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Comparison of experimental and calculated shielding factors for modular buildings in a radioactive fallout scenario

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ABSTRACT

Experimentally and theoretically determined shielding factors for a common light construction dwelling type were obtained and compared. Sources of the gamma-emitting radionuclides ^{60}Co and ^{137}Cs were positioned around and on top of a modular building to represent homogeneous fallout. The modular building used was a standard prefabricated structure obtained from a commercial manufacturer. Four reference positions for the gamma radiation detectors were used inside the building. Theoretical dose rate calculations were performed using the Monte Carlo code MCNP6, and additional calculations were performed that compared the shielding factor for ^{137}Cs and ^{134}Cs. This work demonstrated the applicability of using MCNP6 for theoretical calculations of radioactive fallout scenarios. Furthermore, the work showed that the shielding effect for modular buildings is almost the same for ^{134}Cs as for ^{137}Cs.

1. Introduction

After an airborne release of radionuclides to inhabited environments, external gamma irradiation from deposited radioactivity can contribute considerably to the radiation exposure of the population. The shielding of gamma radiation by buildings can, however, reduce this exposure and sheltering of inhabitants is one of the principal countermeasures considered for areas potentially affected by radioactive release. Detailed knowledge of the shielding properties of buildings is therefore an important component of risk assessment in radiological emergency preparedness. Representing the shielding effect of a single-storey building, the UNSCEAR used a location factor of 0.1 (UNSCEAR, 2016) which describes the reduction in ambient dose equivalent from external exposure to deposited material that is achieved when indoors.

As the geometry of building structures is too complex for simple methods such as the point kernel model (Spencer et al., 1980), Monte Carlo calculations are needed to calculate shielding factors as shown in a comparison performed by Jensen and Thykier-Nielsen (1989). The shielding properties can vary greatly for different types of buildings (e.g., Finck, 1991) leading to the use of Monte Carlo simulations in the late 1980s at the GSF (now the Helmholtz Zentrum München German Research Center for Environmental Health) (Jacob and Meckbach, 1987; Meckbach and Jacob, 1988; Meckbach et al., 1987, 1988) An early Monte Carlo code SAM-CE (Lichtenstein et al., 1979) was applied to calculations for four different types of houses. Inhabited area external dose estimates in the European standard decision support systems ARGOS and RODOS rely entirely on these few old datasets. Monte Carlo calculations were repeated for one of these building types using the modern code MCNP6 (Goorley et al., 2012), and agreements and deviations within the order of magnitude for different parts of the building are described in a report that is still to be published. Further Monte Carlo simulations were performed for an industrial area (Kis et al., 2003; 2004), for various scenarios of U.S. residential structures (Dickson and Hamby, 2014; 2016; Dickson et al., 2017), for typical houses in Brazil (Salinas et al., 2006), and typical buildings in Japan (Furuta and Takahashi, 2015). To the best of our knowledge this is the first occasion where Monte Carlo calculations of shielding factors have been experimentally verified, employing a building type with lightweight walls that is used in Scandinavia for e.g. preschools, schools and habitation.

The aim of this study was to compare numerical simulation results from a theoretical calculation with practical measurements in a modular building geometry by using point sources of ^{137}Cs and ^{60}Co distributed over an area of about 800 m^2 around the building to mimic a surface deposition. By doing so we aim to show the applicability of the Monte Carlo simulation for this purpose, both in terms of the accuracy of the shielding estimate as well as the ability to find suitable, representative indoor points for obtaining the shielding factor. The comparison study was performed for a lightweight prefabricated

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modular building which was selected because this type of construction is not uncommon in Scandinavia as solutions for kindergartens, office-complexes and habitation in areas with rapid population growth. Another aspect of this type of building is the poor shielding provided by the light walls, and are therefore of special concern in emergency preparedness. The focus was on the two cesium radionuclides ^{134}Cs and ^{137}Cs, which have been of main concern in connection with the Chernobyl and Fukushima incidents (Imanaka et al., 2015). ^{137}Cs is also represented among those important high-activity sealed sources that could become dispersed in an accident or as a consequence of a terrorist attack (Andersson et al., 2008). However, this study also considered ^{60}Co as a representative of higher-energetic sources, as it also is directly relevant to plausible terrorism scenarios (Ferguson et al., 2003).

2. Materials and methods

2.1. Concept of the shielding factor

The shielding factor represents the reduction of the absorbed dose rate by attenuation and scattering when the radiation passes through matter. The shielding factor at a point inside a building structure acting on a radiation source outside the building can be defined as

$$S_{bld} = \frac{\dot{D}_{bld}}{\dot{D}_{ref}}, \quad 0 \leq S_{bld} \leq 1 \tag{1}$$

where $\dot{D}_{bld}$ is the absorbed dose rate at a point inside the building and $\dot{D}_{ref}$ is the absorbed dose equivalent at the same point in air without the presence of the building for an identical source geometry (Finck, 1991). This factor is based on the barrier shielding factor concept that was originally defined by Spencer (1962) and compares the dose rate at one position caused by the same source to the dose rate at the same position replacing the building with air. A second concept developed by Spencer (1962) is geometry shielding, which compares the dose rate at one position caused by a given source and replacing the building by air to the dose above an infinite, uniformly contaminated plane-surface source at a reference height of 1 m. Geometry shielding can be combined with the barrier-shielding concept by multiplication. The resulting factor is also called reduction factor. In the theoretical calculation, the shielding factor can be determined by first calculating the absorbed dose rate with the building in place, and then dividing it by the absorbed dose rate calculated at the same point but with the building removed and replaced by air. Of course, this is not possible in an experimental situation for buildings that already exist.

When shielding factors are determined experimentally by measuring dose rates with a dose rate instrument, it is necessary to separate the natural background component as defined by IAEA (IAEA, 2007) from the signal originating from a specific radiation source. This is done in two steps. First, the natural background is measured both inside the building and outside using one location as a reference. Then, the shielding factor for the radiation from the source is calculated from the relationship

$$S_{bld} = \frac{\dot{D}_{tot,bld} - \dot{D}_{bgd,bld}}{\dot{D}_{tot,ref} - \dot{D}_{bgd,ref}} \tag{2}$$

where $\dot{D}_{tot,bld}$ and $\dot{D}_{tot,ref}$ are the total measured absorbed dose rates inside the building and outside at the location chosen as reference with the radiation sources present. $\dot{D}_{bgd,bld}$ and $\dot{D}_{bgd,ref}$ are the dose rate contributions from the natural background in the building and outside at the location chosen as reference as measured in the absence of the source.

The focus of this study was on the shielding factors considering contamination on outdoor horizontal surfaces (ground and roof). In fallout scenarios where the deposition mainly has arisen from rainout or washout of fission products from the passing plume, radionuclides on the ground and on the roof of buildings can be expected to contribute significantly to the total dose (Andersson, 2009), although buildings naturally also protect against radiation from contamination, e.g., on all vertical surfaces, on other indoor surfaces, on vegetation and in the air (primary contaminant plume or resuspended radioactive matter).

Fig. 1. Setup of the modular building.

2.2. Description of the experiment

The applied modular building consisted of two standard office modules with outer measurements 900 cm × 330 cm × 300 cm (L x W x H) rented by the company Bilsby®, that were fitted together side by side (Fig. 1). The modules were placed in an open field (> 100 m clear in all directions) and raised with wooden beams from the uneven ground to make them level. Each module had one window on each short side and one door on each long side. The outer measurements of the windows were 140 cm × 120 cm (W x H) and of the doors 90 cm × 200 cm (W x H), so the fraction of windows was about 7% of the wall surface of the entire modular building and that of the doors was about 4%. The outer wall thickness was 12.5 cm and consisted mainly of wood and mineral wool. The combination thus had four windows, two doors, and one opening between the modules. The inner wall thickness was 25 cm. Inside one of the modules an “inner room” of lightweight expanded clay aggregate (LECA) was set up (Fig. 2) to investigate the impact of heavier material for constructing buildings. This room had a wall thickness of 15 cm, height of 152 cm, and outer measurements of 103 cm × 88 cm due to the measures of the used bricks.

Dose rate instruments (Automess Dose Rate Meter 6150 AD 6/H with a plastic scintillator probe 6150 AD-b/H) were used to experimentally determinate the dose rates. They were calibrated to the ambient dose rate, H*(10), according to the ICRP definition (ICRP, 2010). This is the absorbed dose rate at a point 10 mm below the surface in the 300 mm diameter ICRU sphere (consisting of tissue-equivalent matter) subjected to a parallel and aligned radiation field. One detector was calibrated by the Swedish Radiation Safety Authority (SSM) for calibration factors regarding the ambient dose rate equivalent, H*(10), and the angular efficiency (30°, 60°, and 90°) for ^{241}Am, ^{137}Cs, and ^{60}Co. The calibration factors for the other detectors were determined by placing a source at 1 m distance from the center of a scintillator crystal at 0° in a low background level room, with the calibrated detector as a reference instrument for ^{60}Co and ^{137}Cs. The deviations were within a range of 10%. It is assumed that the ratio of ambient dose, with and without shielding, at a given observation point, is the same as the corresponding ratio of the absorbed dose at that point. In the same low-background-level room, sources were also placed at 30°, 60°, and 90°to assess the angular efficiency. The results of those measurements were within a range of 6%. Four detectors were positioned inside the modules (Fig. 2) and one detector outside, about 14 m away from the