Decontamination effectiveness for wiping vehicle in screening during a nuclear emergency

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ABSTRACT

Evacuation by private vehicle is a basic evacuation strategy during a nuclear emergency in Japan. When vehicles are evacuated from the contaminated areas, screening is conducted to inspect for radioactive contamination. If the radioactive contamination of vehicles exceeds criteria, decontamination is performed by wiping with wet waste cloths. Therefore, insights into the effectiveness of wet cloth wiping are necessary to conduct decontamination in an optimized manner. However, detailed information on the effectiveness of wiping each component of a vehicle by wet waste cloths is not sufficient. The present study simulated cesium contamination deposited on vehicle surfaces during a nuclear accident and experimentally assessed the effectiveness of wet cloth wiping for decontaminating newly manufactured vehicle components (windshield, hood panel, and aluminum alloy).

The results showed that the decontamination factor (*DF*) for the windshield was approximately 8 to 26, while the *DF* for the hood panel was more than 32 and that for the aluminum alloy was more than 31. Furthermore, it was observed that decontamination effectiveness did not change after the second wiping.

Keywords: Nuclear emergency, Screening, Decontamination, Wiping, Vehicles

I. Introduction

Two types of zones are established for preparedness and response for a nuclear emergency in Japan [1]. Precautionary Action Zone (hereafter “PAZ”) is established within the distance of 5 km from a nuclear power plant (hereafter “NPP”) to avoid severe deterministic effects to the public. The residents living in the PAZ evacuate prior to the release of radioactive materials. Outside of the PAZ to 30 km from the NPP, Urgent Protective Action Planning Zone (hereafter “UPZ”) is established. In the UPZ, evacuation is taken based on the ambient dose rate following the deposition of radioactive materials on to the ground. Near the boundary of the UPZ, evacuees and their vehicles undergo contamination screening to confirm that contamination levels are below the decontamination criteria. A beta-ray count rate of 40,000 cpm is used as the operational criterion to keep the surface contamination below 120 Bq/cm^2 [1].

According to the government manual for contamination screening [2], at first, the contamination level on the exterior surfaces of a vehicle is measured using a GM survey meter or a similar device. If contamination levels exceeding the criteria are detected, the exterior surfaces of the vehicle are decontaminated by wiping twice. If the contamination level still exceeds the criteria after the decontamination, the vehicle is kept at the screening site. Then, the evacuees who were using that vehicle are transported from the screening site to an evacuation center by another vehicle.

If the number of vehicles kept exceeds the parking capacity of the screening site, it will hinder the smooth operations in the screening site. Therefore, to achieve efficient operation in the screening site, it is important to estimate in advance the number of vehicles kept, depending on the scale of a nuclear accident. In such assessments, the decontamination effectiveness of wiping is essential information. From this perspective, the Japan Atomic Energy Agency investigated the decontamination effectiveness of wiping tires and hood panels [3]. However, no previous studies are known for other parts remains, such as tires, body, windshield, and aluminum wheels, contaminated by radioactive materials.

Against this background, the purpose of this study is to clarify the decontamination effectiveness for cesium on the components of vehicles (body, windshield, and aluminum wheels) through experimental assessment. The experiment simulated cesium deposition onto the surfaces of the vehicle components in the environment after a nuclear emergency. We then measured the beta-ray count rate before and after wiping to determine the decontamination effectiveness of wiping.

II. Materials and methods

II.A. Radioactive cesium for simulating contamination

II.A.1. Theory for simulating contamination

Radioactive materials are released in an NPP accident. It is known that the main elements of the released radioactive materials are cesium and iodine, with the chemical forms including CsI and CsOH [4]. Measurements after the Fukushima Daiichi NPP accident in 2011 showed that radioactive cesium was mainly transported by attaching to sulfate aerosols [5]. Radioactive materials in the atmosphere deposit on the ground, vehicles, and other surfaces through wet and dry depositions. Cesium was primarily deposited through wet deposition in the Fukushima Daiichi NPP accident [6]. In this study, deposited cesium on vehicle surfaces after an accident was simulated using cesium chloride (CsCl) because chloride is expected to be similar to iodine. In addition, to simulate wet deposition, we dissolved cesium chloride in water and dropped the solution onto samples cut from vehicle parts.

To simulate contamination by radioactive materials released from a nuclear reactor, it is necessary to adjust the surface density of cesium atoms on the sample surface. When the surface density exceeds a certain threshold, cesium atoms are considered to overlap (FIGURE 1). The interaction between the sample surface and cesium atoms differs from that between cesium atoms themselves; therefore, the decontamination effectiveness is expected to vary. In this study, the threshold surface density at which cesium atoms begin to overlap was determined under the assumption that the atoms are uniformly distributed. Since the metallic radius of cesium is 265 pm [7], the cross-sectional area of the atom is considered to be 2.2×10^{-15} cm². Therefore, the threshold is 4.5×10^{14} atoms/cm². When cesium isotopes are deposited in their natural abundance, the threshold corresponds to 0.10 μg/cm².

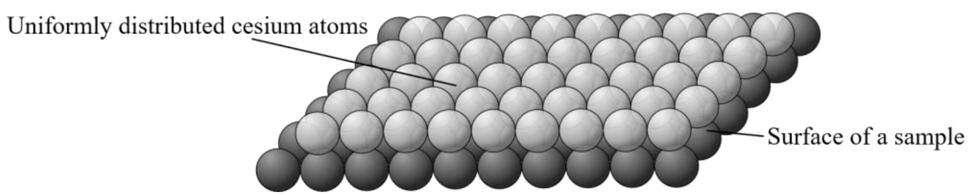


FIGURE 1. The image showing the amount of cesium deposited on a sample

When applying this threshold, it is necessary to take both radioactive and stable cesium atoms into account. For example, Nishihara et al. [8] estimated the nuclide weights per reactor core (g/core) immediately after the shutdown of Fukushima Daiichi NPP Unit 1, as shown in TABLE I. In this table, the values for "g/core" are referred from Nishihara et al. [8], while those for “TBq/core” are calculated from the value for “g/core” by the authors. However, isotopes with quantities less than 100 g/core are not included in the table.

TABLE I. Amount of substance in the core of Fukushima Daiichi NPP Unit 1 (Immediately after shutdown)

	^{133}Cs: Stable	^{134}Cs: Radioactive	^{135}Cs: Radioactive	^{137}Cs: Radioactive
Half-life [year] [9]	-	2.0652	1.33×10^{6}	30.08
g/core [8]	6.24×10^{4}	3.98×10^{3}	2.46×10^{4}	6.30×10^{4}
TBq/core	0	1.90×10^{5}	1.81	2.02×10^{5}

Assuming that cesium deposits on the vehicle surface at a density of 120 Bq/cm² and that its isotopic composition corresponds to that shown in TABLE I, the surface density of cesium atoms is estimated to be 2.10×10^{11} atoms/cm², which is well below the threshold. Therefore, in this study, it was necessary to adjust the surface density of cesium to remain below the threshold. Accordingly, we prepared radioactive cesium solutions in which the amount of stable nuclides could be determined.

II.A.2. Preparation of radioactive cesium solution

Initially, radioactive cesium was produced using the research reactor JRR-3 of the Japan Atomic Energy Agency, to easily adjust the concentration of cesium atoms in the solution. Approximately 1 mg of cesium chloride (Fujifilm Wako Pure Chemical Corporation) was sealed in a capsule and irradiated with neutrons in the reactor core of JRR-3. This capsule was irradiated for

20 minutes with thermal neutrons at a flux of 4.7×10^{17} n/(m^2·s) [10]. This irradiation produced ^{134}Cs through nuclear reaction: ^{133}Cs(n, γ)^{134}Cs, ^{133}Cs(n,γ)^{134m}Cs and ^{134m}Cs→^{134}Cs.

The radioactivity of ^{134m}Cs and ^{134}Cs in the cesium chloride were measured using a Ge semiconductor detector 22 hours and 50 minutes after the end of neutron irradiation. The radioactivity of ^{134m}Cs and ^{134}Cs immediately after the irradiation were determined to be 17 MBq and 27 kBq, respectively. In a reactor with a thermal neutron flux of 1.0×10^{17} n/(m²·s), it is known that the radioactivity of ^{134}Cs generated per 1 g of cesium after 1 hour of irradiation is 4.6×10^4 kBq [9]. Therefore, we assessed the mass of the cesium atoms in the cesium chloride including stable isotopes to be 0.38 mg. In other words, the mass of cesium chloride was 0.48 mg. We prepared two solutions (hereafter "Solution A" and "Solution B") one month after the irradiation. The concentration of Solution A was adjusted to 0.95 kBq/ml using 30 mL of pure water and 0.48 mg of cesium chloride. The concentration of Solution B was adjusted to 0.15 kBq/ml using 6.27 mL of Solution A and 33.73 mL of pure water. The concentration of cesium atoms in Solution B was 2.0 µg/mL at that time.

II.B. Preparation of contaminated samples

The samples used in the experiment were 6 cm × 4 cm in size. We dropped the radioactive solution onto the central 5 cm × 4 cm area of the sample (hereafter "droplet deposition area") as shown in FIGURE 2.

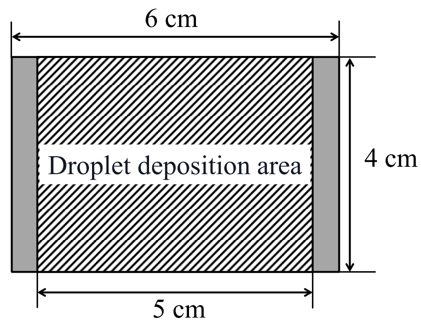


FIGURE 2. Area of the sample where the radioactive cesium solution was dropped

These samples were cut from newly manufactured windshields and hood panels. In addition, aluminum alloy plates were prepared to simulate aluminum wheels. Five samples of each type were prepared.

Solution B of 1.0 mL was dropped onto the droplet deposition area of each sample using a micropipette. The surface density of cesium atoms on the droplet deposition area was approximately 0.1 µg/cm², which was close to the threshold value of 0.10 µg/cm². Furthermore, the radioactivity of ^{134}Cs deposited to the droplet deposition area was 0.15 kBq per sample. FIGURE 3 shows photographs of the solution droplets on each sample. On the windshield samples (FIGURE 3A), the droplets of solution coalesced to form larger clusters. In contrast, the droplets on samples of aluminum alloy (FIGURE 3B) and hood panel (FIGURE 3C) did not coalesce and exhibited water-repellent properties.

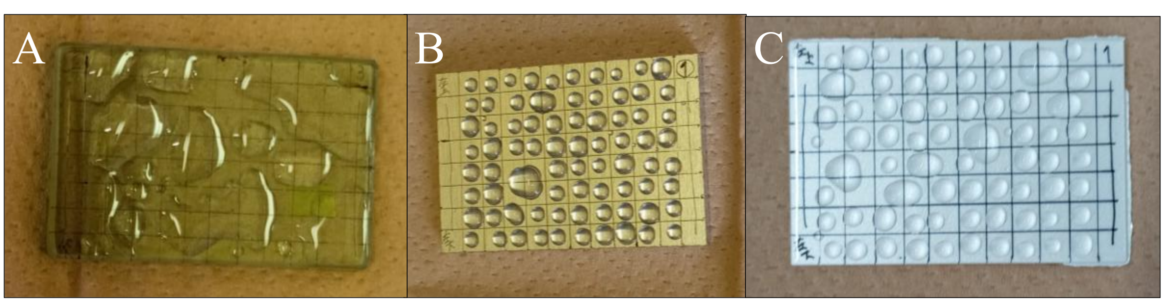


FIGURE 3. Droplets of the radioactive cesium solution on the samples (A: windshield, B: aluminum alloy, C: hood panel)

These samples were placed in a fume hood for seven days and dried. The reason for drying the samples for seven days is that residents are required to evacuate within seven days after receiving the evacuation order, in the case of evacuation, based on a criterion of 20 μSv/h.

II.C. Experiment to investigate the decontamination effectiveness

II.C.1. Wiping off contamination and measuring counts

According to the manual for contamination screening [2], the decontamination of vehicles is carried out by wiping the surface with wet waste cloths. The cloth is changed after each wipe in one direction. Each contaminated area can be wiped a maximum of two times. This study simulated these methods and the experimental procedure is shown in FIGURE 4.

A new cloth was soaked in tap water until saturated. The droplet deposition area of the sample was wiped only once in one direction with the new cloth. This wiping was performed on an electronic balance, and the wiping force was approximately 1 kgf, as shown in FIGURE 5. The beta-ray count of the sample was measured before and after each wiping with a GM survey meter. To reduce geometric measurement errors, the distance between the sample surface and the GM survey meter was fixed at 5 mm as shown in FIGURE 6. The wiping was repeated 2 to 5 times. If the count was below the background level, no further wiping was conducted. The background level was determined by a 10-minute count measurement under no sample conditions.

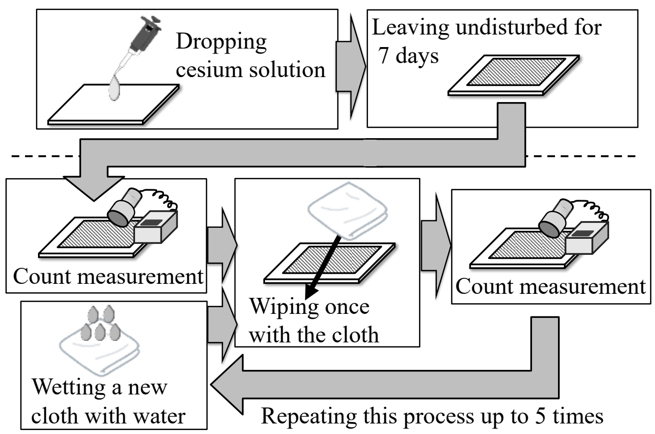


FIGURE 4. The workflow of the experiment

FIGURE 5. Wiping a sample

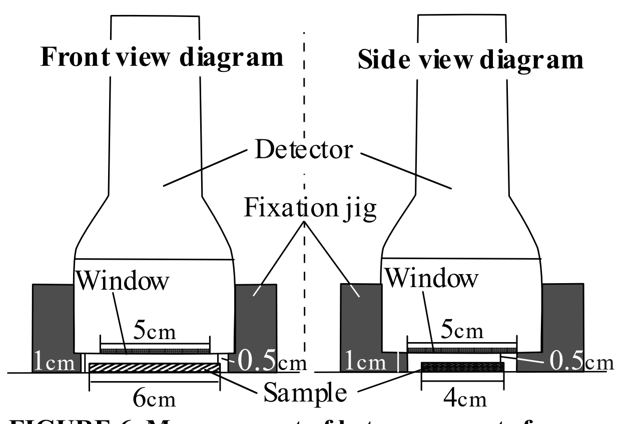


FIGURE 6. Measurement of beta-ray counts from a sample

II.C.2. Calculation of the decontamination factor

The decontamination factor (hereafter "*DF*") was calculated from the counts obtained after each wiping. The *DF* value is defined by equation (1), with reference to IAEA glossary [11]:

$$DF = \frac{r_0 - r_B}{r_i - r_B} \quad , \tag{1}$$

where, r_i is the count rate after the i-th wiping [cpm], r_0 is the count rate before the first wiping [cpm], and r_B is the count rate obtained from the background measurement [cpm]. However, while *DF* in the glossary [11] is defined as "the ratio of the activity", the *DF* in this study is defined as the ratio of the count rate.

In some cases, the count rate fell below the background level. Hence, the under limit of *DF* was calculated based on the relationship between the count rate before the first wiping and the background, as shown in the following equation (2):

$$DF > \frac{r_0 - r_B}{r_L} \quad , \tag{2}$$

where, r_L is the detection limit value. The value of $\frac{1}{2} r_B$ was assumed as the limit in the present study. As described in equation (2), the value of *DF* depends on the background level. In a non-emergency situation, measurements are performed in an uncontaminated environment. However, in an emergency situation, measurements will be performed under high-background conditions. Therefore, we have to define the *DF* taking into account influence of such conditions, as shown in equation (2).

III. Results and discussion

III.A. Count rate of background

The backgrounds measured on each experimental day were summarized in TABLE II.

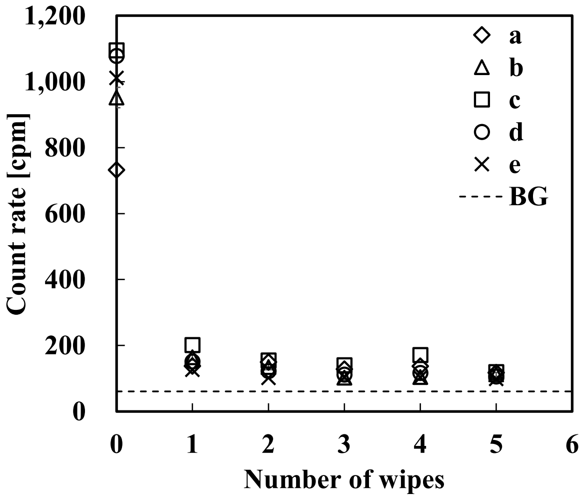
TABLE II. The background measured on each experimental day

Sample type	Sample label	Count rate of the background [cpm]	Measurement time [min]
Windshield	a, b, c	60.6 ± 2.5	10
	d, e	62.4 ± 2.5	
Aluminum alloy	a, b, c, d, e	67.3 ± 2.6	
Hood panel	a, b, c	60.6 ± 2.5	
	d, e	70.8 ± 2.7	

The value after '±' indicates the statistical error.

III.B. Count rate and *DF*

FIGURE 7 shows the results of the experiment for the windshield. The count rate before the first wiping was approximately 1,000 cpm. It decreased to 130 to 200 cpm after the first wiping and 100 to 150 cpm after the second wiping. However, there was no further decrease after subsequent wiping. The *DF*s ranged from 7 to 15 after the first wiping and from 8 to 26 after second wiping onward.



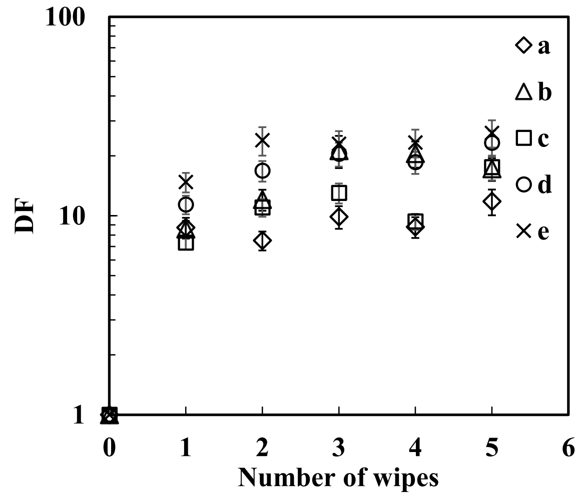


FIGURE 7. Result of the windshield (Left fig.: count rate after each wiping, Right fig: *DF* after each wiping)
Five samples of each type were labeled ‘a’, ‘b’, ‘c’, ‘d’, and ‘e’, respectively. The error bars represent statistical errors.

The results for the aluminum alloy are shown in FIGURE 8. The count rate before the first wiping was approximately 1,100 cpm. It decreased to approximately 60 to 70 cpm after the first and second wiping, which was comparable to the background level. Because the count rate decreased to the background level, the wiping process was stopped after the second wiping for samples ‘b’, ‘d’ and ‘e’, and after the third wiping for sample ‘c’. Sample ‘a’ may has reduced decontamination effectiveness due to a tear in the waste cloth during the first wiping. The *DF* for the aluminum alloy was to be $DF > 31$ using equation (2).

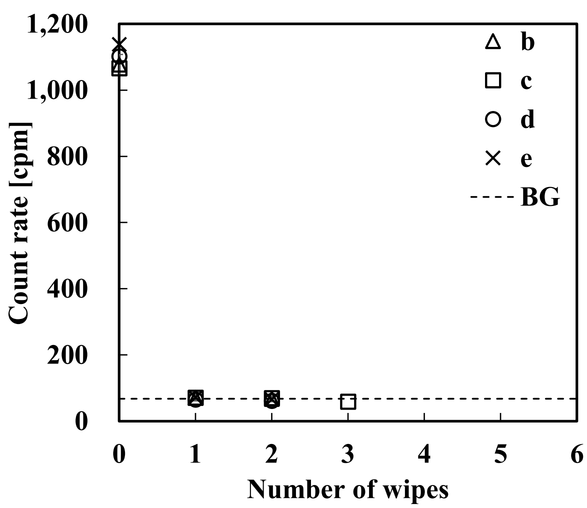


FIGURE 8. Count rate of aluminum alloy after each wiping

FIGURE 9 shows the results of the experiment for the hood panel. The count rate before the first wiping was approximately 1,000 cpm. It decreased to approximately 50 to 80 cpm after the first wiping, which was comparable to the background level. Because the count rate decreased to the background level, the wiping process was stopped after the second wiping for samples ‘a’, ‘b’, ‘c’, and ‘e’, and after the fourth wiping for sample ‘d’. The *DF* for the hood panel was $DF > 32$ using equation (2).

In the previous study [3], three new hood panel samples were tested, and two wiping processes were conducted. TABLE III summarizes the measured count rates and the *DF* values. The results of our study were consistent with those of the previous study [3].

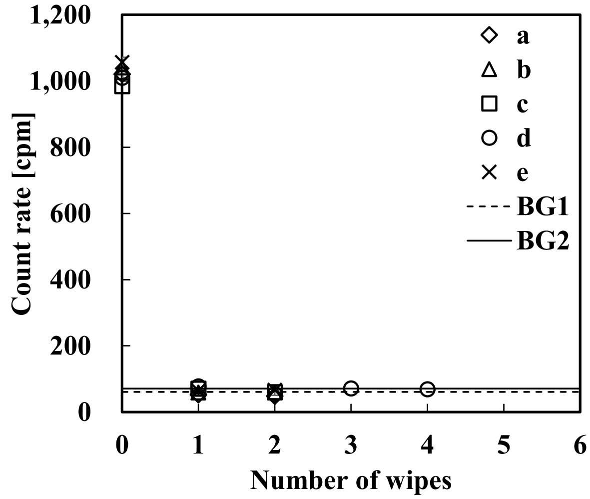


FIGURE 9. Count rate of hood panel after each wiping

TABLE III. *DF* of hood panel

	This study	The previous study [3]		
		Sample 1	Sample 2	Sample 3
The count rate before wiping [cpm]		32,184	31,684	29,234
The count rate after two wiping [cpm]		1,576	1,612	848
DF	> 32	20	20	34

One of the reasons why *DF* differs depending on the surface material is the difference in the water repellency of the surface. As mentioned in Section II.B, the aluminum alloy and hood panel were more water-repellent than the windshield. Therefore, the solution barely adhered to the surfaces of the aluminum alloy and hood panel immediately after the solution was dropped.

In addition, since the count rate did not decrease after the third and subsequent wipes for all types of samples, it can be considered reasonable that the guideline of the Japanese authority [2] stipulates that wiping can be conducted up to a maximum of two times.

IV. CONCLUSIONS

In this study, we evaluated the decontamination effectiveness for parts used in newly manufactured vehicles: windshield, hood panel, and aluminum alloy simulating aluminum wheels. The effectiveness was evaluated using the decontamination factor, *DF*, defined as the ratio of contamination levels before and after wiping the vehicle samples. To evaluate the *DF*, experiments were conducted by simulated wet deposition of cesium on the samples and then decontamination were performed by wiping with a wet waste cloth. The *DF* for the windshield was approximately 7 to 15 after the first wiping. Although it slightly decreased after the second and subsequent wiping, it remained within the range of 8 to 26. The *DF* for the aluminum alloy was *DF* > 31 after the second wiping. Similarly, that for the hood panel was *DF* > 32. Our results are expected to contribute to the formulation of plans for screening sites in nuclear emergency situations.

ACKNOWLEDGMENTS

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