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Published in:
Journal of Environmental Radioactivity

Link to article, DOI:
[10.1016/j.jenvrad.2018.04.005](https://doi.org/10.1016/j.jenvrad.2018.04.005)

Publication date:
2018

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Hinrichsen, Y., Finck, R., Östlund, K., Rääf, C., & Andersson, K. G. (2018). Comparison of experimental and calculated shielding factors for modular buildings in a radioactive fallout scenario. *Journal of Environmental Radioactivity*, 189, 146-155. <https://doi.org/10.1016/j.jenvrad.2018.04.005>

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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 .

Keywords:

Shielding factor, Monte Carlo simulations, Experimental validation

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 m² 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 prefabri-

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cated modular building which was selected because that 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

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

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

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

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).

Figure 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 x 330 x 300 cm (L x W x H) rented by the company Bilsby[®], that were fitted together side by side (Figure 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 x 120 cm (W x H) and of the doors 90 x 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 (Figure 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 x 88 cm due to the measures of the used bricks.

Figure 2: Detector positions inside the modular building. The top and bottom wall have two windows each. The left and right wall have one door each, and there is a doorway connecting both modules where the modules are fitted together. The U-shape in the top-left corner represents the clay brick structure (LECA).

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 (Figure 2) and one detector outside, about 14 m away from the modules. All detectors were placed 1 m above the floor surface in the modules. The bottom level of the modules was 26 cm beneath the floor surface and was used as ground surface, as the ground was uneven and thus the modules had to be put on beams.

^{137}Cs and ^{60}Co point sources as well as one point source with physical diameter <10 mm of ^{60}Co were used in the experiments. The respective details including uncertainties are presented in Table 1.

Table 1: Sources used for the measurement of shielding factors. The uncertainties represent a coverage factor of $k=2$.

Radionuclide	Source number	Activity in MBq
^{137}Cs	1	1400 ± 200
	2	880 ± 80
	3	850 ± 150
^{60}Co	4	6100 ± 1600
	5	45 ± 4
	6	45 ± 4
	7	94 ± 9
	8	94 ± 9

Figure 3: Schematic overview of the measurement grid. All crossings of red and blue lines indicate source position points. The width of one row and column represented by the letters and numbers at the frame is 1 m.

The measurement scheme used in the study followed a grid system that was 29 m x 26.5 m, as represented in Figure 3 for the source positions. The red grid in Figure 3 represents a distance between the source points of 4 m and the blue grid represents a subdivision of the red grid to a distance between the source points of 2 m. Every crossing between the red, blue, and red-blue lines in the figure represents a source point. Thus, the number of source points is denser along the short side of the module configuration in order to reduce systematic uncertainties for measurements of radiation penetrating the windows. The 4 m density of source points is also too coarse for measuring the shielding factor on the roof; hence, it was decreased to a 2 m density as seen by the crossings of the red, blue, and red-blue lines in Figure 3. The height of the positioned sources was chosen to be on a plane that would have been level with the ground if the modules were placed on a level ground surface.

To calculate the shielding factor, the background values for all detectors and their respective positions were recorded daily prior to the measurements with the sources present. These values were eventually subtracted from the instrument reading of the source points. The ambient dose rate was also corrected with the calibration factors and the angular efficiencies via a calculation of the incident angle from each source point.

Figure 4: Birds-eye view of the modular building model.

The $H^*(10)$ rates measured with the detector outside the modules were also corrected using the same method mentioned above (subtraction of measured background values and correction with calibration factors and angular efficiencies). Ambient dose rates for different source points were compiled and the data set was used to fit a mathematical expression that displayed $H^*(10)$ as a function of distance. This expression was then used to extract the reference $H^*(10)$ for the exact distance from each detector to each source point. The measured $H^*(10)$ from each source point and each detector was then divided by this value

to determine the shielding factor.

Table 2: Material specifications with definite atomic compositions (rounded) and densities that were used for the Monte Carlo calculations.

Material	Atomic composition	Density in kg/L
Particle board	46.24 % H; 32.34 % C;	0.7
Profile boards	0.28 % N; 20.88 % O;	0.6
Plywood	0.06 % Mg; 0.12 % S;	0.5
Window frame	0.04 % K; 0.04 % Ca	0.45
Mineral wool	42.5 % O; 1.7 % Na; 5.4 % Mg; 10.6 % Al; 18.2 % Si; 1.9 % K; 14.3 % Ca; 0.5 % Mn; 4.9 % Fe	0.167
Glas	60.39 % O; 8.81 % Na; 25.18 % Si; 5.62 % Ca	2.4
Plastic	50.00 % H; 33.33 % C; 16.67 % Cl	1.51
LECA bricks	63.33 % O; 0.69 % Na; 0.92 % Mg; 9.47 % Al; 21.91 % Si; 0.01 % P; 1.09 % K; 0.99 % Ca; 0.20 % Ti; 0.01 % Mn; 1.38 % Fe	2.2
Steel	3.41 % C; 4.87 % N; 0.97 % Si; 0.05 % P; 0.03 % S; 18.88 % Cr; 8.69 % Mn; 65.92 % Fe; 4.65 % Ni	7.86
Soil	31.69 % H; 50.16 % O; 4.00 % Al; 14.16 % Si	1.52
Air	0.02 % C; 78.44 % N; 21.07 % O; 0.47 % Ar	0.001205

Measurements for the following four setups were performed:

Setup 1: All 92 grid points on the ground according to Figure 3 were measured with three ^{137}Cs point sources totaling 3.1 GBq (Sources number 1-3 in Table 1) placed in a 200 mL plastic container (inner wall $\varnothing = 67$ mm and inner wall thickness = 1.9 mm). This container was placed on a height-adjustable tripod in order to place the sources in the measurement plane.

Setup 2: ^{137}Cs measurements were taken of the 15 grid points on the roof of the modules (L11 to P19 in Figure 3). The scintillators were now re-oriented so that their front surfaces were directed towards the ceiling of the building, instead of downwards in the previous experiments with the center of the plastic crystal remaining 1 m above the floor surface. For these measurements, one point source was used with activity 880 MBq (Source number 2 in Table 1), and it was also placed in a 200 mL plastic container.

Setup 3: All 92 source points on the ground, according to Figure 3, were measured with the point source of 6100 MBq

Figure 5: Ratio of the experimentally determined to the theoretically calculated shielding factor according to source region position around the modules, for four different detector regions inside the modules (red spot) for Setup 1 (^{137}Cs). According to a material compendium <McConn Jr et al., 2011>, the density of the clay bricks in the calculations was assumed to be $\rho = 2.20\text{kg/L}$, and it was later measured to be $\rho = 0.65\text{kg/L}$.

(^{60}Co - source number 4 in Table 1). Due to its high activity, complementary measurements were made with weaker sources at the points closer to the modules in order to avoid saturating the detectors. The source points where one or more detectors saturated and for which complementary measurements were necessary were N9, L9, P9, R9, J11, R11, J13, R13, J15, R15, J17, R17, J19, R19, J21, L21, N21, P21, J23, L23 and N23 (Figure 3). Measurements were taken by using three point sources of ^{60}Co that contained a total 180 MBq (Sources number 5, 6, and 7 or 8 in Table 1). The sources were placed in a 200 mL plastic container with inner wall diameter 67 mm, which, in turn, was placed on a height-adjustable tripod.

Setup 4: For the ^{60}Co measurements of the 15 grid points on the roof of the modules (L11 to P19 in Figure 3), the detectors were turned 180° with the center of the plastic crystal remaining 1 m above the floor surface. Two point sources totaling an activity of 190 MBq (Sources number 7 and 8 in Table 1) were used for the measurements on the roof. As in Setup 3, the

sources were placed in a 200 mL plastic container.

For all the measurements that used the 200 mL plastic container, the maximum displacement of the sources within the container was 30 mm. Source number 4 in Table 1 was somewhat more difficult to place in exact position because of its higher activity and attached handling equipment. Because of this, the displacement varied from measurement point to measurement point, in the range 10 cm to 40 cm.

2.3. Description of the calculations

The Monte Carlo calculations for the setup of the modular building were performed with the transport code MCNP6 <Goorley et al., 2012>, using the nuclear cross-section data set ENDF/B-VII.0 <Chadwick et al., 2006>. Among other processes, it accounts for photon creation and loss through relevant mechanisms such as bremsstrahlung, fluorescence, Compton scattering, photon capture, pair production and p-annihilation.

Figure 6: Ratio of the experimentally determined to the theoretically calculated shielding factor according to source region position on top of the modules, for four different detector regions inside the modules (black spot) for Setup 2 (^{137}Cs). According to a material compendium <McConn Jr et al., 2011>, the density of the clay bricks in the calculations was assumed to be $\rho = 2.20\text{kg/L}$, and it was later measured to be $\rho = 0.65\text{kg/L}$.

The code allows for the definition of complex three-dimensional geometries through a combinatorial geometry technique. The definition of the geometry is based on the construction drawings and descriptions made available by Bilsby <Bilsby[®], ->, and measurements for the real modules included an additional construction made of clay bricks (Figure 4). The regions in space were constructed by a logical combination (union, intersection, difference) of elementary geometric bodies and surfaces. Different databases <McConn Jr et al., 2011; Websides, 2016> were used to assign the material specifications with definite atomic compositions and densities as summarized in Table 2 to the input data for the different building structures and environmental regions.

For each setup separate computations were performed for the different source positions and for reference values without the building structure. The setups corresponded to the four different measurement setups. The source regions were defined in all calculations as cylinders with a diameter and height of 1

cm. The source energies were either monoenergetic sources of 0.662 MeV representing the ^{137}Cs sources, or they were multi-energetic sources with energies of 1.173 MeV and 1.332 MeV representing the ^{60}Co sources, also taking into account the emission probability of both energies. Internal scatter within the source material was neglected, and there was no extra material composition attached to the source regions apart from the surrounding air, but from a simple comparison calculation without building can be assumed that about 12 % of the calculated ambient dose is caused by gamma radiation that was scattered by the soil for ^{137}Cs and about 8 % for ^{60}Co .

To compare the shielding factors for the ^{134}Cs sources with those for the ^{137}Cs sources, additional Monte Carlo computations were performed for 70 source points on the roof (K11 to Q20 in Figure 3) of the modules for the ^{137}Cs sources as well as poly-energetic gamma sources with energies of 0.475 MeV, 0.563 MeV, 0.569 MeV, 0.605 MeV, 0.796 MeV, 0.802 MeV, 1.039 MeV, 1.168 MeV, and 1.366 MeV. These latter rep-

Figure 7: Ratio of the experimentally determined to the theoretically calculated shielding factor according to source region position around the modules, for four different detector regions inside modules (red spot) for Setup 3 (^{60}Co). According to a material compendium <McConn Jr et al., 2011>, the density of the clay bricks in the calculations was assumed to be $\rho = 2.20\text{kg/L}$, and it was later measured to be $\rho = 0.65\text{kg/L}$.

represent the ^{134}Cs sources accounting for the emission probability of these energies, and they lead to a weighted mean value of 0.698 MeV. The reference values were determined as in the other setups without the building structure.

The detection regions were defined as air-filled spheres with a diameter of 30 cm. Four detector regions were positioned according to the detector positions in the real modular building 1 m above floor level of the modules (Figure 2). In those regions, the number and energies of the gamma particles passing through were scored. By using conversion coefficients <ICRP, 2010>, the fluence was transferred to the ambient dose equivalent $H^*(10)$ at the end of the calculation, as the applied dose rate instruments in the experiment were calibrated to the ambient dose rate $H^*(10)$.

In order to obtain sufficiently good statistics below a level of 5 % standard deviation within acceptable computation times in MCNP6 various variation reduction techniques can be ap-

plied. The defined regions in space are called cells and for each of them a weight window was generated. The number of a particle's weight in MCNP6 represents the number of physical particles which in these calculations are photons with different random walks being represented by one MCNP particle. For each space cell, a lower weight bound is supplied by the user and the upper weight bound is a specified multiple of the lower. These weight bounds define a window of acceptable weights. If a particle emitted from the source and generated by interactions with the materials is below the lower weight bound, then "Russian roulette" is played and randomly the particle's weight is either increased to a value within the window or the particle is terminated. If a particle is above the upper weight bound, it is split so that its parts are within the window. No action is taken for particles within the window. The weight windows were determined using the Weight Window Generator, which estimates the importance of the cells in the space. The importance of cells is defined as the expected score generated by a unit weight particle after entering the cell. By using the cell-based genera-

Figure 8: Ratio of the experimentally determined to the theoretically calculated shielding factor according to source region position on top of the modules, for four different detector regions inside the modules (black spot) for Setup 4 (^{60}Co). According to a material compendium <McConn Jr et al., 2011>, the density of the clay bricks in the calculations was assumed to be $\rho = 2.20\text{kg/L}$, and it was later measured to be $\rho = 0.65\text{kg/L}$.

tor, the average importances of the space cells can be estimated.

3. Results

3.1. Comparison of the theoretical and experimental shielding factors

The shielding factors determined from the experiment were compared to those calculated theoretically. This was done by using the ratio of the experimentally and computationally determined shielding factors.

Setup 1: The resulting ratios of the experimentally determined to the theoretically calculated shielding factors for ^{137}Cs were plotted in heat maps, in which individual values are represented graphically by a color code, for the corresponding distances from the respective detector region. This allowed an investigation into any possible influence of the different source positions around the modules (Figure 5) on the ratio. The ranges

of the plotted ratios show that the clay bricks in the real modules provided less shielding than those in the theoretical model. Measurements of the real clay bricks showed that their density was $\rho = 0.65\text{kg/L}$, which is lower than the clay density applied to the model: $\rho = 2.20\text{kg/L}$ taken from a material compendium <McConn Jr et al., 2011>. On average, the shielding factor over all source and detector regions was experimentally determined to be 0.66 ± 0.02 and theoretically calculated to be 0.60 ± 0.02 . The overall ratio of the experimentally determined to the theoretically calculated shielding factors was determined to be 1.39 ± 0.04 . If the combinations of source positions to detector regions are divided into those that cross the clay bricks looking at the direct line and those that do not cross the clay bricks at the direct line the ratios are determined to be 1.03 ± 0.02 without and 2.53 ± 0.06 with the clay bricks.

Setup 2: The resulting ratios of the experimentally determined to the theoretically calculated shielding factors for ^{137}Cs were plotted in heat maps for the corresponding source posi-

Table 3: Ratios and standard error of the mean of the experimentally determined and theoretically calculated shielding factors for different scenarios for a density of the clay bricks (LECA) of $\rho = 2.20\text{kg/L}$ if not a different value is mentioned.

Gamma source	Influences assumed	Source region	
		Ground	Roof
^{137}Cs	None	1.39 ± 0.04 ($\rho_{LECA} = 2.20\text{kg/L}$)	1.24 ± 0.10
		1.00 ± 0.01 ($\rho_{LECA} = 0.65\text{kg/L}$)	
	Without clay bricks or metal case	1.03 ± 0.02	1.10 ± 0.03
	Clay bricks	2.53 ± 0.06	2.68 ± 0.20
^{60}Co	Metal case	–	0.64 ± 0.04
	None	1.33 ± 0.04	1.12 ± 0.07
	Without clay bricks or metal case	1.02 ± 0.05	1.02 ± 0.02
	Clay bricks	2.22 ± 0.05	2.17 ± 0.15
	Metal case	–	0.67 ± 0.03

Table 4: Ratios and standard error of the mean of the experimentally determined and theoretically calculated shielding factors for the different setups and detectors for a density of the clay bricks (LECA) of $\rho = 2.20\text{kg/L}$ if not a different value is mentioned.

Setup		Detector			
		#1	#2	#3	#4
^{137}Cs	Ground ($\rho_{LECA} = 2.20\text{kg/L}$)	2.38 ± 0.08	1.07 ± 0.03	1.05 ± 0.03	1.06 ± 0.03
	Ground ($\rho_{LECA} = 0.65\text{kg/L}$)	0.95 ± 0.02	1.02 ± 0.02	0.99 ± 0.02	1.03 ± 0.02
	Roof	2.14 ± 0.25	0.96 ± 0.08	0.95 ± 0.06	0.91 ± 0.06
^{60}Co	Ground	2.02 ± 0.06	1.10 ± 0.04	1.10 ± 0.05	1.10 ± 0.04
	Roof	1.76 ± 0.18	0.92 ± 0.06	0.90 ± 0.06	0.88 ± 0.06

tions on top of the modules to the respective detector region. This allowed an investigation into any possible influence of different source positions on top of the modules (Figure 6) on the ratio. The ranges of the plotted ratios show that the clay bricks in the real modules provide less shielding than those in the theoretical model, as the clay density was assumed to be higher in the model than that of the real bricks. The ranges of the plotted ratios also show that the sources that were positioned on the line where the two modules were fitted together lead to greater shielding from the real modules than that seen in the theoretical model. This can be explained because the edges of the real modules are encased in metal, which was not included in the model. The overall ratio of the experimentally determined to the theoretically calculated shielding factors was determined to be 1.24 ± 0.10 . If the combinations of source positions to detector regions are divided into those that cross the clay bricks looking at the direct line and those that do not cross the clay bricks as well as those where the sources were positioned on the metal case the ratios are determined to be 1.10 ± 0.03 without the clay bricks or metal case, 2.68 ± 0.20 with the clay bricks and 0.64 ± 0.04 with the metal case.

Setup 3: The resulting ratios of the experimentally determined to the theoretically calculated shielding factors for ^{60}Co were plotted in heat maps as in Setup 1 (Figure 7). The ranges of the plotted ratios show again that the clay bricks in the real modules provide less shielding than those in the theoretical model, as the clay density was assumed to be higher in the model than that of the real bricks. On average, the shielding factor over all source and detector regions was experimentally determined to be 0.73 ± 0.02 and theoretically calculated to be 0.65 ± 0.02 .

This resulted in an overall ratio and the standard error of the mean of the experimentally determined to the theoretically calculated shielding factors of 1.33 ± 0.04 . If the combinations of source positions to detector regions are divided into those that cross the clay bricks looking at the direct line and those that do not cross the clay bricks at the direct line the ratios are determined to be 1.04 ± 0.02 without and 2.22 ± 0.05 with the clay bricks.

Setup 4: The resulting ratios of the experimentally determined to the theoretically calculated shielding factors for ^{60}Co were plotted in heat maps as in Setup 2 (Figure 8). The ranges of the plotted ratios show again that the clay bricks in the real modules provide less shielding than those in the theoretical model, as the clay density was assumed to be higher in the model than that of the real bricks. Furthermore, the ranges of the plotted ratios again show that the sources that were positioned on the line where the two modules were fitted together lead to greater shielding of the real modules than that seen in the theoretical model. This can be explained because the edges of the real modules are encased in metal which was not included in the model. The overall ratio of the experimentally determined to the theoretically calculated shielding factors was found to be 1.12 ± 0.07 . If the combinations of source positions to detector regions are divided into those that cross the clay bricks looking at the direct line and those that do not cross the clay bricks, as well as those where the sources were positioned on the metal case the ratios are determined to be 1.02 ± 0.02 without the clay bricks or metal case, 2.17 ± 0.15 with the clay bricks and 0.67 ± 0.03 with the metal case.

Figure 9: Ratio of the experimentally determined to the theoretically calculated shielding factor according to source region position around the modules for four different detector regions inside the modules (red spot) for Setup 1 with corrected density of the clay bricks (^{137}Cs).

Table 3 provides a summary of the ratios of the compared experimentally determined and theoretically calculated shielding factors.

To find a suitable and representative indoor point for the shielding factor the overall ratios were also determined per detector region and are summarized in Table 4. The ratios are the highest for detector #1 as it was almost surrounded by the clay bricks and thus its shielding factor was the most affected. The ratios determined for the source positions on the roof were lower than the respective ratios for source positions on the ground, since one third of the source positions on the roof were affected by the metal case.

3.2. Impact of the clay density on the result

For various brick clays, the firing temperature has a high impact on the development of their pore structure <Hill, 1960> and correspondingly their density. Moreover, some clay brick types have large perforations that enhance their thermal insu-

lating capacity <Gosmartbricks, 2017>, which naturally also considerably reduces the bulk density of the brick. To investigate the impact of the different densities of clay bricks in this case and to show that the Monte Carlo calculations are also applicable for the clay brick structure, additional calculations were performed for clay brick densities of $\rho = 2.20\text{kg/L}$ and $\rho = 0.65\text{kg/L}$. The ratio comparing $H^*(10)$ caused by ^{60}Co and ^{137}Cs crossing a clay brick for both densities was calculated using the MCNP6 code <Goorley et al., 2012>. The ratios were determined for different thicknesses of clay brick (Figure 10), as the radiation can cross the clay brick structure in the building model at different angles. The ratio of the difference of the shielding factor ratios for the respective source point detector combinations that were affected by the clay brick structure are in the right range.

Additionally, the calculations were repeated for all source points that were influenced by the clay brick structure according to Setup 1, but this time using the measured density of the clay brick structure. The resulting ratios of the experimentally deter-

Figure 10: Ratio of the difference in $H^*(10)$ after crossing clay bricks with a density $\rho = 0.65\text{kg/L}$ to bricks with density $\rho = 2.20\text{kg/L}$.

mined to the theoretically calculated shielding factors for ^{137}Cs were plotted in heat maps for the corresponding distances from the respective detector region, as they were for the first calculations (Figure 9). The presented results show good agreement with the measurements (slight variations will always be expected due to small imperfections in the model compared with real life, due to ground unevenness, surface texture, etc.). The ratio of the experimentally determined to the theoretically calculated shielding factors was now determined to be 0.95 ± 0.02 for detector #1, 1.02 ± 0.02 for detector #2, 0.99 ± 0.02 for detector #3, 1.03 ± 0.02 for detector #4 (Table 4), and 1.00 ± 0.01 averaging over all detector regions (Table 3). The results show that all detector regions are of similar quality. The average theoretical shielding factor increased with the new calculations to 0.68 ± 0.02 .

3.3. Comparison of shielding factors for ^{137}Cs and ^{134}Cs

The comparison of the theoretically determined shielding factors for ^{137}Cs and ^{134}Cs is presented in Figure 11. The ratio and the standard error of the mean of the shielding factor of ^{134}Cs and of ^{137}Cs was determined to be 1.02 ± 0.05 on average over all of the different source positions.

4. Discussion

In conclusion, the theoretically calculated shielding factors showed good agreement with the experimentally determined shielding factors for the modular building in case of source point and detector area combinations that were not directly influenced by the clay brick structure or the metal case. The ratios determined for the source points, for which the direct radiation path crosses the clay structure before reaching the detector, were within the predicted range, considering the clay density in the model and the density in the experiment. Further calculations also showed the agreement between the model and experiment. For future calculations, it will be important to know

Figure 11: Shielding factor of ^{134}Cs compared to the shielding factor of ^{137}Cs for source region positions on top of the modules (red crosses, the black line has a slope of 1)

the actual density of bricks and other important construction elements used in building houses. If not properly accounted for, construction materials with highly deviating density or atomic composition may strongly affect the accuracy in the calculated shielding factors of a building, depending on the choice of reference point in the building. In the present study, however, the metal case only influenced the result when the source was directly positioned on top of it. For future models has to be considered, that a structure of this type might have to be included, especially when a major part of the unscattered radiation crosses the structure before reaching the detector, which is usually not the case as the metal case normally only covers a very small part of a modular building as in the presented case.

The difference between the calculated and experimentally determined shielding for two different radionuclides with primary gamma energies of 0.662 to 1.25 MeV appeared to be negligible for the reference points not directly affected by the clay bricks (Detector points 2-4). As an example, the ratio between the measured and calculated shielding factors ranged from 1.06 to 1.10 for the ground source geometry (Table 4). Hence, the results showed that the gamma energy, in practice, has no influence on the level of agreement between experiment and calculation, provided that the construction materials are accurately characterized in terms of density and atomic composition. Therefore, the applicability of theoretical calculations using MCNP6 for radioactive fallout scenarios has been demonstrated in practice.

Additionally, it was shown that the shielding effect for modular buildings is almost the same for ^{134}Cs as for ^{137}Cs , meaning that a common value for the shielding factor for this type of building can be used for the two radionuclides that dominate the external gamma fluence in connection with nuclear power plant fallout.

In future investigations that will also use MCNP6, method-

ologies will be demonstrated to, for example, enable optimization of dose reductive interventions in contaminated inhabited areas by calculating dose isolines. The influence on the dose rate of different building features will also be examined. Such calculation estimates are important, as the justification and optimization of an intervention should be based on estimates of residual dose <ICRP, 2007>, and the dose rate conversion factors for the gamma exposure inside and outside resulting from radionuclides deposited on different surfaces at the required level of detail are at most available for 4 to 5 different building types. With modern day computing power, much less time is required to obtain reliable Monte Carlo model estimates with good statistics, and with constant improvements to model data libraries, tools such as MCNP6 will play an increasing role in the optimization of an intervention. Further Monte Carlo models will enable the computation of differential shielding factors, where the shielding of an incoming photon at a given angle of incidence and for a given construction material can be expressed.

5. Conclusions

An agreement within 2 % between the measured and calculated shielding factor (Table 4) can be obtained using Monte Carlo simulations, provided that the atomic composition and density of the majority of the construction materials are accurately specified. This agreement appears to be independent of the primary photon energy of the surrounding gamma sources. The applicability of theoretical calculations using MCNP6 for radioactive fallout scenarios has thus been demonstrated in practice.

6. Acknowledgements

This study was supported by the Swedish Radiation Safety Authority (SSM).

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