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MCNPX CALCULATIONS OF DOSE RATE DISTRIBUTIONS INSIDE SAMPLES TREATED IN THE RESEARCH GAMMA IRRADIATING FACILITY AT CTEx

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ABSTRACT

A cavity-type cesium-137 research irradiating facility at CTEx has been modeled by using the Monte Carlo code MCNPX. The irradiator has been daily used in experiments to optimize the use of ionizing radiation for conservation of many kinds of food and to improve materials properties. In order to correlate the effects of the treatment, average doses have been calculated for each irradiated sample, accounting for the measured dose rate distribution in the irradiating chambers. However that approach is only approximate, being subject to significant systematic errors due to the heterogeneous internal structure of most samples that can lead to large anisotropy in attenuation and Compton scattering properties across the media. Thus this work is aimed at further investigating such uncertainties by calculating the dose rate distribution inside the items treated such that a more accurate and representative estimate of the total absorbed dose can be determined for later use in the effects-versus-dose correlation curves. Samples of different simplified geometries and densities (spheres, cylinders, and parallelepipeds), have been modeled to evaluate internal dose rate distributions within the volume of the samples and the overall effect on the average dose.

1. INTRODUCTION

Irradiation is an interesting technology that has been used for a great number of purposes [1]. The controlled exposure to ionizing radiation is a physical process that can be used to disinfest, decontaminate and preserve food and to improve the characteristics or sterilize various types of materials [2].

Irradiation can be also used in the treatment of blood (to reduce the risk of rejection), ensuring the biological safety (sterilization) of medical materials and destroying toxic substances [3]. It can also be used for preservation and restoration of books, historical documents and artistic products by disinfestation and consolidation [4]. In addition, it can be used for improvement of properties or testing of products, such as shields, body armors, sensors, displays, optical materials, semiprecious stones, tires, wires, cables, polymeric compounds, conductors and electronic circuits.

Furthermore, investigating the behavior of materials such as metallic, glassy, polymeric or electronic components exposed to massive doses of ionizing radiation can also be regarded as a fundamental test related to nuclear defense, considering the possible use of such materials in highly radioactive environments such as nuclear reactor cores, irradiation facilities or highly contaminated areas.

The irradiation facility at Centro Tecnológico do Exército (CTEx), shown in Figures 1 and 2, is a 19-ton cavity-type research irradiator. Currently, its 42 kCi cesium-137 (CsCl) source provides a maximum gamma dose rate of 1.6 kGy/h inside two 68 x 137 x 20 cm^3 irradiation chambers. The gamma source consists of 28 parallel evenly-spaced and doubly-encapsulated plates containing cesium chloride. In addition, a pneumatic system allows both the source and one of its shielded doors to be moved by using a control panel. Dosimetric mappings of the chambers have consistently yielded dose rate distributions with agreement better than ± 4%, when correction is made for the decay of the ^{137}Cs source. Across the central volume of the chambers (36 x 48 x 19 cm^3), there is a vertical dose gradient of ± - (3-4) %/cm as positions further away from the plane of the source are considered. In addition, at a certain height the dose rate can be assumed approximately constant with mean error of ± 7% [5].

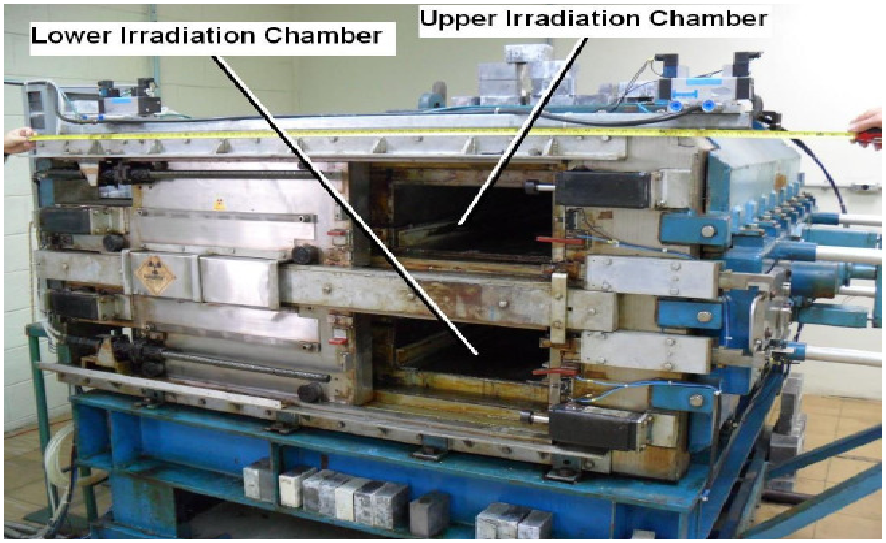


Figure 1. Front view of the research gamma irradiator at CTEx with doors open

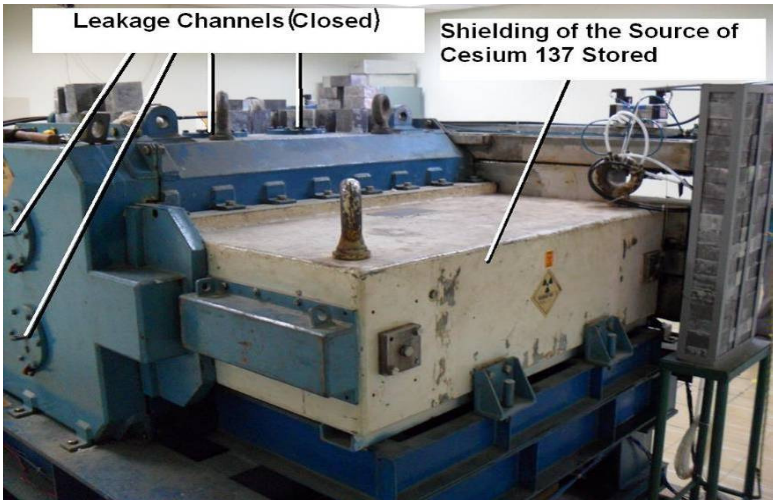


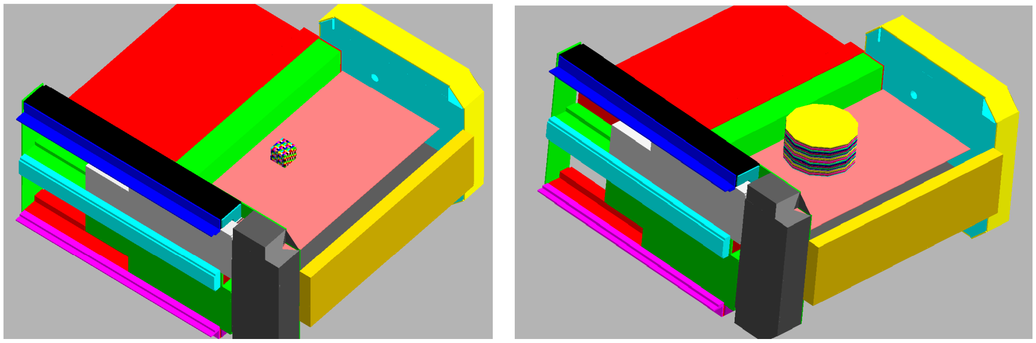
Figure 2. Rear view of the research gamma irradiator CTEx

However, dose rate distributions across extensive and massive samples, where attenuation of the gamma flux can sometimes become very severe, have not yet been measured. Therefore, the purpose of this work is to calculate the dose rate distributions inside samples of simple geometries positioned in the irradiation chambers using the MCNPX. The calculations will take into account the shape, composition and density of the items to be irradiated. Such data will be used to refine the current dose estimates in the irradiated samples by using accurate attenuation factors calculated as function of penetration into extensive samples.

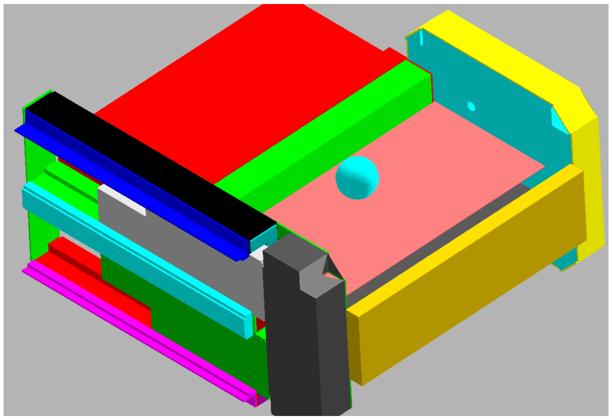
MCNPX is a nuclear code used to calculate radiation transport based on the Monte Carlo Method and it has been extensively used in complex computer simulations related to modeling gamma fluxes and dose rate distributions in radioactive environments [6]. It has been successively used by the authors to calculate the transport of gamma radiation within the irradiation chambers. The calculated relative dose rate distribution closely matched the experimental one and accurately reproduced its double peak at the center of the useful volume of the chambers.

2. CALCULATIONS

In order to simplify the calculations, three simple geometrical figures have been used to represent the various shapes of possible items treated in the irradiator, namely: the parallelepiped, the cylinder and the sphere. The calculations were performed for each figure at a time, assuming that the sample would be resting on the surface of the upper chamber at a point exactly above the geometric center of the gamma source. Depicted in Figure 3 is a stratified schematic view of the configuration to be found during irradiation of such objects as produced by the Moritz program [7] included in the MCNP Code Package.



Parallelepiped **Cylinder**



Sphere

Figure 3. Positioning of samples of simple geometries in the upper irradiation chamber

Most irradiated items have the approximate shape of parallepipeds and food items usually have more than 70% of water content. Thus, water was used as the composition of a 900 cm^3 parallepiped-shaped sample with dimensions (10 cm x 10 cm x 9 cm). In addition, the dose rate was evaluated for each of the 900 virtual 1cm^3 cubic cells modeled in the calculations (the volume of the parallelepiped was limited due to the large number of cells used for calculation of the dose rates).

A significant fraction of irradiated samples are enclosed in cylindrical recipients. For that reason, simulations of samples in that geometry have also been performed and 4 compositions were separately tested: water, aluminum, iron and polypropylene (PP). The cylindrical simulation modeled was 19 cm tall and 10 cm in radius. Those figures have been chosen in order to practically span the entire height of a chamber, besides representing the radius of a typical large cylindrical sample. The cylinder with 23876 cm^3 was represented by a grid of 0.5cm-spaced horizontal layers, so that the vertical dose rate distribution could be investigated with sufficient resolution for each of the four compositions tested.

The spherical geometry has also been tested in the calculations since some samples treated in the irradiation chambers have such shape. The calculations considered a sphere with 3591 cm^3 and 9.5 cm in radius, entirely consisting of one of the following substances: water, aluminum, iron or polypropylene (PP). Concentric spherical shells 0.5 cm-thick have been modeled so as to inform on the behavior of the dose rate distribution as a function of penetration into spherical samples. Figure 4 depicts samples modeled in simple geometries.

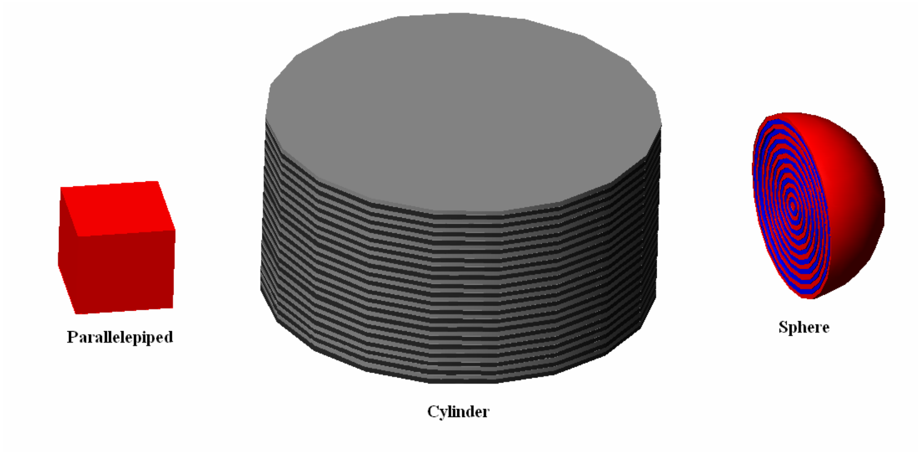


Figure 4. Details of geometric forms simulated with the sphere shown in half cut

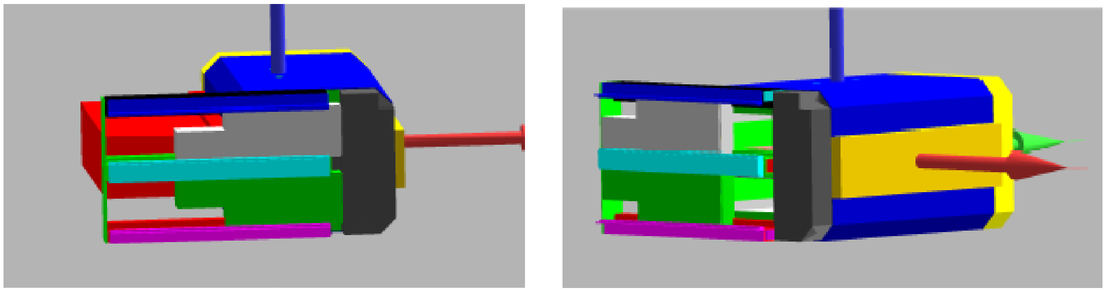
Since its plane geometry was known, the cesium-137 source could be accurately simulated. Each cell used in its representation was modeled as an isotropic source of gamma radiation and its composition and double encapsulation were also considered in the calculations, enabling investigations of self shielding in the source and its surrounding structures.

For visualization of the geometry modeled in the input, the programs Vised and Moritz have been used. Figure 5 shows a real image of the irradiator while Figure 6 provides a schematic visualization of the irradiator made with the Moritz program.

Irradiator with doors closed

Irradiator with doors open

Figure 5. Images of the irradiator with doors closed and open



Simulation of the irradiator with doors close Simulation of the irradiator with doors open

Figure 6. View of the research gamma irradiator at CTEx obtained with Moritz

In this work dose rates are expressed in Gy/min and have been calculated for June 01, 2011 by accounting for the decay of the cesium-137 source. For each simulation 15 million histories have been used, yielding uncertainties lower than 1%.

3. RESULTS

As expected, the dose rate distributions inside samples of different geometries tend to follow the overall trend inside the irradiation chambers, exhibiting variations mainly due to changes in the vertical distance from the source plane and, to a lesser extent, horizontally, as locations further from the geometric center of the source are considered.

Thus, the calculated dose distribution inside a parallelepiped sample being irradiated in the gamma facility at CTEx have indicated that the horizontal distribution is barely homogeneous (±7%), while the vertical dose rate profile is heterogeneous, exhibiting a negative dose rate gradient and causing average dose rates to decrease significantly as thicker samples are irradiated. Figures 7 and 8 depict such variations, that are amplified by attenuation of the gamma ray flux across the sample (parallelepiped filled with water). It can be easily noticed that regions at the base of the sample, closer to the source, are subjected to dose rates about 2.5 times higher than the most distant ones (at the top layer of the sample or 9 cm above the surface of the upper irradiation chamber).

The representation used in the calculations to investigate the cylindrical sample is shown in Figure 9. A 19 cm-high vertical stack, comprising 38 half-centimeter-thick cylindrical layers was modeled. As expected, the dose rate decreases as higher layers are considered, due to the increasing distance from the source. In addition, greater attenuation occurs with increasing penetration into the sample, especially when compositions of higher densities are considered.

The dose rate profile for the spherical sample has been found to roughly follow the same trends as those observed in the calculations for the cylindrical sample. As shown in Figure 10, it was modeled as a set of 0.5 cm-thick concentric spherical shells. Dose rate calculations were performed as each layer was added to the sphere, starting from 0.5 up to 9.0 cm in radius. It has been observed that the outer spherical layers exhibit dose rates that are larger than the inner ones due to the attenuation of the gamma ray flux. In addition, lower dose rates have been calculated for the interior of spheres made of iron or aluminum in comparison with water or plastic spheres of the same volume.

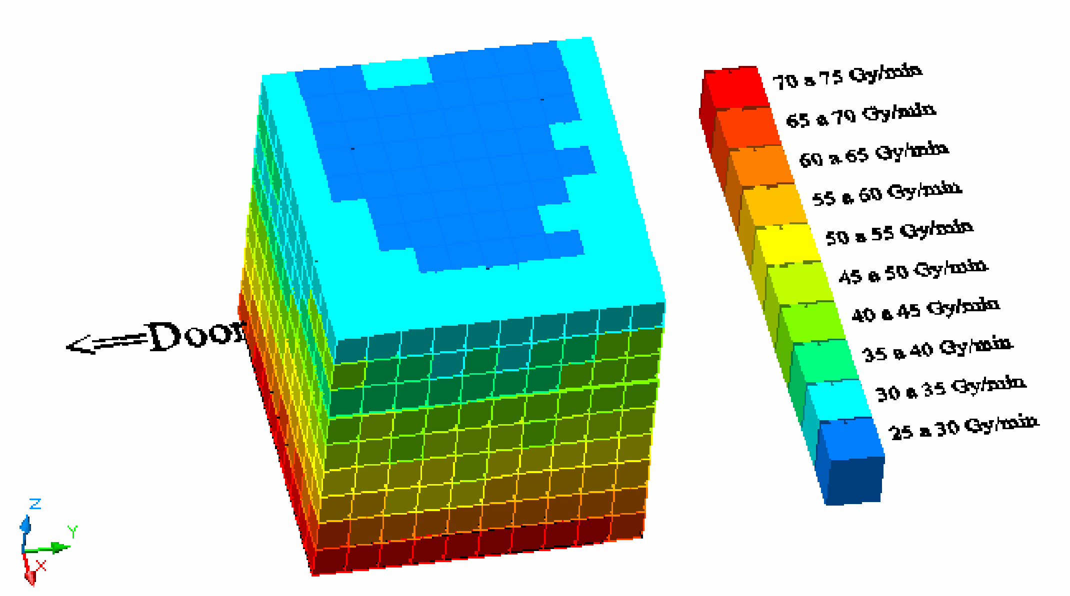


Figure 7. Dose rate distribution in a water parallelepiped

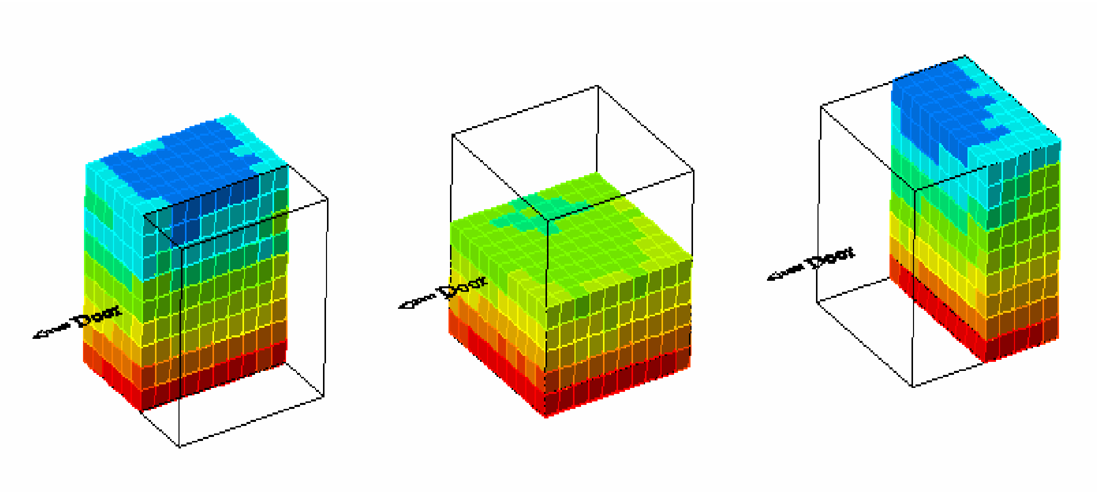


Figure 8. Schematic view of a water parallelepiped in half cuts

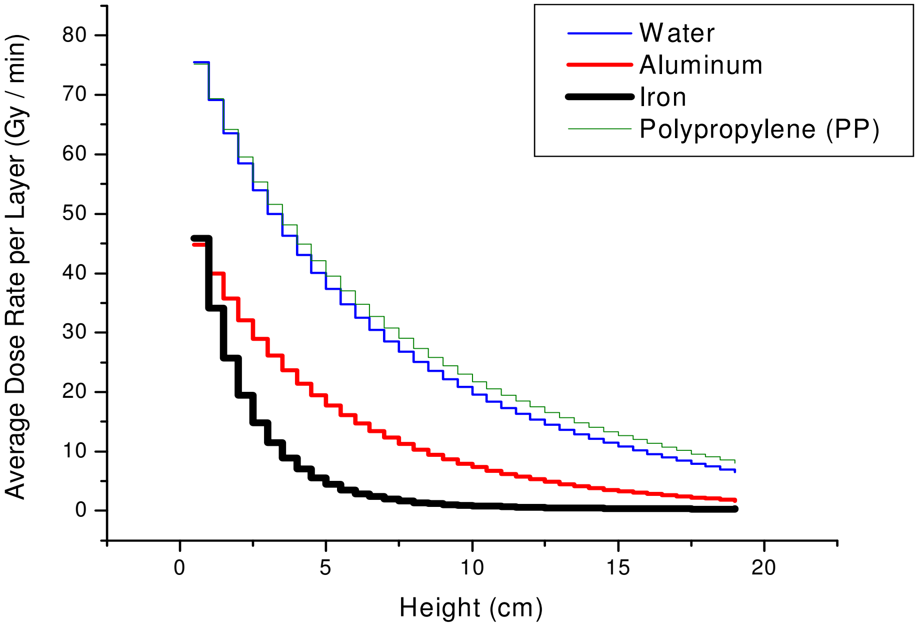


Figure 9. Dose rate distributions in cylindrical samples of different compositions

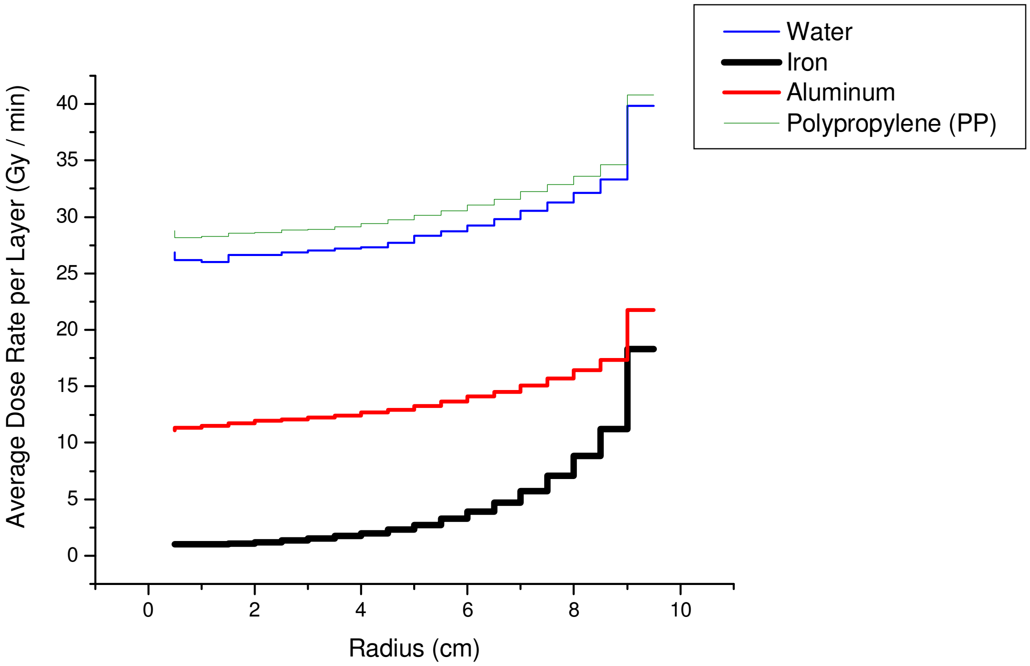


Figure 10. Dose rate distributions inside spherical samples of different compositions

With basis on those results, it can be concluded that dose rates inside samples of different geometries (parallelepiped, cylinder and sphere) decrease upwards as positions further away from the source plane are considered. Such finding is consistent with the vertical dose gradient measured inside the upper irradiation chamber.

4. CONCLUSIONS

The complex calculations performed in this work with the MCNP code, based on a detailed modeling of the cesium-137 source and the inner structures of the research gamma irradiator at CTEx, provided an accurate description of the heterogeneous dose rate distributions inside samples of varying geometries, compositions and densities. Such data will be used to refine predictions of exposure times and to implement new irradiation procedures in order to obtain more homogeneous dose distributions throughout samples.

Based on the results from the calculations it can be concluded that the attenuation of the gamma flux can become severe in many cases. Although horizontal dose gradients have been found to be relatively small across the central volume of the irradiation chambers, the dose rate distribution can indeed become highly heterogeneous inside samples thicker than 10cm. Thus in order to determine an accurate mean dose for each irradiated sample, a precise evaluation of such effect is fundamental.

Suggestions for future works include: measuring the dose distribution inside samples by using high precision dosimeters; improving the simulation of food samples by using more detailed compositions and geometries in order to obtain a better description of the effects of irradiation on food components; modeling small structures assembled with lead bricks that would be positioned inside the upper irradiation chamber in order to provide much lower dose rates, appropriate for experiments of seed excitation and finally calculating the gamma-ray spectrum at several locations of interest in order to investigate the attenuation and scattering behaviors of the gamma fluxes.

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