Safety evaluation of temporary storage, etc.

1. Background and purpose

Soil and combustibles containing radioactive materials generated by decontamination (hereinafter referred to as "removed soil, etc.") should be stored in temporary or on-site storage places (hereinafter referred to as "temporary storage, etc.") until delivered to the interim storage facilities set up by the government. Since the amount of removed soil, etc. by decontamination is enormous, it is difficult to secure a storage place that is large enough to store the entire amount and isolated from the living environment. Therefore, a respective method of storing decontaminated materials is adopted for each place or area. As these temporary storages, etc. exist in public areas, there is concern about their impact on human health and the environment due to the management of the removed soil, etc. in temporary storage, etc. Therefore, in the management of temporary storage facilities, it is important to keep public exposure as low as reasonably achievable by implementing safety measures as necessary. Additionally, even after taking safety measures for facility management, it is important to consider appropriate responses to type-specific accidents should they occur.

On the basis of the above considerations, the purpose of this study report is to identify important scenarios for public exposure in relation to the management of removed soil, etc., and to organize and evaluate public exposure routes, including those during accidents. Moreover, as regards the evaluation results, it was determined that evaluation be also made of the safety of temporary storage, etc. by comparing it with the concept of radiation protection when managing removed soil, etc., which will be described later.

2. Method and contents of implementation measures

2.1. Evaluation target areas

Decontamination of areas contaminated with radioactive materials released in connection with the accident of TEPCO (Tokyo Electric Power Company)'s Fukushima Daiichi Nuclear Power Station (hereinafter referred to as the "nuclear accident") is to be carried out by the municipalities and the national government. The intensive contamination survey areas designated for decontamination by municipalities are defined as shown in Fig. 1. Since the prefecture is supposed to play a role in supporting the decontamination of municipalities, the intensive contamination survey areas were selected as the evaluation target areas in this study.

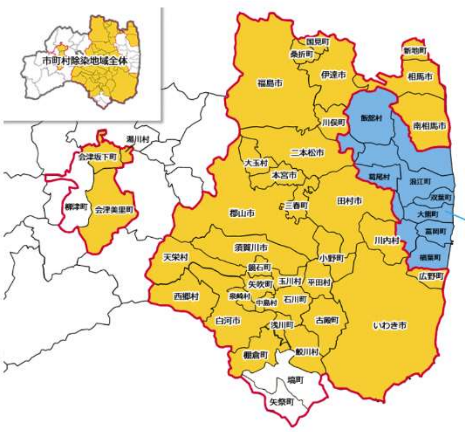

Fig. 1.Evaluation target areas

2.2 The current status and scope of evaluation of the management of removed soil, etc.

The removed soil, etc. containing radioactive materials generated by decontamination is to be managed by the scheme shown in Fig. 2. The amount of removed soil, etc. shown in Table 1 has already been generated, and these are stored in the temporary storages and on-site storages in the prefecture. In addition, the total amount of soil removed by decontamination including future, follow-up decontamination is estimated by the Ministry of the Environment to be as much as 28 million m^3 [1)]. In this study report, the storage process in temporary storage, etc., which is currently the most important management process, was evaluated.

Implementation of decontamination

⇩

Temporary storage at temporary depositories and decontamination sites

⇩

Storage in interim storage facilities (in the prefecture)

⇩

Disposal at the final disposal site (out of the prefecture)

Fig.2 The flow of removed soil, etc.

Table 1 Storage status of removed soil, etc. generated by decontamination in the prefecture in temporary storage, etc. [2),3)]

Area	**Storage status**	**Number of places**	**Total number of occurrences/stored substance (10,000 m^3)**
Special decontamination areas (as of the end of March 2019)*1	Temporary storage	194	565
Intensive contamination survey areas*2 (In Fukushima prefecture only, as of the end of March2019)	Temporary storage	616	529
	Storage at the site	86,175	
Total			1,094

*1 In addition to temporary storages, temporary depositories, temporal temporary storage, etc. are included.

*2 Fifty-two municipalities are the target localities, except Naraha-Machi, Tomioka-Machi, Okuma-Machi, Futaba-Machi, Namie-Machi, Katsurao-Mura, Iitate-Mura.

2.3. Structure of generally used temporary storages

Three requirements are presented for the safety measures of temporary storages, i.e.; i) shielding and separation, ii), dispersal prevention of removed soil, and iii) prevention of rainwater intrusion, etc.[4] In addition to the above facility requirements, the storage type and structure of temporary storages are determined in consideration of workability at the time of removal and the site area that can be secured. Fig. 3 shows the structure of a generally used ground storage type temporary storage. This structure is designed in consideration of the fact that the target nuclide is radioactive cesium. Specific points to note include the following items:[4]

・Prohibition of unnecessary entry by installing fences

・Appropriate shielding by installing sandbags for shielding or separation from residential areas

・Measures to prevent rainwater intrusion by using an impermeable sheet etc.

・Securing a catch basin and preventing leakage of radioactive materials with the lower impermeable sheet

・Taking measures against the generation of gas and heat storage caused by the decay of combustibles through installation of gas removal pipes

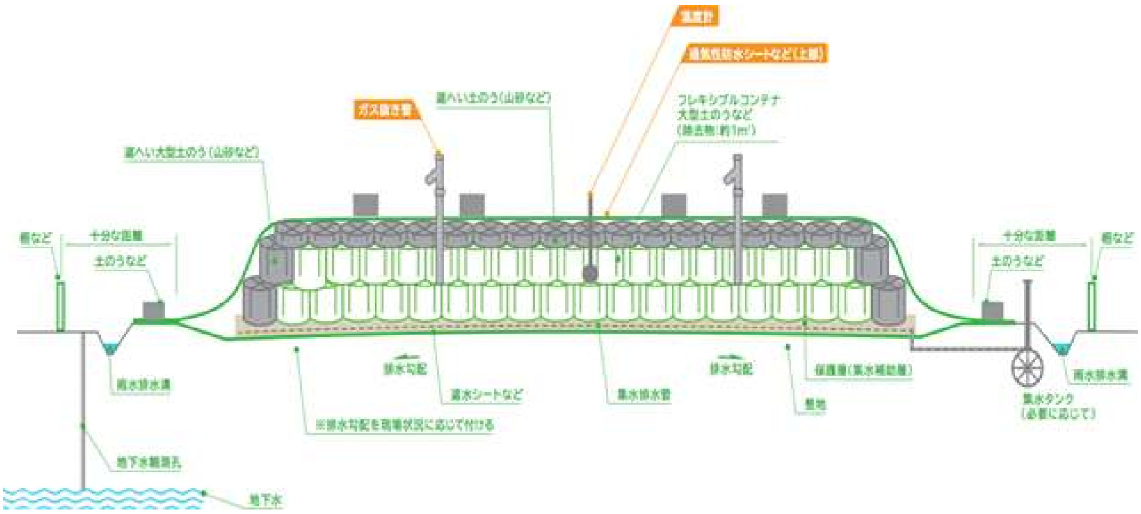

Fig. 3 Structure of a generally used ground storage type temporary storage[5]

2.4. Concept of radiation protection in management of removed soil, etc.

Subjects affected by radiation from removed soil, etc. include workers involved in work such as installation of decontamination and temporary storage, etc., light workers involved in work such as regular monitoring, and the general public. In view of this, radiation protection regulations for these subjects are summarized below.

To prevent harmful radiation exposure to workers engaged in work such as decontamination, the Ministry of Health, Labour and Welfare has enforced the “regulations on prevention of ionizing radiation hazards related to work, etc. for decontamination of soil contaminated with radioactive materials generated by the Great East Japan Earthquake”[6)] (hereinafter referred to as “regulations on prevention of ionizing radiation hazards caused by decontamination”). The work targeted for the application of the regulations on prevention of ionizing radiation hazards caused by decontamination includes collection, transportation, or storage of removed soil, etc., which are subject to safety evaluation, and the regulations applied to workers involved in installation work etc. for decontamination and temporary storage, etc. On the other hand, the general public and light workers involved in regular monitoring etc. are not subject to the regulations on prevention of ionizing radiation hazards caused by decontamination. The Guideline for Decontamination-related Measures stipulates that “the relevant facilities shall be designed so that the additional public radiation exposure dose from the removed soil is less than 1 mSv per year.” This is believed to be in line with, “it is necessary to ensure that the dose received by the local residents does not exceed 1 mSv/year caused by treatment, etc., and (...) special consideration is required to control the exposure of the local residents,” as shown in the “concept of ensuring safety in the current situation regarding the treatment and disposal of waste affected by TEPCO’s Fukushima Daiichi Nuclear Power Station accident”[7)] by the Nuclear Safety Commission in June 2011. Additionally, in the evaluation presented at the time of the accident in the "simplified safety evaluation of interim storage facilities" and the "safety evaluation method 2013 for trench disposal in shallow ground," it was estimated that excessive radiation exposure would not be exerted unless it exceeded 5 mSv per accident. Therefore, this study report summarizes the relationship between related regulations and subjects affected by radiation from removed soil, etc. in Table 2.

Table 2 Relationship between related regulations and subjects affected by radiation from removed soil, etc.

	The regulations on prevention of ionizing radiation hazards caused by decontamination are applied (Dose limit: 50 mSv/year, or 100 mSv in 5 years)	The regulations on prevention of ionizing radiation hazards caused by decontamination are not applied (Reference level: 1 mSv/year, 5 mSv at the time of accident)
Workers involved in installation work etc. for decontamination, temporary storage, etc.	○	×
Light workers involved in regular monitoring etc.	×	○
General public	×	○

Here, workers to whom regulations on prevention of ionizing radiation hazards caused by decontamination are applied are excluded as evaluation targets because individual doses are managed, and only cases to which regulations on prevention of ionizing radiation hazards caused by decontamination are not applied are treated as evaluation targets.

2.5 Definition of a model temporary storage

There are about 800 temporary storages, etc. in the prefecture, and it is difficult to evaluate them individually. Therefore, the safety of the entire temporary storage system is evaluated by appropriately setting an example of the typical temporary storage, etc., and evaluating it. Main parameters and typical set values are shown in Table 3. Here, as there is a considerable difference between storage at the site and temporary storage in respect to the scale, we defined a representative case for each. As for the scale of temporary storages, we defined it on the basis of the average value of the stored quantity at each temporary storage site in the prefecture. In addition, as for the radioactivity concentration in soil, on the basis of the maximum value of air dose rate by the 3rd aircraft monitoring outside the evacuation order zones in the prefecture, we calculated the ground surface pollution density from the conversion factor between the ground surface pollution density (Bq/m^2) and the air dose rate (μSv/h) when the ground surface was uniformly contaminated. Using the obtained ground surface pollution density value, we calculated the soil concentration (Bq/kg) on the assumption that the surface layer of 5 cm was decontaminated, then attenuated and corrected the value to the concentration as of April 2015, and adopted the value rounded up to the nearest multiple of 500 Bq/kg. At this time, we assumed that the ratio of cesium-134 to cesium-137 as of March 2011 was 1: 1. For the radioactivity concentration, the value rounded out to hundreds was adopted.

Table 3 The model temporary storage as defined

No.	Parameter	Unit	Value	
1	Scale	m^3	Temporary storage	800
			Storage at the site	4
2	Radioactivity concentration of removed soil, etc.	Bq/kg	^{134}Cs	2500
			^{137}Cs	8500
3	Density of removed soil	kg/m^3	1600[7]	

2.6 Identification of exposure routes

Under the premise that the target nuclides assumed from the exposure routes of removed soil, etc. stored in the temporary storage are cesium-134 and cesium-137, we identified the exposure routes assumed for the storage period as shown in Table 4 below.

Table 4 Scenarios assumed at the time of storage

	Event	Radiation source	Exposure type	Evaluation target
Normal conditions	Living in the neighborhood	In-place removed soil, etc.	External (Route 1)	General public
	Regular monitoring	In-place removed soil, etc.	External (Route 2)	Worker(s)
At the time of the accident	Release of removed soil, etc. due to fire and loss of shielding function	Dust released into the atmosphere	Inhalation (Route 3)	General public
			External (Route 4)	General public
		Removed soil, etc. deposited on the ground surface	External (Route 5)	General public
		Removed soil, etc. remaining on the premises	External (Route 6)	General public
		Contaminated crops (In-house cultivation)	Ingestion (Route 7)	General public
	Outflow of removed soil, etc. due to heavy rain	Removed soil outflowed to the ground surface	External (Route 8)	General public
	Loss of leakage prevention function to the outside of the facility through the water system	Drinking water	Ingestion (Route 9)	General public
	Outflow of removed soil, etc. due to flooding of rivers	Contaminated crops (In-house cultivation)	Ingestion (Route 10)	General public
		Contaminated soil	External (Route 11)	General public
		Contaminated soil	Inhalation (Route 12)	General public

2.7 Evaluation method

<Evaluation of external exposure from removed soil, etc., and route>

$D_{ext}(i) = C_{waste}(i) \cdot S_0 \cdot t \cdot DF_{ext}(i) \cdot (1-\exp(-\lambda \cdot t)) / (\lambda \cdot t)$ (1)

Here,

$D_{ext}(i)$: External exposure dose of radionuclide i (μSv/y)

$C_{waste}(i)$: Concentration of radionuclide i in removed soil, etc. (Bq/kg)

t: Exposure time (at normal times: h/y; at the time of the accident t: h/accident)

$DF_{ext}(i)$: Dose conversion factor for external exposure of radionuclide i (μSv/h)/(Bq/kg)

λ: Decay constant of radionuclide i (1/h)

S_0: Shielding factor for external exposure (-)

The dose conversion factor $DF_{ext}(i)$ used for evaluating the external exposure dose from volume radiation source with an arbitrary 3D shape was obtained by MCNP code and QAD‐CGGP2R.

<Evaluation of external exposure from ground surface, and route>

$$D_{ext}(i) = C_{ground}(i) \cdot S_0 \cdot t \cdot DF_{ext}(i) \quad (2)$$

Here,

$D_{ext}(i)$: External exposure dose of radionuclide i (μSv/y)

$C_{ground}(i)$: Concentration of radionuclide i on ground surface (Bq/m^2)

t: Exposure time (h)

$DF_{ext}(i)$: Dose conversion factor for external exposure of radionuclide i (μSv/h)/(Bq/m^2)

λ: Decay constant of radionuclide i (1/h)

S_0: Shielding factor for external exposure (-)

Meanwhile, we obtained the concentration of radionuclide on ground surface according to the following method for each contamination route:

・Concentration of radionuclide on ground surface through the atmospheric release route

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As for contamination of ground surface through the atmospheric release route, the following formula (3) was used.

$$C_{ground}(i) = Q_A(i) \cdot (\chi/Q) \cdot V_g \cdot \frac{f_1}{\lambda}\left(1 - e^{-\lambda T_0}\right) \quad (3)$$

$Q_A(i)$: Released radionuclide (Bq/s)

χ/Q: Relative concentration in the atmosphere (s/m^3)

V_g: Emitted particle deposition rate (m/s)

f_1: Percentage of remaining deposited radionuclide (-)

T_0: Nuclide release period (h)

It needs to be noted that, while we do not describe the details of the derivation method of relative concentration in the atmosphere (χ/Q) here, we used the plume formula based on the "Meteorological Guidelines for Safety Analysis of Power Reactor Facilities" to derive the relative concentration in the atmosphere (χ/Q). In this study report, within the area from the temporary storage to the temporary storage site boundary, i.e. from the surface of the removed soil, etc. to points 8 meters or more away, we selected an evaluation point with the maximum landing concentration point due to dry deposition, and derived the relative concentration in the atmosphere of the relevant point (χ/Q).

・Concentration of radionuclide in the soil contaminated by use for irrigation in the case of release route to water system (Outflow of removed soil into rivers)

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The concentration of radionuclide in the soil in association with the irrigation through the release route to water system was obtained by the formula (4). Here, instant equilibrium was assumed for the transition of radionuclide from irrigation water to the soil.

$$C_{ground}(i) = C_{soil}(i) \cdot \rho_V \quad (4)$$

$$C_{soil}(i) = C_{water}(i) \cdot \left(K_d(i) + \frac{\varepsilon}{\rho(1-\varepsilon)}\right) \quad (5)$$

$$C_{water}(i) = C_{waste}(i) \cdot \left(\frac{C_{ss}}{1 + K_{dss}(i) \cdot C_{ss}}\right) \quad (6)$$

$$C_{ss} = \rho \cdot V_{waste} / (V_{river} \cdot t) \quad (7)$$

$C_{soil}(i)$: Concentration of radionuclide in the farm soil contaminated by irrigation (Bq/kg)

ρ: Soil density (kg/m^3)

V_{waste}: Volume of the removed soil, etc. outflowed into rivers (m^3)

V_{river}: River flow volume (m^3/d)

t: The period required for all the removed soil, etc. to be washed downstream (d)

C_{ss}: Suspended substances derived from removed soil, etc. in rivers (kg/m^3)

$C_{waste}(i)$: Concentration of radionuclide i in removed soil, etc. (Bq/kg)

$C_{water}(i)$: Concentration of radionuclide i contained in river water (Bq/m^3)

$Kd_{ss}(i)$: Suspended substances in river water - Partition coefficient for radionuclide i contained in river water (m^3/kg)

Kd(i): Farm soil - Partition coefficient for radionuclide i contained in irrigation water (m^3/ kg)

P_V: Effective density of soil (kg/m^2)

<Evaluation of external and inhalation exposure from dust, and route>

$D_{sub}(i) = C_{air}(i) \cdot DF_{sub}(i) \cdot t$ (8)

$D_{inh}(i) = C_{air}(i) \cdot R_{inh} \cdot DF_{inh}(i) \cdot t$ (9)

Here,

$D_{sub}(i)$: External exposure dose of radionuclide i in the atmosphere (μSv/y)

$DF_{sub}(i)$: Conversion factor for external exposure due to immersion from radionuclide i in the atmosphere (μSv/h)/(Bq/m^3)

D_{inh} (i): External exposure dose of radionuclide i (μSv/y)

R_{inh}: Absorption rate (m^3/h)

$DF_{inh}(i)$: Dose conversion factor for inhalation exposure of radionuclide i (μSv/h)/(Bq/m^3)

$C_{air}(i)$: Concentration of radionuclide i in the atmosphere (Bq/m^3)

t: Exposure time (h)

Since it is an evaluation at the time of a short-term accident and when the half-life of the evaluation target nuclide is long, physical attenuation is not considered.

In addition, the concentration of radionuclide in the atmosphere was calculated as follows according to the route of contamination.

・Concentration of radionuclide in the air through atmospheric release route

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$C_{air}(i) = Q_A \cdot (\chi/Q)$ (10)

Here,

$Q_A(i)$: Released radionuclide (Bq/s)

χ/Q: Relative concentration in the atmosphere (s/m^3)

・Concentration of radionuclide in the air with soaring soil contaminated by use for irrigation in the case of release route to water system (Outflow of removed soil into rivers)

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$C_{air}(i) = C_{soil}(i) \cdot d_R$ (11)

Here,

d_R: Atmospheric dust concentration (kg/m^3)

Here, the value of $C_{soil}(i)$ was obtained through steps (5) to (7).

<Evaluation of ingestion exposure, and route>

$D_{ing} = C_{food}(i) \cdot H_f \cdot DF_{ing}(i) \cdot G_f$ (12)

Here,

D_{ing}: Ingestion exposure dose of radionuclide i (μSv/y)

$C_{food}(i)$: Concentration of radionuclide i in food (Bq/kg)

H_f: Food intake volume (kg/y)

DF_{ing}: Dose conversion factor for ingestion exposure of radionuclide i (μSv/h)/(Bq/kg)

G_f: Market dilution factor of food (-)

In the exposure routes under consideration here, the foods that are assumed to be contaminated are agricultural products and drinking water. As for foods, those that are expected to be ingested from non-distributed products in the market are targeted. For example, river fish are excluded in view of the current situation where dietary restrictions in Fukushima prefecture are still imposed in many areas. Livestock farming is also excluded because it is not generally assumed that animal husbandry will be carried out for self-consumption. In addition, the specific evaluation targets for agricultural products are roughly divided into three types: leafy vegetables, rice, and other (fruits and non-leafy vegetables). The concentration of radionuclide in food for each contaminated route was calculated as follows.

・Concentration of radionuclide in agricultural products due to atmospheric release route

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$$C_{\text{leaf}}(i) = Q_A(i) \cdot (\chi/Q)\left(\frac{V_g \cdot (1 - e^{-\lambda_{eff}T_0})}{\lambda_{eff}\rho_V} + \frac{V_g \cdot \mathrm{TF}_{\text{soil-leaf}}(\mathrm{i}) \cdot (1 - e^{-\lambda t0})}{\lambda(i)P_V}\right)f_t f_d \quad (13)$$

$C_{rice}(i) = C_{soil}(i) \cdot TF_{soil\text{-}rice}(i)$ (14)

$C_{other}(i) = C_{soil}(i) \cdot TF_{soil\text{-}other}(i)$ (15)

$C_{soil}(i) = C_{ground}(i)/P_V$ (16)

Here,

$C_{leaf}(i)$: Concentration of radionuclide in leafy vegetables (Bq/kg)

$Y_{Ground\text{-}veg}$: Cultivation density of leafy vegetables (kg/m^2)

$TF_{soil\text{-}leaf}(i)$: Transition coefficient between leafy vegetables and the soil (Bq/kg-wet / Bq/kg-dry)

$C_{rice}(i)$: Concentration of radionuclide in rice (Bq/kg)

$TF_{soil\text{-}rice}(i)$: Transition coefficient between rice and the soil (Bq/kg-wet / Bq/kg-dry)

$C_{other}(i)$: Concentration of radionuclide in other agricultural products (Bq/kg)

$TF_{soil\text{-}other}(i)$: Transition coefficient between other agricultural products and the soil (Bq/kg-wet / Bq/kg-dry)

Pv: Effective surface density of soil (kg/m^2)

Here, the value of $C_{ground}(i)$ was obtained from formula (3).

・Concentration of radionuclide in potable water through release route to water system (transition of radionuclide from removed soil to groundwater)

$V_I = R_I \times A_P \times N_P \times DR_P$ (17)

$R_{Fi} = 1 + (\rho_W \times K_{di} \div W_{RW})$ (18)

$L_{Ri} = R_I \div (W_{RW} \times H_P \times R_{Fi})$ (19)

$V_{Ai} = H_P \times A_P \times N_P \times DR_P \times \rho_W \times C_{Wi} \times LR_i$ (20)

$C_{Gi} = V_{Ai} \div (V_I + V_G) \times 0.001\ m^3/L$ (21)

Here,

V_I: Outflow volume of leachate per year (Unit: m^3/year)

R_I: Outflow rate per unit area of leachate (m/year)

A_P: Bottom area of flexible container (m^2)

N_P: Number of flexible containers (-)

DR_P: Damage rate of flexible containers (-)

RF_i: Delay factor of radionuclide i (-)

ρ_W: Density of stored substance (kg/m^3)

K_{di}: Partition coefficient of radionuclide i (Bq/kg-dry per Bq/L)

W_{RW}: Moisture content (-)

LR_i: Outflow rate per year of radionuclide i (-)

H_P: Height of the flexible container (m)

V_{Ai}: Outflow volume of radionuclide i per year (Bq/year)

C_{Wi}: Concentration of radionuclide i in stored substance (Bq/kg)

C_{Gi}: Concentration of radionuclide i in groundwater (Bq/L)

・Concentration of radionuclide in agricultural products due to release route to water system (Outflow of removed soil into rivers)

$C_{leaf}(i) = C_{soil}(i) \cdot TF_{soil\text{-}leaf}(i)$ (22)

Here, the value of $C_{soil}(i)$ was obtained from formulas (5) to (7). In addition, the concentration of radionuclide in rice and other agricultural products other than leafy vegetables was obtained from formulas (14) to (17).

2.8 Evaluation parameters

In this section, the parameters used for evaluation in each scenario are shown.

<Living in the neighborhood (Route 1)>

Evaluation of external exposure possibly occurring while living in the neighborhood of the storage place for removed soil, etc. stored in temporary storages as specified for Route 1 is carried out with formula (1). Table 5 shows the parameters used in formula (1). Here, the dose conversion factor for external exposure by direct radiation and skyshine radiation we used was based on the result derived and provided by the Japan Atomic Energy Agency using the MCNP code.

Table 5 Parameters used for evaluation for Route 1

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Concentration of radionuclide	^{134}Cs	$C_{waste}(i)$	Bq/kg	2500	Table 3
	^{137}Cs			8500	
Shielding factor for external exposure		S_0	-	0.6	Assuming that people will stay indoors for 16 hours in a day, we adopted 1.0 as the shielding factor for indoor stay and 0.4 based on IAEA TECDOC-1162 as the shielding factor for outdoor stay.
Exposure time		t_0	h/y	8760	A period of one year was assumed.
Dose conversion factor for external exposure (Temporary storage)	^{134}Cs	$DF_{ext}(i)$	μSv/h per Bq/kg	2.15E-06	The analysis was performed using the following system using the MCNP code. The shielding conditions were set according to the guideline. Shape of the radiation source: 20 m×20 m×2 m Density of the radiation source:1.5 g/cm^3 Shielding conditions: Side shield of 30 cm Evaluation point:8 m from the surface of 20 m×2 m Evaluation height:1 m
	^{137}Cs			8.17E-07	
Dose conversion factor for external exposure (Stored at the site)	^{134}Cs	$DF_{ext}(i)$	μSv/h per Bq/kg	5.02E-07	The analysis was performed using the following system using the MCNP code. The shielding conditions were set according to the guideline. Shape of the radiation source: 2 m×2 m×1 m Density of the radiation source:1.5 g/cm^3 Shielding conditions: None Evaluation point: General public living 4 m away from the surface of 2 m×1 m Evaluation height:1 m
	^{137}Cs			1.91E-07	
Decay constant of radionuclide	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	

<Regular monitoring (Route 2)>

The external exposure during monitoring work in the storage place for removed soil, etc. stored in temporary storages as specified for Route 2 was evaluated by formula (1). The parameters used in formula (1) are shown in Table 6.

Table 6 Parameters used for evaluation for Route 2

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Concentration of radionuclide	^{134}Cs	$C_A(i)$	Bq/kg	2500	Table 3
	^{137}Cs			8500	
Shielding factor for external exposure		S_0	-	1.0	It was conservatively set to 1.
Exposure time		t_0	h/y	365	It was assumed that the monitoring in the temporary storage would be performed for 1 hour, daily.
Skyshine + Direct radiation (temporary storage)	^{134}Cs	$DF_{ext}(i)$	μSv/h per Bq/kg	6.75E-06	The analysis was performed using the following system using the MCNP code. Shielding conditions were set according to the guideline. Shape of the radiation source: 20 m×20 m×2 m Density of the radiation source:1.5 g/cm^3 Shielding conditions: Side shield of 30 cm Evaluation point: 1 m from the surface 20 m×2 m Evaluation height:1 m
	^{137}Cs			2.57E-06	
Decay constant of radionuclide	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	

<Release of removed soil, etc. due to fire and loss of shielding function (Routes 3 to 7)>

Fig. 4 shows the assumed situation of the accident when the radionuclide was released into the atmosphere as defined for Routes 3 to 7.

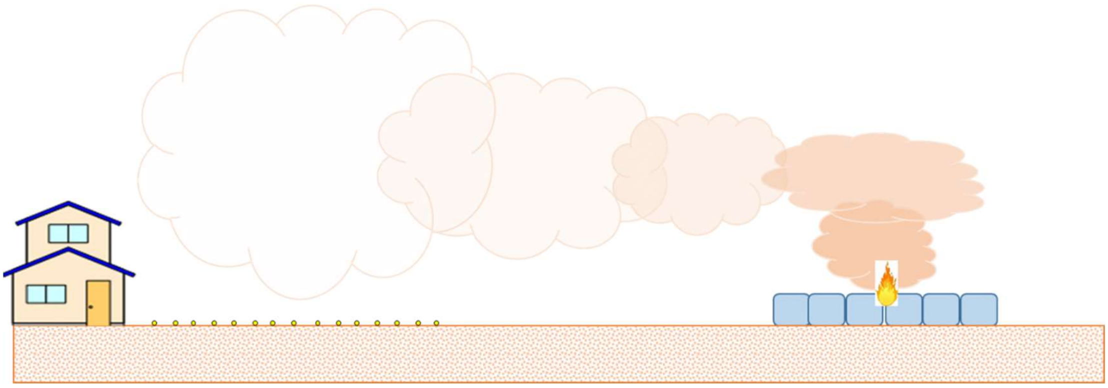


Fig. 4 An example of the situation of the accident assumed, when the removed soil, etc. was released into the atmosphere

(a) External exposure and inhalation exposure due to dust released into the atmosphere (Route 3 and Route 4)

The exposure routes shown for Route 3 and Route 4 were evaluated with formulas (8) to (10). The parameters used in formulas (8) to (10) are shown in Table 7.

Table 7 Parameters used for evaluation for Routes 3 and 4

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Concentration of radionuclide	^{134}Cs	$C_A(i)$	Bq/kg	2500	Table 3
	^{137}Cs			8500	
Relative concentration in the atmosphere		χ/Q	s/m^3	2.74E-02	Calculation of atmospheric diffusion was performed based on the results of meteorological statistics in Fukushima prefecture, and the maximum concentration on the safest side was adopted.
Exposure time (From outbreak to extinction of fire)		t_0	h/accident	12	The time required to complete the fire extinguishing was assumed to be 12 hours.
Weight of waste etc. burned in a fire		W_w	kg	1.28E+5	The affected ratio was conservatively set to 0.1, which is the upper limit of the width, with reference to Release Fractions in Table 4 of IAEA-TECDOC-401, Trench Fire Scenario, and the weight was derived based on the parameters in Table 3.
Transition rate of radionuclide to exhaust in a fire		R_{C_s}	-	1	It was assumed that the entire amount of cesium was transferred to the exhaust.
Dose conversion factor for external exposure (Plume)	^{134}Cs	$DF_{ext}(i)$	μSv/h per Bq/m^3	2.51E-04	The value of the conversion factor for plume set in the RI clearance evaluation was used.
	^{137}Cs			9.09E-05	
Dose conversion factor for inhalation exposure	^{134}Cs	$DF_{inh}(i)$	μSv/Bq	6.6E-03	The exposure conversion factor for inhalation by general public (adults) shown in ICRP Publ.72 was used here.
	^{137}Cs			4.6E-03	

Meanwhile, the relative concentration in the atmosphere was calculated by setting the main parameters as follows based on the results of meteorological statistics in Fukushima prefecture.

- Wind speed (m/s): 2 (m/s)
- Atmospheric stability D
- Release width 0 m
- Release height 2 m
- Evaluation height 1 m

Here, we adopted the value of the point showing the concentration of the maximum landing concentration in relation to the distance for the relative concentration in the atmosphere

(b) External exposure due to removed soil, etc. deposited on the ground surface (Route 5)

The exposure route shown for Route 5 was evaluated with formulas (2) and (3). The parameters used in formulas (2) and (3) are shown in Table 8.

Table 8 Parameters used for evaluation for Route 5

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Concentration of radionuclide	^{134}Cs	Cground(i)	Bq/kg	2500	Table 3
	^{137}Cs			8500	
Exposure time		t_0	h/y	8760	We assumed no decontamination conservatively.
Weight of removed soil burned in a fire		W_w	Kg	1.28E+5	The affected ratio was conservatively set to 0.1, which is the upper limit of the width, with reference to Release Fractions in Table 4 of IAEA-TECDOC-401, Trench Fire Scenario, and the weight was derived based on the parameters in Table 3.
Transition rate of radionuclide to exhaust in a fire			-	1	It was assumed that the entire amount of cesium contained in the affected waste was transferred to the exhaust.
Shielding factor for external exposure (At the time of the accident)	General public	S_0	-	0.6	It was set in consideration of the shielding effect (shielding factor: 0.4) when staying indoors (16 hours) during the day.
Soil residue coefficient of radionuclide		f_1	-	1	We conservatively assumed that the entire quantity persisted.
Dose conversion factor for external exposure (Nuclide-deposited soil)	^{134}Cs	$DF_{ext}(i)$	Sv/s per Bq/m^2	1.6E-15	It was set based on US EPA Federal Guidance Report No. 12.
	^{137}Cs			5.7E-16	
Emitted particle deposition rate (Dry deposit)		V_g	m/s	0.0015	It was set based on IAEA TECDOC-1777.
Decay constant of radionuclide	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	
Nuclide release period		T_0	h	12	The time required to completely extinguish the fire was assumed to be 12 hours.
Relative concentration in the atmosphere		χ/Q	s/m^3	2.74E-02	Calculation of atmospheric diffusion was performed based on the results of meteorological statistics in Fukushima prefecture, and the maximum concentration on the safest side was adopted.

(c) Removed soil, etc. remaining on the premises (Route 6)

The exposure route shown for Route 6 was evaluated with formula (1). Here, assuming a situation where the shielding function was lost in association with the effect of the accident, we evaluated the external exposure received by neighboring residents. Parameters used in formula (1) are shown in Table 9.

Table 9 Parameters used for evaluation for Route 6

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Concentration of radionuclide	^{134}Cs	$C_A(i)$	Bq/kg	2500	Table 3
	^{137}Cs			8500	
Shielding factor for external exposure		S_0	-	0.6	Assuming that people will stay indoors for 16 hours in a day, we adopted 1.0 as the shielding factor for indoor stay and 0.4 based on IAEA TECDOC-1162 as the shielding factor for outdoor stay.
Exposure time		t_0	h/y	730	We assumed it would take a month to repair the temporary storage.
Skyshine + Direct radiation (temporary storage)	^{134}Cs	$DF_{ext}(i)$	μSv/h per Bq/kg	1.78E-05	The analysis was performed using the following system using the MCNP code. The shielding conditions were set according to the guideline. Shape of the radiation source: 20 m×20 m×2 m Density of the radiation source:1.5 g/cm^3 Shielding conditions: None Evaluation point:8 m from the surface of 20 m×2 m Evaluation height:1 m
	^{137}Cs			6.79E-06	
Decay constant of radioactive cesium	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	

(d) Internal exposure due to ingestion of contaminated agricultural products (Route 7)

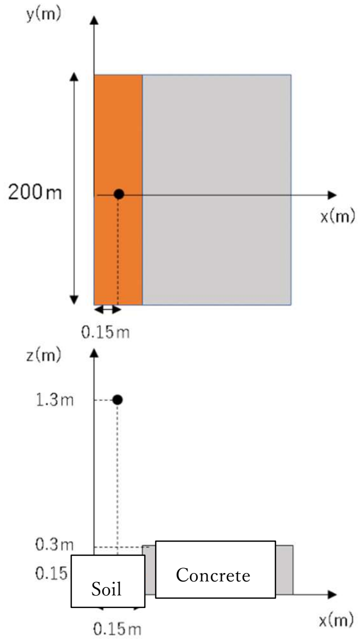
The exposure route shown for Route 7 was evaluated with formulas (12) to (16). Here, in association with the effect of the accident, we assumed there was internal exposure through ingestion of agricultural products contaminated through contamination of the surrounding agricultural soil. Parameters used in formulas (12) to (16) are shown in Table 10. Meanwhile, the value we used for $C_{ground}(i)$ was calculated with the parameters in Table 8.

Table 10 Parameters used for evaluation for Route 7

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Effective surface density of soil		P_v	kg/m^2	280	We set the values used in U.S. NRC Regulatory Guide 1.109.
Annual food intake volume	Leafy vegetables and the like	H_f	kg/y	20.3	It was set based on the safety evaluation method 2013 for trench disposal in shallow ground.
	Rice and the like			58.5	
	Other agricultural products			160.5	
	Rice and the like			1	Based on the safety evaluation method 2013 for trench disposal in shallow ground, it was conservatively set to 1.
Market dilution factor	Leafy vegetables and the like	G_f	-	0.1	The value of self-cultivation was set based on the safety evaluation method 2013 for trench disposal in shallow ground.
	Other agricultural products			0.1	
Dose conversion factor	^{134}Cs	$DF_{ing}(i)$	Sv / Bq	1.30E-8	The value of IAEA-SS-115 was used.
	^{137}Cs			1.90E-8	
Transition coefficient between soil and crop	Rice and the like	$TF_{soil\text{-}leas}(i)$	(Bq/kg-wet/ Bq/kg-dry)	0.0016	We adopted the measured value (white rice) in Japan for ^{137}Cs of fallout shown in IAEA TECDOC 1616 (P248).
	Leafy vegetables and the like	$TF_{soil\text{-}leas}(i)$,		0.04	The value of IAEA SRS 19 was adopted.
	Other agricultural products	$TF_{soil\text{-}others}(i)$			
Cultivation density (Leafy vegetables)		ρv	Kg/m^2	2	We set the value on the basis of the dose evaluation of the general public.
Decay constant of radionuclide	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	
Effective attenuation constant of radionuclide on leafy vegetables	^{134}Cs	λ_{eff}	1/y	18.436	We set the value on the basis of the dose evaluation of the general public.
	^{137}Cs			18.123	
Emitted particle deposition rate (Dry deposit)		V_g	m/s	0.0015	It was set based on IAEA TECDOC-1777.
Annual ratio of cultivation period		f_t	-	1	It was conservatively set to 1.
Residual ratio after washing before ingestion		f_d	-	1	It was conservatively set to 1.

<Outflow of removed soil, etc. due to heavy rain (Route 8)>

The exposure route shown for Route 8 was evaluated with formula (1). Here, in association with the accident of Route 8, as shown in Fig. 5, we assumed the external exposure occurred when people walked through gutters after the removed soil had flowed out into the road and accumulated there. The parameters used in formula (1) are shown in Table 10.



* Scale is not accurate

Fig. 5 Outflow accident of removed soil, etc. due to heavy rain

Table 11 Parameters used for evaluation for Route 8

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Concentration of radionuclide	^{134}Cs	$C_A(i)$	Bq/kg	2500	Table 3
	^{137}Cs			8500	
Shielding factor for external exposure		S_0	-	1.0	It was conservatively set to 1.
Exposure time		t_0	h/y	365	We assumed a lifestyle of walking on roads for one hour every day.
External exposure Dose conversion factor	^{134}Cs	$DF_{ext}(i)$	μSv/h per Bq/kg	2.6E-05	It was assumed that heavy rain causes 10% of removed soil, etc. to flow out and 10% of it to be deposited on in gutters. Using the QAD-CGGP2R code, we performed the following analysis for the system below: Shape of the radiation source: 0.15 m×0.3 m×180 m Density of the radiation source:1.5 g/cm^3 Shielding conditions: None Evaluation point: As shown in Fig. 5
	^{137}Cs			9.5E-06	
Decay constant of radioactive cesium	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	

<Loss of leakage prevention function to the outside of the facility through the water system (Route 9)>

As Route 9, we set up a scenario in which the function to prevent leakage of radioactive cesium from removed soil, etc. through water was lost, and assumed a situation where the upper and lower impermeable sheets were torn and the storage container was damaged had occurred. As for the exposure route, we assumed that the radioactive cesium leaked to the outside of the temporary storage would be transferred to the groundwater and then used as drinking water. Fig. 6 shows the assumed accident situation. Based on the above, the additional exposure dose that could occur when radioactive cesium leaked via groundwater was evaluated using equations (12) and (18) to (22). The parameters used for the evaluation are shown in Table 12.

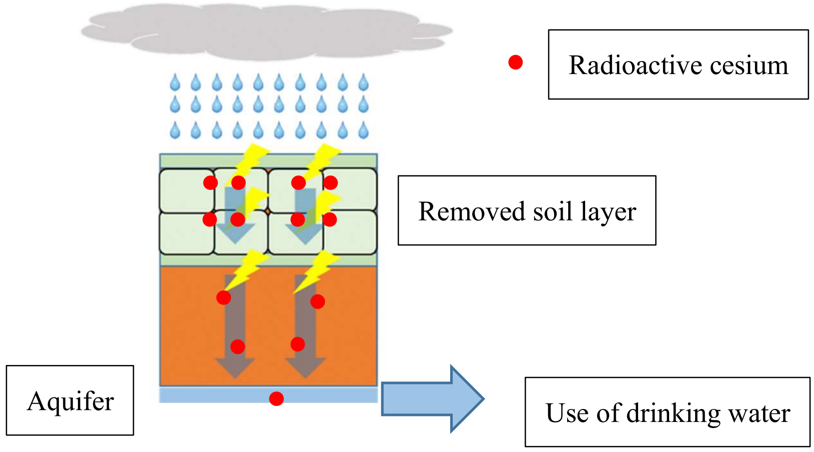


Fig. 6 Leakage of radioactive cesium into groundwater due to rainwater intrusion

Table 12 Parameters used for evaluation for Route 9

Name of parameter	Symbols used in the formula	Specified value	Unit	Grounds for specifying the value
Height of container	H_P	m	1.1	Guideline for Decontamination-related Measures
Bottom area of container	A_P	m^2	1.1	
Damage rate of container	DR_P	-	0.2	20% damage was assumed.
Width perpendicular to the flow of groundwater in temporary storage	W_S	m	20	The length of the long side of temporary storage was specified.
Density of stored substance	ρ_W	g-dry /cm^3	1.6	About the simplified safety evaluation of interim storage facilities
Moisture content	WR_W	-	0.3	Set based on the safety evaluation method 2013 for trench disposal in shallow ground.
Partition coefficient	K_{di}	Bq/kg-dry	270	IAEA TRS-364[4]
Leachate runoff rate per unit area	R_I	m/year	0.4	Groundwater Handbook[5]
Aquifer thickness	T_G	m	5	Specified value
Effective porosity of the aquifer	EP_G	-	0.3	Same as for stored substances
Groundwater flow velocity	R_G	m/d	1	Same as above[5]
Conversion factor from concentration of radioactive materials related to drinking water to exposure dose	DCF_{Gi}	µSv/year per Bq/L	^{134}Cs:15.45 ^{137}Cs:10.57	IAEA SRS-19[7]

<Outflow of removed soil, etc. due to flooding of rivers (Route 10)>

As for Route 10, as a scenario for the release of removed soil, etc. due to flooding of the river, we assumed ingestion of contaminated agricultural products, external exposure from contaminated soil, and insulation exposure from airborne soil through the use of river water for irrigation, which was contaminated through accumulation of a part of removed soil, etc. on the river bottom and the constant elution of radioactive cesium into the river water had occurred. This exposure route was evaluated with formula (12). Furthermore, the concentration of radionuclide obtained by formula (12) was calculated with formulas (5) to (7), (14), (15) and (23). Fig. 7 shows the accident situation we assumed. Additionally, Table 13 shows the parameters used in formulas (5) to (7). Meanwhile, the parameters used in formulas (14), (15) and (23) were the same as for Table 10.

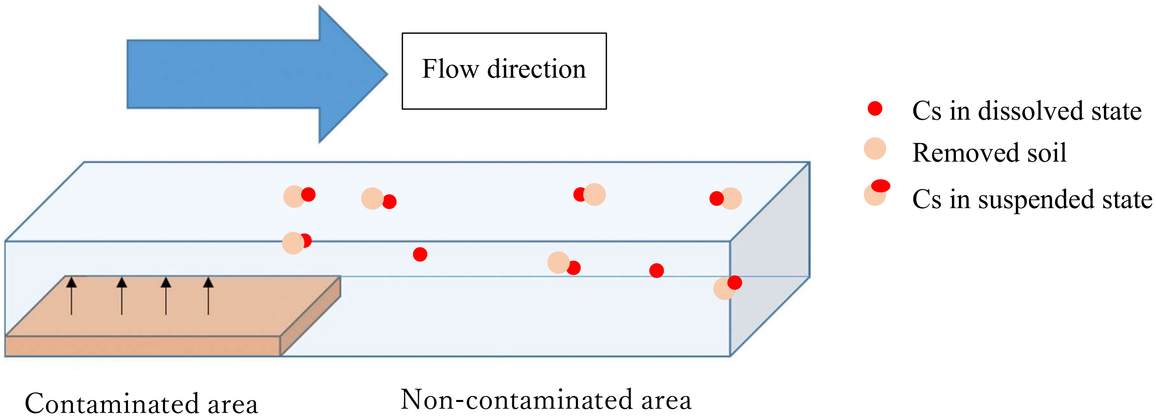


Fig. 7 Sedimentation of soil removed after river flooding

Table 13 Parameters used to evaluate soil contamination associated with irrigation through the release route to water system associated with river flooding

Name of parameter		Symbols used in the formula	Unit	Specified value	Remarks
Removed soil remaining time		t	d	365	We assumed that all removed soil would be washed out of the sediment in one year.
Soil density		ρ	kg/m^3	1600	Table 3
Soil outflow volume		V_{waste}	m^3	800	We assumed that 100% of the total material would flow out and settle on the riverbed.
Concentration of radionuclide	^{134}Cs	$C_{waste}(i)$	Bq/kg	2500	Table 3
	^{137}Cs			8500	
Decay constant of radionuclide	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	
Partition coefficient between soil and river water		Kd_{ss}	m^3/kg	1000	It was specified from ORNL-5786.
River flow volume		V_{river}	m^3/d	5.7×10^6	The average value of the Abukuma River flow over the past 5 years at the Motomiya Observatory was used.
Soil porosity		ε	-	0.38	It was set based on the safety evaluation method 2013 for trench disposal in shallow ground.

Table 14 Parameters used for evaluation for Route 10

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Concentration of radionuclide in soil	^{134}Cs	$C_{soil}(i)$	Bq/kg	6.6E-1	The value was obtained by using the parameters shown in Table 10 with formula (5).
	^{137}Cs			2.3	
Annual food intake volume	Leafy vegetables and the like	H_f	kg/y	20.3	The values in the 2004 National Health and Nutrition Survey Report were used.
	Rice and the like			58.5	
	Other agricultural products			160.5	
Market dilution factor	Leafy vegetables and the like	G_f	-	0.1	The value of the farmer was set based on the safety evaluation method 2013 for trench disposal in shallow ground.
	Rice and the like			1	Based on the safety evaluation method 2013 for trench disposal in shallow ground, it was conservatively set to 1.
	Other agricultural products			0.1	The value of the farmer was set based on the safety evaluation method 2013 for trench disposal in shallow ground.
Dose conversion factor	^{134}Cs	$DF_{ing}(i)$	Sv / Bq	1.30E-8	The value of IAEA-SS-115 was used.
	^{137}Cs			1.90E-8	
Transition coefficient between soil and crop	Leafy vegetables and the like	$TF_{soil\text{-}leas}(i)$,	(Bq/kg-wet/ Bq/kg-dry)	0.04	The value of IAEA SRS 19 was adopted.
	Rice and the like	$TF_{soil\text{-}leas}(i)$		0.0016	Measured values in Japan for fallout radioactive cesium shown in IAEA TECDOC 1616 (P248) (white rice) were adopted.
	Other agricultural products	$TF_{soil\text{-}others}(i)$		0.04	The value of IAEA SRS 19 was adopted.
Decay constant of radioactive cesium	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	

<Outflow of removed soil, etc. due to flooding of rivers (Route 11)>

The exposure route shown for Route 11 was evaluated with formulas (2) and (4) to (7). Table 15 shows the parameters used in formulas (2) and (4). The parameters used in formulas (5) to (7) were the same as for Table 13.

Table 15 Parameters used for evaluation for Route 11

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Concentration of radionuclide on ground surface	^{134}Cs	$Cg_{round}(i)$	Bq/m^2	1.9E+2	Derived from formula (4)
	^{137}Cs			6.3E+2	
Exposure time		t_0	h/y	500	The value of the farmer was set based on the safety evaluation method 2013 for trench disposal in shallow ground.
Shielding factor for external exposure		S_0	-	1	It was conservatively set to 1.
Dose conversion factor for external exposure (Nuclide-deposited soil)	^{134}Cs	$DF_{ext}(i)$	Sv/s per Bq/m^2	1.6E-15	It was set based on US EPA Federal Guidance Report No. 12.
	^{137}Cs			5.7E-16	
Decay constant of radioactive cesium	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	
Effective surface density of soil		P_v	kg/m^2	280	We set the values used in U.S. NRC Regulatory Guide 1.109.

<Outflow of removed soil, etc. due to flooding of rivers (Route 12)>

The exposure route shown for Route 12 was evaluated with formulas (5) to (7), (9) and (11). Table 16 shows the parameters used in formulas (9) and (11). The parameters used in formulas (5) to (7) were the same as for Table 13.

Table 16 Parameters used for evaluation for Route 12

Name of parameter		Symbols used in the formula	Unit	Specified value	Grounds for specifying the value
Atmospheric dust concentration		d_R	kg/m^3	5.0E-7	The value of the farmer was set based on the safety evaluation method 2013 for trench disposal in shallow ground.
Concentration of radionuclide in the air	^{134}Cs	$C_{air}(i)$	Bq/m^3	3.3E-7	Derived from formula (11)
	^{137}Cs			1.1E-6	
Exposure time		t_0	h/y	500	The value of the farmer was set based on the safety evaluation method 2013 for trench disposal in shallow ground.
Dose conversion factor for inhalation exposure	^{134}Cs	$DF_{inh}(i)$	μSv/Bq	6.6E-03	The exposure conversion factor for inhalation by the general public (adults) shown in ICRP Publ.72 was used.
	^{137}Cs			4.6E-03	
Decay constant of radioactive cesium	^{134}Cs	λ	1/y	0.336	The value was set on the basis of the half-life defined in ICRP Publ.107
	^{137}Cs			0.023	
Absorption rate		R_{inh}	m^3/h	1.2	Calculated on the basis of ICRP Publ.89.

3. Evaluation results

Table 17 shows the results of the dose evaluation for the scenarios shown in Table 4.

Table 17 Dose evaluation in each scenario

Route	Situation	Exposure dose (mSv)	Target
1-(a)	Normal times	6.0×10^{-2}	General public
1-(b)		1.4×10^{-2}	General public
2		7.9×10^{-3}	Monitoring worker(s)
3	At the time of the accident	5.2×10^{-2}	General public
4		1.5×10^{-3}	General public
5		3.0×10^{-1}	General public
6		4.6×10^{-2}	General public
7		8.4×10^{-1}	General public
8		4.9×10^{-2}	General public
9		3.0×10^{-5}	General public
10		1.2×10^{-4}	General public
11		3.2×10^{-3}	General public
12		1.3×10^{-8}	General public

As a result of evaluating the assumed exposure scenarios for the model temporary storage as of April 2015, we predicted that the additional exposure dose at normal times would be less than the reference value of 1 mSv per year. Additionally, the additional exposure dose at the time of the accident was expected to be less than 5 mSv per reference value.

In our evaluation of radioactive nuclide at the time of the accident, the ingestion exposure route of contaminated agricultural products at the time of the fire event was assumed to have the greatest impact. Therefore, in the event of a large-scale fire accident in the temporary storage that exists in the residential area, it is necessary to pay attention to this route. That is, it is particularly necessary to measure the radioactivity of leafy vegetables, which may be contaminated by initial deposition, if air dose rates are to be measured to determine if agricultural products are at a level of concern, or if there is concern of contamination based on the results. By taking these measures appropriately, it is possible to prevent unnecessary exposure even if a large-scale accident occurs.

In addition, it was shown that the external exposure route of general public, which was used as the exposure route of normal times, can keep the additional exposure dose as low as 0.06 mSv/year by designing temporary storage according to the guideline. However, since this scenario will inevitably occur, it is considered to be the most important scenario among those assumed at this time.

Meanwhile, in this study report, only the scale of the hazard in each exposure route is evaluated, and the probability of occurrence is not mentioned, but risks are evaluated based on the hazard and the probability of occurrence, and even if the accident has a large hazard, the risk will be limited if the probability of occurrence is small. For example, it is reported that the probability of a fire accident, which is estimated to have the greatest impact this time, is about 0.1% in 2004-2007 in the case of the final disposal site. In addition, even in the temporary storage of removed soil, etc. in the prefecture, only one case has been clarified so far. Therefore, it can be determined that the risk of the outflow of removed soil, etc. into the environment, such as through the atmosphere and water system, caused by the occurrence of fire or heavy rain in temporary storage will be sufficiently small.

Meanwhile, since the analysis was made for the period during storage this time, we evaluated a system in which shielding and separation were properly performed. However, when transporting removed soil, etc. in the future, the removal of shielded soil may temporarily increase the air dose rate in the surrounding area. Therefore, it is necessary to thoroughly consider the impact of removing the shield soil at the transportation planning stage.

Acknowledgments

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