# Dose Reduction Factor of Decontamination for the Use in Dose Assessment after the Fukushima Daiichi Nuclear Power Plant accident

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**Abstract.** Dose reduction factor (DRF) is one of important parameters for dose assessment after a nuclear accident taking into account the effects of decontamination. To evaluate the DRFs based on the experiences of the Fukushima Daiichi Nuclear Power Plant accident, we investigated decontamination effects for house surfaces (roof, wall) and the living environment (road, garden). In addition, we developed a house model and an urban area model based on typical characteristics (material, size, form) in Fukushima prefecture. The DRFs were evaluated as the ratio of dose rate inside a house model before/after the decontaminations by Monte Carlo particle transport simulation using the developed models. As the results, the DRFs of decontamination for a house and an urban area were evaluated 0.67–0.84 and 0.75–0.84, respectively.

***KEYWORDS: Fukushima Daiichi Nuclear Power Plant accident, decontamination, dose reduction factor.***

## 1 INTRODUCTION

Decontamination is one of protective actions for reducing radiation doses to the public living in the areas contaminated by radioactive materials. In general, effectiveness of decontamination is represented by decontamination factor (DF) evaluated from the reduction of surface density or surface radiation dose rate. However, the DF cannot be used directly for human dose assessment because that represent the reductions of dose and radioactivity for decontaminated surface only. The dose assessments taking into account the decontamination effects require another index, such as the dose reduction factor (DRF) evaluated from the dose rate in a room or dose equivalent to human body. In this study, we evaluated the DRFs of decontamination for dose assessment based on the experiences of the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident.

## 2 MATERIALS AND METHODS

### 2.1 DECONTAMINATION EFFECTS ON SURFACES

After the FDNPP accident, decontaminations were performed according to the standard procedure of decontamination designated by Ministry of the Environment (MOE) (MOE, 2019) [1]. Several types of decontamination methods are described in this procedure for various surfaces of houses, buildings, and the environment. The DFs for those are reported in a report on the decontamination pilot project performed by Japan Atomic Energy Agency (JAEA) [2], and debrief reports after the decontamination in each municipality. We obtained an debrief report of decontamination performed in Namie town in 2015, and reviewed the DFs.

**Table 1** shows the summary of the DFs for houses described in JAEA's report [2] and the debrief report in Namie town. In this table, decontamination methods, which were mainly used after the FDNPP accident, for roof, wall, and the ground (soil surface and paved surface) are summarized. The DFs is defined as the ratio of surface dose rate measured before/after the decontamination, and those listed in **Table 1** are the averaged values based on JAEA (2014) [2] and the debrief report of decontamination in Namie town.

For roof and wall, scrubbing without water using nylon brushes were adopted, and the arithmetic mean of the DFs were 0.88 and 0.60, respectively. Radioactivity on the ground surface were removed by stripping of surface soils. The DFs for the ground surface by this technique was 0.18. In addition, high-pressure water jet washing was used for paved surfaces such as road. In this case, the DF for this technique was 0.73. The DF values listed in **Table 1** was evaluated from actual information after the

FDNPP accident. In general, the DFs depend on the deposition condition (i.e., dry or wet). Therefore, these values are applicable in the same condition of deposition with the FDNPP accident, that means wet deposition by rainfall.

**Table 1**: Decontamination Factor (DF) for decontamination method adopted after the FDNPP accident.

| Surface | Decontamination method | DF |
|---|---|---|
| Roof [(1)] | Scrubbing without water using nylon brushes | 0.88 |
| Wall [(1)] | Scrubbing without water using nylon brushes | 0.60 |
| Ground [(1)(2)] | Surface soil stripping | 0.18 |
| | High-pressure water jet washing (20 MPa) | 0.73 |

[(1)] JAEA (2012) [1]. [(2)] Debrief report of decontamination in Namie town in 2015.

## 2.2 METHODS

### *2.2.1 Calculation system*

The ambient dose equivalent rate was calculated using Monte Carlo particle transport simulation code PHITS [3] taking into account the contribution from the outdoor surfaces of a house including roof and outer-wall, as well as the other surfaces around a house such as the paved and unpaved ground. The DRF evaluations were performed considering the contributions of deposited $^{134}$Cs and $^{137}$Cs. The $^{134}$Cs:$^{137}$Cs ratio was assumed based on UNSCEAR report (UNSCEAR, 2014) [4], and the value of 1 was used as of contamination occur. These radioactive cesium isotopes were deposited uniformly within a radius of 500 m from a center. The house model and urban area model was located at the center of a half-sphere with a radius of 1000 m filled with air. Ground soil was considered up to 1 m below the ground surface, and the soil density was assumed to be 1.6 g cm$^{-3}$ according to a previous study (Eckerman and Ryman, 1993) [5].

### *2.2.2 House model*

The contributions from the surfaces were calculated using a model of typical Japanese wooden house (Furuta and Takahashi, 2014) [6]. The size of house model was adjusted for the averaged value in Fukushima prefecture (Statistics of Japan, 2015) [7]. Building-area is set to 102 m$^2$ (12 m × 8.5 m) and other parameters relevant to structure of house model was determined by the ratio with the original model. **Figure 1** shows computation scheme for the house model and the 3D outside appearance of the house model. Heigh of house model is 6.7 m, and window area is 12% of the total wall area. The contributions from the ground were calculated by classifying the area into four subareas: (i) the area within 5 m square (Area 1), (ii) the area within 10 m square except for Area 1 (Area 2), (iii) the area 20 m square except for Area 1 and 2 (Area 3), and (iv) outside of 20 m square from the target house (Area 4).

According to the survey on typical house in Japan, it is well known that roof of Japanese typical wooden house uses three type of materials: tile, slate, and metal. We adopted slate for our calculations because most of current Japanese houses are constructed by this material (JHFA, 2018) [8]. Based on the technical report (SKC, 2005) [9] and the domestic standard in Japan (JIS A 5430) [10], the density and thickness of roofs were determined as 1.5 g/cm3 and 5 mm, respectively. Wall is constituted from inner-wall and outer-wall. For inner-wall and outer-walls, gypsum board and ceramic siding were adopted as the construction material because most of Japanese houses use these materials (JSMA, 2016) [11]. The density and thickness of gypsum board was 9.5 mm and 0.7 g/cm$^3$, respectively (JISA 6901:2014) [12]. Those for ceramic siding was 16 mm and 1.1 g/cm$^3$, respectively (JSMA, 2016) [11].

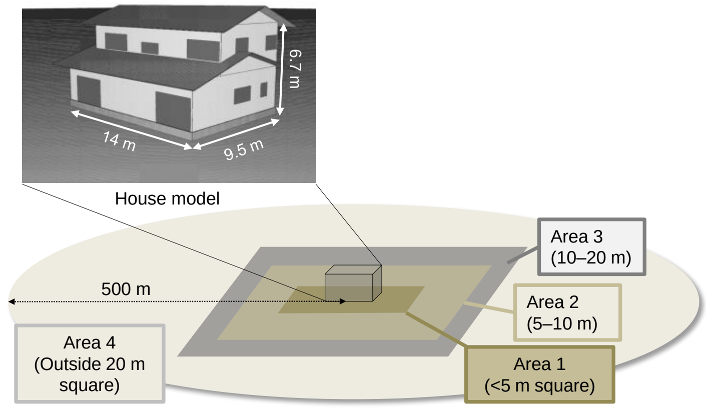

**Figure 1** Computation scheme of a house model

*2.2.3 Urban area model*

The relationship of dose rate measured inside and outside a house depend of the distribution of radionuclides around the house. Therefore, if we evaluated the DRFs for a house on an infinite plane, those values cannot be used for urban environment directly. To evaluate the DRFs for urban environment, it is needed to make urban area model based on actual environment reflecting the target area. For this purpose, we made the urban model based on the survey on the geographical information of Fukushima city. This city is the prefectural capital of Fukushima prefecture, which has a population of about 280,000 and an area of about 760 square kilometers. About 80% of the inhabitants live in one- or two-story wooden houses. Fukushima city is located to the northwest of FDNPP with the distance of approximately 60 km. Although contamination occurred in this city after the FDNPP accident, the concentration of radioactivity was relatively low compared to those in evacuation areas. Therefore, after the accident, the people continued to live in this city without evacuation orders, and decontamination had been made until 2018 (Fukushima city, 2018) [13].

The geographical survey was performed by using google map. We surveyed the averaged value for the distance between houses, width of road in front of house, building-to-land ratio. **Figure 2** shows the urban model based on the geographical information. The distance between houses is 5 m, and the width of road in front of house is 10 m. Number of neighboring houses and its location were determined based on the building-to-land ratio of about 40%.  We used the same model for the neighboring houses with the target house as described in *2.2.2*. Outside the urban area model, the ideal plane extends over a radius of 500 m.

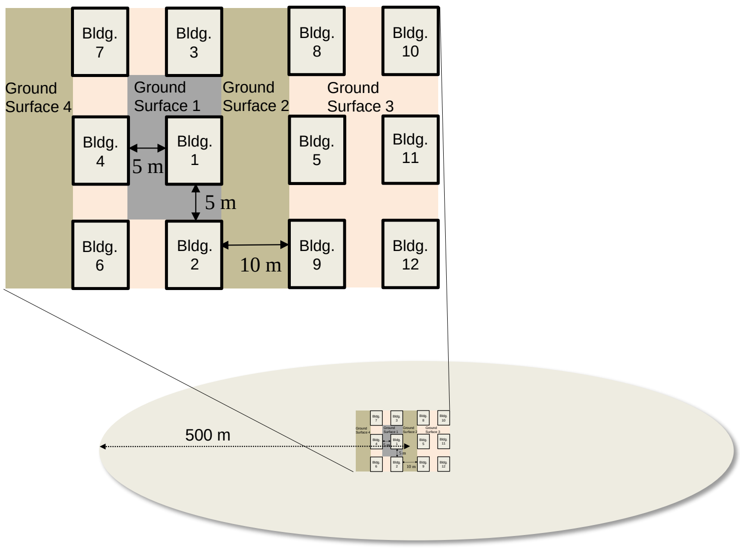

**Figure 2** Computation scheme of urban area model

In our calculations by urban area model, two type of decontamination scenarios were assumed (**Table 2**). The first scenario is that decontamination was performed for target house (Building 1 in **Figure 2**) and its garden (ground surface 1 in Figure 2). In the second scenario, we assumed that decontamination was performed for not only the target house and its garden but also the vicinal community (Buildings 2–12, and ground surfaces 2–4 in Figure 2).

**Table 2**: Decontamination Scenarios for urban area model.

| Scenario No. | Description of Scenario |
|---|---|
| 1 | Decontamination works are performed for the target house and its surfaces only (House Building 1, Ground Surface 1). |
| 2 | Decontamination works are performed for the vicinity area of the target house including target house and neighboring houses and their garden, and roads (House Building 1–12, and Ground Surfaces 1–4). |

*2.2.3 Initial deposition density on surfaces*

To evaluate the DRF, initial deposition density for each surface has to be known taking into account the deposition condition (i.e., dry or wet). Jones et al (2009) [14] reported the initial deposition density corresponding to chemical form and particle size based on the experiences of the Chernobyl accident. After the FDNPP accident, main deposition event, which contribute to the deposition density significantly, occurred on 15 March, 2011 with wet deposition condition. In addition, according to Kaneyasu et al. (2012) [15], the activity median aerodynamic diameters (AMADs) of $^{134}$Cs and $^{137}$Cs were 0.54 and 0.53 μm, respectively for Fukushima-derived particles. Thus, we adopted the initial deposition density for of the particle size of <2 μm under the wet deposition condition. As the results, for roof and wall, relative surface density of 0.85 and 0.01 to the ground surface were used assuming wet deposition condition (Jones et al., 2009; Yoshimura, 2014) [14 ,16].

## 3 RESULTS AND DISCUSSION

**Table 3** shows our calculation results of contributions from surface *i* inside a house model, $c_i$ , by PHITS code. From this table, the DRF is evaluated as following equation:

$$DRF = \frac{\sum_i RD_{i,k} \cdot c_{i,1}}{\sum_i RD_{i,k} \cdot c_{i,0}}, \tag{1}$$

where, $RD_{i,k}$ is relative initial deposition density of surface *i* to the ground surface under the condition $k$. Index $k$ means deposition condition (i.e., dry or wet). Indices of 0 and 1 mean before and after decontamination, respectively. The parameter of $c_{i,1}$ is calculated by $c_{i,1} = DF_i \cdot c_{i,0}$. As described in **Table 1**, the DFs is obtained from the debrief report of decontamination work and a previous study after the FDNPP accident (JAEA, 2012) [2].

Before the decontamination, the contribution weighted by the relative initial deposition density from own surfaces of a house model (roof and wall) and the ground surfaces (Area 1–4) is 23% and 77%, respectively. The breakdown of the contribution of 77% from Area 1, 2 and 3, is 16%, 10%, and 11%, respectively. Remaining contribution of 40% is attributed to the contributions from Area 4.

The DRFs were evaluated by eq. (1) using the $DF_i$, $RD_{i,k}$, and $c_{i,0}$ given in **Table 3**. As the results, the DRFs for a house and the around areas within 5 m, 10 m, and 20 m square is 0.84, 0.76, and 0.67, respectively. That these results are the averaged value for the first floor and second floor of the model of typical Japanese wooden house.

**Table 3**: Decontamination factor and contribution of each surface to dose rate inside a house.

| Surface, $i$ | Decontamination Factor, $DF_i^{(1)}$ | Contribution weighted by relative initial deposition density to dose rate inside of a house, $RD_{i,wet} \cdot c_{i,j}$, (μSv/h)/(Bq/m²) [(2)] | |
|---|---|---|---|
| | | Before decontamination, $RD_{i,wet} \cdot c_{i,0}$, | After decontamination, $RD_{i,wet} \cdot c_{i,1}{}^{(3)}$ |
| Roof | 0.88 | $1.90 \times 10^{-6}$ | $1.67 \times 10^{-6}$ |
| Wall | 0.60 | $3.91 \times 10^{-8}$ | $2.35 \times 10^{-8}$ |
| Ground | | | |
| Area 1 | 0.18 | $1.31 \times 10^{-6}$ | $2.36 \times 10^{-7}$ |
| Area 2 | 0.18 | $2.09 \times 10^{-6}$ | $3.76 \times 10^{-7}$ |
| Area 3 | 0.18 | $3.02 \times 10^{-6}$ | $5.44 \times 10^{-7}$ |
| Area 4 | — [(4)] | $3.31 \times 10^{-6}$ | — [(4)] |

(1) The DFs shown here are reproduced from **Table1**.
(2) Contributions were calculated as the average value for the first floor and the second floor of house model.
(3) Contributions from each surface after decontamination were evaluated assuming wet deposition condition.
(4) Decontaminations were not assumed for this area.

**Table 4** shows the results of calculation by urban area model. In this table, component of "target house" and "other houses" means the sum of contribution from their roofs and walls. The target house and other houses are building 1 and building 2–12 in **Figure 2**. As described in this table, before the decontamination, the contribution weighted by the relative initial deposition density from own surfaces of target house (roof, wall and its garden (ground surface 1)), other houses (Building 2–12), and other ground surfaces (ground surface 2–4) is 43%, 13% and 15%, respectively. Remaining contribution of 29% is attributed to the contribution from the ground surface outside urban area model. The breakdown of the contribution from other houses is that Building 2–4, 5–9, and 10–12, is 2%–3%, ~1%, and < 0.1%, respectively.

From this table, the DRFs for the scenario No. 1 and 2 was derived as the value of 0.84 and 0.75, respectively. In the scenario No. 1, decontamination of the house surfaces (roof and wall) and garden (Ground surface 1) resulted in dose reductions of 79% and 21% for the dose rates in the target house. For the second decontamination scenario, 62% of the DRF are attributed to the decontaminations for target house itself including roof and wall (component of Target House) and garden (Ground Surface 1). The breakdown of remaining 38% of dose reduction consisted of the surrounding ground surface (Ground surface 2–4) (31%) and the other houses (Building 2–12) (7%).

The evaluation results of the DRFs described here cannot avoid uncertainty from calculation relevant parameters (i.e., DF, initial deposition density), and the house model and the urban area model. Therefore, to explore proper values of DRF for the Fukushima case, further considerations will be needed taking into account these uncertainties.

**Table 4**: Contribution of each surface c to dose rate inside of the target house in the urban area model.

| Component or surface | Contribution weighted by relative initial deposition density to dose rate inside of a house, $RD_{i,wet} \cdot c_{i,j}$, (μSv/h)/(Bq/m²) [(2)] | |
|---|---|---|
| | Before decontamination, $RD_{i,wet} \cdot c_{i,0}$ [(4)] | After decontamination, $RD_{i,wet} \cdot c_{i,1}{}^{(3)}$ |
| Target house | $1.94 \times 10^{-6}$ [(1)] | $1.71 \times 10^{-6}$ [(1)] |
| Other houses | $8.94 \times 10^{-7}$ [(1)] | $7.88 \times 10^{-7}$ [(1)] |
| Ground surface 1 | $1.05 \times 10^{-6}$ | $1.87 \times 10^{-7}$ |
| Ground surface 2 | $5.73 \times 10^{-7}$ | $4.06 \times 10^{-7}$ |
| Ground surface 3 | $4.40 \times 10^{-7}$ | $7.86 \times 10^{-8}$ |
| Ground surface 4 | $5.90 \times 10^{-8}$ | $4.18 \times 10^{-8}$ |
| Outside Urban area model | $2.02 \times 10^{-6}$ | — [(5)] |

(1) Contributions from "Target house" and "Other houses" means the total value of those from their roof and wall.
(2) Contributions were calculated as the average value for the first floor and the second floor of target house.
(3) Contributions from each surface after decontamination were evaluated assuming wet deposition condition.
(4) Values in bracket is the fraction of contribution relative to the sum of all components and surfaces.
(5) Decontaminations were not assumed for outside of urban area model.

## 4 CONCLUSION

Dose reduction factor (DRF) was evaluated based on the experiences of the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident for the use of dose assessment. We investigated on decontamination factor (DF) for roof, wall and ground surfaces which were evaluated from the results of decontamination works performed after the FDNPP accident. The initial deposition densities for those surfaces were obtained by literature reviews on the Chernobyl accident. In addition, we developed a house model and urban area model based on typical characteristics (material, size, form) in Fukushima prefecture. Based on the initial deposition density, we determined the distributions of radioactive cesium in the models. The DRFs were evaluated as the ratio of dose rate inside a house model before/after the decontaminations by using Monte Carlo particle transport simulation code PHITS. As the results, the DRFs of decontamination for a house and urban area were evaluated 0.67–0.84 and 0.75–0.84, respectively. It is noted that these results include large uncertainties caused by the DFs, initial deposition densities, and models. Therefore, to explore proper values of DRF for the Fukushima case, further considerations will be needed taking into account these uncertainties.

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