification of physical, chemical and biological properties of several materials. Placed at the same campus operates an extremely important radiopharmaceutical production facility when almost all disposable supplies used to produce medical products as the technetium-99m are continuously sterilized by gamma radiation. Many university biomedical research laboratories specially those working with equipment for cell cultures and vaccine production also make use of the gamma sterilization. Animal feed and shavings used by certified bioteries are routinely disinfected. Alternative underwater irradiation methods were developed to meet the demand of gemstone color enhancement. Human tissues including bone, skin, amniotic membranes, tendons, and cartilage belonging to National Banks are usually irradiated too. Different kind of polymers, hydrogels, foods as well native fruits, have been irradiated in this facility. Cultural heritage objects as books, paintings and furniture are disinfected routinely by gamma radiation. The success of the implementation of radiation processing in this facility is due to research and development of irradiation and dosimetry methods suitable for each condition. In this work are presented some considerations about the distribution dose and the two-faces stationary irradiation method developed and validated for this facility.

1. INTRODUCTION

Radiation processing technology currently is widely applied around the world. Over 250 gamma irradiation facilities are in operation for a variety of purposes in 55 countries; 140 of these plants are located in Europe and North America [1]. Products sterilized by gamma radiation have wide range of applications among them medical devices and medical supplies such as syringes, surgical gloves, catheters, masks, adhesive bandages, packaging, etc. Food irradiation as well has been applied reducing or eliminating disease-causing germs and increasing the quality control. Other materials including artificial joints, animal feed, raw materials for pharmaceuticals and cosmetics, and even wine corks are gamma processed [2]. The last years were enhanced and intensified gamma sterilization treatments of human tissues for transplantation including bones, skin, amniotic membranes, tendons, and cartilage. The same happened with cultural heritage materials as books, parchments, canvas, paintings, textiles, leather, sculptures, furniture, photos, films, etc. where gamma radiation has helped to eliminate insects and fungi. Besides all this, gamma irradiation has an advantage in processing non-uniform and high-density products compared with electron beam technologies; however, it suffers from the fact that it uses a radioactive material.

The Multipurpose Gamma Irradiation Facility is a panoramic wet source storage compact irradiator (IAEA - Category IV) that means, when it not in use, the radioactive sources are stored and fully shielded in a pool of 7m depth deionized water [3], [4]. The facility uses cobalt-60 source pencils (45cm length and 1cm diameter) where the radiative material was encapsulated in corrosion resistant stainless steel such that gamma radiation can come through but not the radioactive material itself, eliminating the risk of contamination. The source pencils (48 units) were loaded into predetermined positions in source modules and distributing these modules over the source racks. The required source geometry is obtained by loading the source pencils. The racks are the structures that house all the source pencils enabling the movement of the source system from the bottom of the pool to the irradiation chamber level [5].

Cobalt-60 ($^{60}Co_{27}$) decays or disintegrates into stable nickel isotope ($^{60}Ni_{28}$), predominantly emitting one negative beta particle of maximum energy 0.313 MeV with a half-life of approximately 5.27 years. Produced Nickel-60 is an excited state, and it immediately emits two photons of energy 1.17 MeV and 1.33 MeV in succession to reach stable state. These two gamma ray photons are responsible for radiation processing. The decay rate of the ^{60}Co represents 50% in around 5.27 years [6], [7].

The product throughput depends largely on the activity of the radiation source currently installed in the irradiator. The current installed activity of the facility is 10.4 PBq (280 kCi). The installed activity should always be less than the maximum activity for which the irradiator was designed, which is referred to as the design capacity (e.g. 1000 kCi). This facility was licensed (CNEN) to have no more source activity than the design capacity, since it is specifically designed for that, especially with respect to the shielding requirements.

The dose rate in the product is directly related to the installed activity of the source, and the operator controls the absorbed dose delivered to the product by adjusting the time that it is exposed to radiation, either by selecting the irradiation time interval or by selecting the conveyor speed. Nowadays, in available commercial gamma irradiators, only 30% of the energy emitted by the radiation source is effectively absorbed by the product. For gamma irradiators, source power depends on the source activity, such that 1 million Ci of ^{60}Co emits about 15 kW of power (4.2 kW for this facility). The only variation in the source output is the known reduction in the activity caused by radioactive decay, which can have a significant impact on the operation of the facility (financial as well as scheduling) if not taken into account. The activity of a cobalt source decreases by about 12% annually. The irradiator operator compensates for this loss of activity (which decreases the dose rate) by incrementally increasing irradiation time (approximately 1% per month) to maintain the same dose to the product. Eventually, irradiation time becomes impractically long (reducing the throughput), requiring the addition of ^{60}Co pencils to the source rack (source replenishment) at regular intervals, depending on operational requirements. The last loading operation was conducted in July 2014, adding almost 7.4 PBq (200 kCi). Cobalt-60 pencils can be eventually removed from the irradiator at the end of their working life, which is typically 20 years. Generally, they are returned to the supplier for reuse, recycling or disposal. In about 50 years, 99.9% of ^{60}Co would decay into non-radioactive nickel.

2. MATERIALS AND METHODS

The success of radiation processing depends largely on the ability of the processor to measure the absorbed dose delivered to the product (reliable dosimetry), determining the dose distribution patterns in the product package (process qualification procedures) and to control the routine radiation process (process control procedures). Since the radiation absorbed dose is the quantity which relates directly to the desired effect in a specific material, the need for suitable and accurate dose measurement techniques must not be underestimated. This is best appreciated by realizing the consequences of using inadequate techniques, causing under or overexposure of the product and the resulting failure to administer an effective treatment. The consequences to the processor can be both legal and economic, while the consumer may not only suffer an economic loss by having to discard an inadequately treated product but also lose confidence in the irradiation process.

In the processing of products by radiation, reliance is placed on the radiation quantity absorbed dose to obtain accurate and expressive information about the relevant radiation effects. The regulatory authority or any other group responsible for the acceptance of the specific application requires information that demonstrates that every part of the process load under consideration has been treated within the range of acceptable absorbed dose limits.

The absorbed dose, *D*, is the amount of energy absorbed per unit mass of irradiated matter at a point in the region of interest. It is defined as the mean energy,$\bar{\varepsilon}$, imparted by ionizing radiation to the matter in a volume element divided by the mass, *dm*, of that volume element [8]:

$$D = \frac{d\bar{\varepsilon}}{dm} \tag{1}$$

The SI derived unit of absorbed dose is the gray (Gy), which replaced the earlier unit of absorbed dose, the rad, 1 Gy = 1 J/kg = 100 rad.

The absorbed dose rate, $\dot{D}$, is defined as the rate of change of the absorbed dose with time:

$$\dot{D} = \frac{dD}{dm} \tag{2}$$

In practical situations, *D* and $\dot{D}$ are measurable only as average values in a larger volume than is specified in the definitions, since it is generally not possible to measure these quantities precisely in a very small volume in the material. In this work, the absorbed dose is considered to be an average value, either as measured in the sensitive volume of the dosimeter used if it is of appreciable size or existing in its immediate vicinity if the dosimeter is very small or thin, where cavity theory is applicable. For any given irradiation conditions, it is necessary to specify the absorbed dose in the particular material of interest because different materials have different radiation absorption properties.

2.1. Dosimetry System

Measurements of the absorbed dose at the Multipurpose Gamma Irradiation Facility were performed using an industrial routine dosimetry system known as dyed polymethyl methacrylate (PMMA). This dosimetry system is based on the measurement of the radiation induced absorbance change in dyed PMMA, creating a broad absorption band in a special region of the UV-VIS spectrum. Harwell Dosimeters-UK has been providing commercial dosimeters for over 40 years for the entire world [9].

Several types of specially prepared PMMA containing certain dyes which become darker upon irradiation are available for dosimetry and are supplied in sealed pouches. Depending on the type (color) of the dye, the change in absorbance is measured at specific wavelengths in a spectrophotometer. A specific dyed allows to dosimeter to work in a different absorbed dose ranges. Absorbed dose can be easily calculated using a normalized ratio between the measurement of the specific absorbance obtained by the UV-VIS spectrophotometer and the thickness of each dosimeter. Then the obtained value is replaced into a calibration curve (fourth-order polynomial regression previously founded by the least squares method) and the absorbed dose value is calculated directly. This procedure is possible because when analyzed the absorbance curves spectrum in function of the wave length after irradiation with doses over 1 kGy, new specific defined absorption optical bands are created (e.g. 530 nm, 651nm, 640 nm, etc.) in function of the dyed of the dosimeter and just is this property allows create a correlation with the absorbed dose.

Dosimeters are positioned in front, in back and if possible in the middle of the objects to be irradiated, special considerations are taken to samples for research objectives. For routine irradiations of large batches, several dosimeters are distributed in many positions to ensure the delivered absorbed required dose. Table 1 shows the Harwell specifications for the available PMMA dosimeters [10], [11], [12]. Harwell also provides an individual calibration curve for each commercialized dosimeter batch however the calibration procedure is performed again inside the laboratories of IPEN only to confirm the results. Harwell is not manufacturing more the Gammachrome type dosimeter (low doses 0.1 – 1.0 kGy) and currently is commercializing the Radspin dosimeter based in alanine amino acid. Alanine when irradiated creates stable free radicals whose concentration depends of the absorbed radiation dose. To calculate the this concentration is necessary an resonance paramagnetic resonance equipment (EPR)

The Multipurpose Gamma Irradiation Facility has an annually calibrated UV-VIS spectrophotometer and other equipment to perform the partial absorbed dose measurements of the irradiated materials but to adopt an external audit system, when the processing is over, the used dosimeters are delivered to special laboratory to execute and additional measurement and to prepare a report.

Table 1: Harwell PMMA Dosimetry System Characteristics

Harwell – PMMA Dosimeter	Working range [kGy].	Measurement precision /Standard deviation	Length Wave [nm]
Gammachrome	0.1 – 3.0	±2.5%	530
Amber 3042	1.0 -30.0	±2.5%	603 and 651
Red 4034	5,0 – 50,0	±2.0%	640

2.2. Distribution of the Absorbed Dose

The dose needed to achieve a desired effect in the product or process dose is determined through several research stages. In general, it involves determine the relationship between different values of absorbed dose with some parameters of interest which can be modified by the irradiation process, for example the sterility level versus dose or a mechanical propriety of the product versus dose. Therefore, the goal of such research is the identification of two dose limits: a) the lower dose limit to achieve a desired effect (e.g. sterility level) and b) the upper dose limit to be sure that radiation will not adversely affect the quality of the product (e.g. degradation of polymers of health care products). Usually, each product or process has a pair of these limits, and these values define an acceptable dose window, such that every part of the product should receive a dose within that range. The ratio of the upper dose limit to the lower dose limit may be referred to as dose limit ratio (DLR) [8].

During a radiation process, gamma radiation interacts with the product through several types of atomic interactions, such as Compton scattering, photoelectric effect and pair production. Through these and subsequent interactions, it imparts energy and consequently radiation dose to the product. As radiation proceeds through the product, its intensity decreases as a result the absorbed dose also decreases with depth. This phenomenon is referred to as depth–dose distribution. The rate of decrease depends on the composition and density of the product and the energy of the gamma radiation. Besides the variation of dose with depth, there is also dose variation in the lateral direction. This variation depends on the geometry of irradiation. Both types of dose variation contribute to the non-uniformity of the dose delivered to the product. Then, variation in dose in the irradiated product is unavoidable. One accepted method of describing this non-uniformity of dose is the concept of dose uniformity ratio (DUR), which is the ratio of the maximum dose in a product (container or package) to the minimum dose. DUR increases with the density of the product as well as with the size of the container or package.

DUR should be close to unity (e.g. less than 1.05) for irradiation of research samples, where the research objective is to correlate radiation effect in the sample to the dose. This is generally achieved by reducing the size of the sample. For commercial operation (industrial scale), this is not possible for economic reasons. A typical product container size can be 60cm×50cm×50cm, and some irradiators are designed to irradiate entire pallets of product, for example, of 120cm×100cm×150cm. DUR would be significantly larger than unity for such large containers. Fortunately, for a large majority of products, there is a wide window of dose that is acceptable to achieve the desired level of sterility without detrimentally affecting the quality of the product. For such products, the dose limit ratio is between 1.5 and 3, and sometimes even larger.

Therefore, the guiding principle to processing by radiation is that the measured dose uniformity ratio should be smaller than the dose limit ratio prescribed for the product (DUR<DLR).

There are different ways to reduce the DUR or increasing the dose uniformity in a product container. The variation along the depth is easily reduced by irradiating the product from more than one side. This can be accomplished either by rotating the product container during irradiation or for the product container to travel around a radiation source. All gamma irradiators use one of these techniques for the purpose. The lateral dose variation may be reduced in several ways, including placing the higher activity source pencils near the periphery of the source rack (source augmentation), and relative arrangement of the product containers and the source (source overlap or product overlap). Different irradiators apply different methods to improve dose uniformity.

2.3. Stationary Irradiation Methods

The Multipurpose Gamma Irradiation Facility can operate in dynamic or stationary modes. In the dynamic mode a container overlap system is used to transport the products around the radioactive sources. Nevertheless, research materials or very delicate objects (e.g. cultural heritage or human tissues) need to be loaded by hand and the stationary method is the more suitable to take care mainly parameters related to the distribution dose (DUR). Then the stationary operations can be described in the following methods in function of the DUR.

2.3.1. One-Face Stationary Irradiation Method

When DUR is close to the unity, this means small research samples or another objects; the irradiation process is performed placing the materials in specific locations inside the irradiation chamber where the dose rate is known. The processed materials are not rotated or moved while the irradiation is happening. The irradiation time calculation will be present soon afterwards.

2.3.2. Two-Faces Stationary Irradiation Method

This method is executed in two stages, first the samples (boxes or packages) are fixed in specific positions inside the irradiation chamber where the dose rate is known, after having passed 50% of the total planned irradiation time, the samples are rotated 180 degrees in a way that the face of the sample was totally opposite (back) to the radioactive sources now is in front of them and then start the second stage of the irradiation process to complete the 50% of time remaining. Fig. 3 shows the depth-dose distribution using this method.

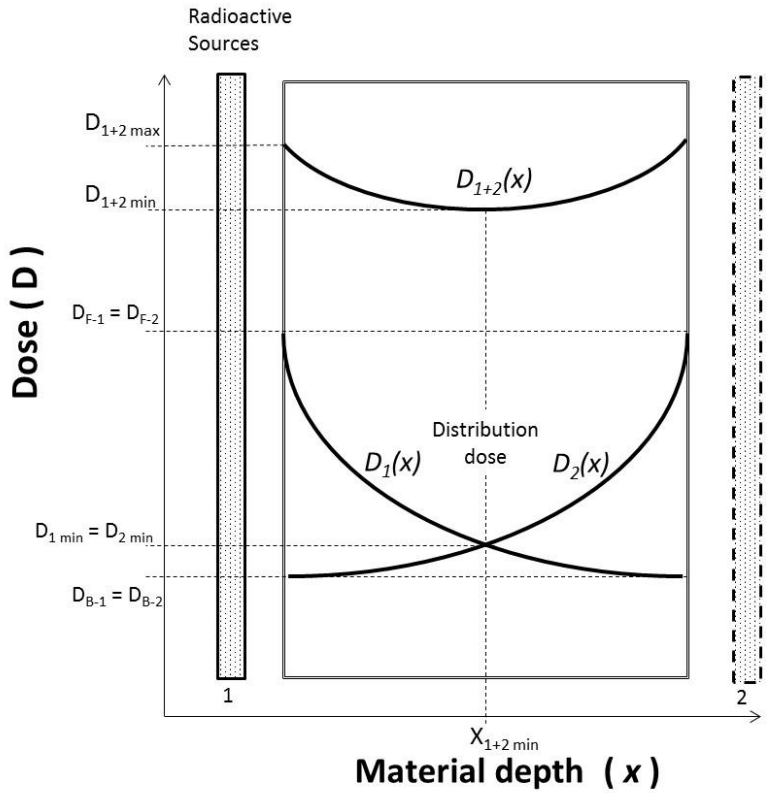

Figure 1: Depth-dose distribution using the Two-Faces Stationary Irradiation Method.

When the sample is irradiated in the first time stage (50% of the total), the maximal value of the absorbed dose D_{F-1} is located on the near side to the radioactive sources (front) and the minimal value on the opposite side, D_{B-1} (back) as shown in Fig. 1 on the dose distribution curve $D_1(x)$. Then the sample is rotated and is completed the 50% of the remaining irradiation time, so that the face of the sample now is in front of the sources will receive an absorbed dose of D_{F-2} and the far side D_{B-2} as shown on the dose distribution curve $D_2(x)$. For cumulative proprieties of the absorbed dose, the total effect of the irradiation will be represented by the distribution curve $D_{1+2}(x)$ where $D_{1+2\ min}$ represent the minimal processing dose. Therefore, $D_{1+2\ max}$ represent the maximal value achieved by an external the dosimeter. DUR can be calculated as shown in Equation 3.

$$DUR = \frac{D_{1+2\ max}}{D_{1+2\ min}} \tag{3}$$

The variation of the absorbed dose (D) in function of the thickness of the sample (x) can be represented by the Equation 4. Solving the differential equation (Equation 5) and integrating between the corresponding limits can be obtained the dose distribution curves $D_1(x)$ and $D_2(x)$ described by the Equation 6 and 7 respectively.

$$\frac{dD}{dx} = \mu . D \tag{4}$$

$$\int_{D_o}^{D_f} \frac{dD}{D} = \int_0^x \mu \, dx \tag{5}$$

$$D_1(x) = D_F e^{-\mu x} \tag{6}$$

$$D_2(x) = D_B e^{\mu x} \tag{7}$$

Where, μ is a proportionality constant representing the effective global attenuation coefficient of the irradiated material. It was assumed that $D_F = D_{F-1} = D_{F-2}$ and $D_B = D_{B-1} = D_{B-2}$ because the partial irradiation intervals of time were the same and thus the absorbed dose is proportional to the time.

This pseudo-exponential behavior of the distribution dose curves is particularly useful when is not possible to place a dosimeter inside the sample, allowing the calculation of the delivered minimal dose in function of the external dosimeters placed in front and back of the irradiated object (maximal dose).

By adding the Equations 6 and 7 is obtained Equation 8 that represents the total distribution of the dose $D_{1+2}(x)$, in both irradiation stages, then differentiating and equaling to zero can be obtained the thickness $x_{1+2\ min}$ that can be replaced in Equation 8 to find the minimal processing dose $D_{1+2\ \mathrm{min}}$ as showed in Equation 11.

$$D_{1+2}(x) = D_B e^{\mu X} + D_F e^{-\mu X} \tag{8}$$

$$\frac{dD_{1+2}(x)}{dx} = \mu D_B . e^{\mu X} - \mu D_F e^{-\mu X} = 0 \tag{9}$$

$$x_{1+2\ min} = \frac{\ln \frac{D_F}{D_B}}{2\mu} \tag{10}$$

$$D_{1+2\ min} = 2.\sqrt{D_F . D_B} \tag{11}$$

Another way to obtain the same result can be dividing Equations 6 and 7 to get the minimal dose in each irradiation stage (Equation 12) but this can be deducted from Equation 11 because each irradiation stage is performed using the same time.

$$D_{1\,min} = D_{2\,min} = \sqrt{D_B . D_T} \tag{12}$$

Through Equations 6, 7 and 8 also is be possible to calculate de global effective attenuation coefficient that can be useful to standardize the irradiation method for the same material.

The Multipurpose Gamma Irradiation Facility to make easy the understanding of these methods usually works with DUR values in sense of a factor *f* as showed in Equation 13. This factor is useful to calculate the minimal processing dose in function of the value registered in the dosimeter (maximal dose).

$$f = \frac{1}{DUR} \tag{13}$$

2.3. Irradiation Time Calculations

The irradiation time *t* is calculates performing partial dosimetric measurements for the dose rate $\dot{D}$ in desired positions (e.g. front, back, middle, etc.). Stipulating a partial irradiation time t_p lower than the total expected to reach the processing desired dose ($t_p << t$) and making measurements of the partial absorbed dose D_P, dose rates can be calculated as shown in Equation 14.

$$\dot{D} = \frac{D_P}{t_p} \tag{14}$$

Then, knowing the dose rates in specifically locations, irradiation time can be obtained. For research samples (DUR≈1) and for the one-face stationary irradiation method, the irradiation time is calculated using Equation 15.

$$t = \frac{D_{min}}{\dot{D}} \tag{15}$$

Where, D_{min} is the minimal processing dose required (e.g. 5, 15, 25 kGy, etc.)

The two-faces irradiation method is used for large volumes and when is not possible to locate a dosimeter inside the samples, partial dose rate measurements are necessary for dosimeter located in front and back of the volume. The methodology to determine the frontal dose rate $\dot{D_F}$ and the back dose rate $\dot{D_B}$is the same used to the one-face method.
Then, analogously to the deductions developed early and using the expression of the Equation 10, the dose rate can be calculated inside the material in the position where is expected the minimal processing dose $\dot{D}_{1min}$ or $\dot{D}_{2min}$ as showed in Equation 16.

$$\dot{D}_{1min} = \dot{D}_{2min} = \sqrt{\dot{D_F} . \dot{D_B}} \tag{16}$$

Next is calculated the irradiation time in the first irradiation stage $t_{50\%}$as shown in Equation 17.

$$t_{50\%} = \frac{\frac{D_{1+2\,min}}{2}}{\dot{D}_{1min}} = \frac{D_{1+2\,min}}{2.\dot{D}_{1min}} \tag{17}$$

However, exist another situations more complicated that no were described in this work and more detail and additional calculations are required.

2.4. Uncertainties and Errors Propagation

In so many cases is important to demonstrate reliability of the dosimetric measurements, since the results are product of mathematical calculations. Table 2 shows the results of the errors propagation for the parameters presented in this work. The expected standard deviation *s* for more used PMMA dosimeters is between 2% and 2.5 %.

Table 2: Standard Deviation for Harwell PMMA Dosimeters

Harwell – PMMA Dosimeter	Parameter	Standard Deviation
Red	D_F	S_F = ±0,02 D_F
Red	D_B	S_B = ±0,02 D_B
Red	$D_{1+2\ max}$	$S_{D_{1+2max}}$=±0,02 $D_{1+2\ max}$
Gammachrome/ Amber	D_B	S_F = ±0,025 D_F
Gammachrome/ Amber	D_T	S_B = ±0,025 D_B
Gammachrome/ Amber	$D_{1+2\ max}$	$S_{D_{1+2max}}$= ±0,025 $D_{1+2\ max}$
Amber/Red/Gammachrome	D_{1min} , D_{2min}	$S_{D_{min}} = \pm\frac{1}{2}\left(\frac{D_B {S_F}^2}{D_F} + \frac{D_F {S_B}^2}{D_B}\right)^{1/2}$
Amber/Red/Gammachrome	$D_{1+2\ min}$	$S_{D_{min}} = \pm\left(\frac{D_B {S_F}^2}{D_F} + \frac{D_F {S_B}^2}{D_B}\right)^{1/2}$

2.4. Validation of the Two-faces Stationary Irradiation Method

The two-faces stationary method was validated irradiation different type of materials used in medical products (plastic, rubber, glass and metal), animal products (feed and shavings) and cultural heritage products (paper) as showed in Table 3.

Table 3: Irradiated Material Properties

Irradiated Material	Type of Packaging	Package Dimensions Length [cm] x depth (x) [cm] x height [cm]	Bulk density [g.cm^{-3}]
Medical device A – Plastic	Box	47.0 x 31.0 x 34.0	0,063
Medical device B – Plastic	Box	47.0 x 31.0 x 34.0	0,057
Medical device C – Rubber	Box	0.49 x 0.25 x 0.38	0,365
Medical device D – Steel	Box	51.0 x 35.0 x 37.0	0,182
Medical device E – Glass	Box	51.0 x 35.0 x 37.0	0,182
Laboratory Material – Plastic and Glass	Box	58.0 x 49.0 x 48.0	0,092
Animal Feed	Bag	60.0 x 45.0 x 15.0	0,494
Animal wood shavings	Bag	60.0 x 45.0 x 15.0	0,045
Cultural Heritage - Paper	Box	49.0 x 39.0 x 26.0	0,423

Several dosimeters were placed in front (D_F), back (D_B) and in the middle (D_M) of the objects, this the last one was used to compare with the calculated absorbed dose value D_{min} . All experimental data were obtained using five samples (n=5). Next, the relative standard deviation (%*RSD*) was calculated for each measurement as shown in Equation 18.

$$\%RSD = \frac{S}{\overline{D}} * 100 \tag{18}$$

Where S is the standard deviation for the sample and $\overline{D}$ is equal to the mean (absorbed dose values).

3. RESULTS AND DISCUSSION

The results of validation for the two-faces stationary method are summarized in Table 4 for the Red Harwell PMMA dosimeter. and in Table 5 for Amber Harwell PMMA dosimeters. The relative standard deviation for the absorbed dose value at the internal point was not greater than 3%.

Table 4: Results of the absorbed measured and calculated dose for Red Harwell PMMA

Irradiated Material	D_M [kGy]	D_{min} [kGy]	DUR	%*RSD*
Medical device A – Plastic	16.8±0.4	16.4±0.3	1,35	1.70
Medical device B – Plastic	20.5±0.5	20.2±0.1	1,25	1.04
Medical device C – Rubber	20.7±0.5	20.8±0.4	1,80	0.34
Medical device D – Steel	20.8±0.5	21.0±0.5	1,62	0.68
Medical device E – Glass	20.4±0.5	20.8±0.4	1,75	1.37
Laboratory Material – Plastic and Glass	25.8±0.6	25.2±0.5	1,56	1.66
Animal Feed	10.8±0.3	11.0±0.5	1,20	1.30
Animal wood shavings	10.5±0.3	10.1±0.3	1,50	2.75
Cultural Heritage - Paper	10.7±0.3	10.5±0.4	1,20	1.33

Table 5: Results of the absorbed measured and calculated dose for Amber Harwell PMMA

Irradiated Material	D_M [kGy]	D_{min} [kGy]	DUR	%*RSD*
Medical device A – Plastic	16.8±0.3	16.5±0.4	1,35	1.27
Medical device B – Plastic	20.8±0.2	20.9±0.5	1,25	0.34
Medical device C – Rubber	20.2±0.3	20.5±0.5	1,80	1.04
Medical device D – Steel	20.3±0.3	20.7±0.5	1,62	1.38
Medical device E – Glass	20.9±0.3	20.5±0.5	1,75	1.37
Laboratory Material – Plastic and Glass	25.9±0.4	25.3±0.6	1,56	1.66
Animal Feed	10.5±0.2	10.8±0.3	1,20	1.99
Animal wood shavings	10.2±0.2	10.6±0.3	1,50	2.72
Cultural Heritage - Paper	10.3±0.2	10.5±0.3	1,20	1.36

3. CONCLUSIONS

The Two-Faces irradiation method was proposed and validated for several irradiated materials with good results. It is also extremely important that the users of the irradiation services of this facility are fully aware of the way the material is processed and thus all procedures possible must be taken to minimize the dose distribution ratio in relation to the required objectives. The dose limit ratio also must be known in advance by the users to avoid additional experimental interferences, which can lead to erroneous conclusions regarding the cause-effect of radiation in a given material.

Comprehensively, the Multipurpose Gamma Irradiation Facility at IPEN/CNEN has been contributing to the develop of many sectors related to research and industry, not only inside the Nuclear and Energy Research Institute and the São Paulo University but also at national level. Some products such as hydroxyapatite compounds were innovated with assistance of this facility. The medical devices and medical supplies used by the Radiopharmacy Center (CR) at IPEN and other laboratories at the USP are constantly sterilized by gamma radiation.

The multidisciplinary activities carried out in this facility have a wide range of operations starting with routine procedures until development of specific detailed irradiation processes for different purposes, without forgetting typical maintenance and control tasks to the production process.

All results obtained in this facility related to radiation processing are fully reproducible in industrial scale, that because this equipment takes into account industry real situations. If necessary, to obtain the dose distribution in non-homogenous materials or difficult to monitoring, could be used Monte Carlo simulations or other tools.

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