Estimation of Internal Exposure Doses of the People Caused by Inhaled Radioactive Materials Released in Early Stage of Fukushima Nuclear Disaster

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Abstract: A large amount of radioactive material was released in the natural environment by the nuclear accident occurred in the Fukushima No.1 nuclear power station. In order to plan protective measures or to examine health effects by the released radioactive material internal exposure doses caused by inhalation of the radioactive materials (I-131, Cs-134, Cs137) in the air were estimated on the basis of the I-131, Cs-134 and Cs137 radioactivities in the air. These radioactivities could be determined by using those in the soil on the assumption that they were originally distributed uniformly in the air up to a height of about 500 m and the washing ratio by rainfall was 0.53 h^{-1}. By taking into consideration of the stay in-house time in winter, equivalent doses by I-131 inhaled during 9 hours from 18:00 pm on March 15 to 3:00 am on March 16 were estimated as 6.8mSv for adults and 13mSv for children, respectively. Effective doses by I-131and both Cs-134 and Cs137 inhalation during the same period were about 0.7mSv and 0.13mSv for children, respectively and 0.36mSv, 0.13mSv for adults, respectively. Based on these internal exposure doses estimated, it seemed possible that the equivalent doses by inhalation intake of I-131 would be less than 20 mSv and effective doses by inhalation intake of I-131, Cs-134 and Cs137 would be less than 1 mSv in the early stage of nuclear disaster by taking into consideration of the total amount of radioactive material released from the power plants and the probability distribution of the wind direction from the power station.

Keywords: Fukushima nuclear disaster, Radioactive materials, Internal exposure, Inhalation

１．Introduction

In the early stage of Fukushima nuclear disaster occurred on March 11 in 2011, large amounts of radioactive material was dispersed to a wide range of distance from the Fukushima No.1 nuclear power station. But, there had been existed less information about the airborne radioactive materials for long time due to malfunction of the emergency monitoring system and the SPEEDI (System for Prediction of Environmental Emergency Dose Information) system, while the monitoring of the radioactive materials deposited on the green vegetables, soil and drinking water were started on March 18[1].

The information on the exposure of the people living in the suburbs of the nuclear power station has been absolutely necessary after the occurrence of nuclear accident from the view points of planning protective measures against nuclear disaster and evaluating health effects of the people by the released radioactive material. So, internal radiation exposure caused by inhalation of the radioactive materials in the early stage of the nuclear disaster has been tried to estimate here on the basis of the airborne radioactivities determined by using the I-131, Cs-134, Cs-137 deposited on the ground surface[2].

The highest radioactivity deposition seemed to be occurred by the precipitation washout on March 15, so the airborne radioactivities on the same day were estimated by using the soil ones extrapolated from the monitored data obtained after March 21. By using the airborne radioactivities estimated, the typical example of the internal doses of the people living in the evacuation preparation area were determined on the assumption that the people were staying outdoors for 1 hour and indoors for 8 hours when the radioactive plume were passing through.

２． Materials and Method

２． １　Deposition of radioactive materials

Estimation of internal exposure was performed around Iidate-mura nagadoro where is situated in the northwest at about 33 km from the Fukushima No.1 nuclear power station. It was chosen because this area was specified as the evacuation preparation area by the Nuclear Emergency Response Headquarters and because relatively large amounts of radioactive materials were deposited on the ground surface by a short time precipitation washout and because there was existed relatively much radiological information for evaluation of the movement of the radioactive materials in the air.

It is considered that the most abundant deposition of the radioactive material was occurred on March 15. Time diagram representing the relation among the release of radioactive materials from the nuclear power plants[3], wind direction[2], duration of precipitation[4] and possible contamination period is shown in figure 1.

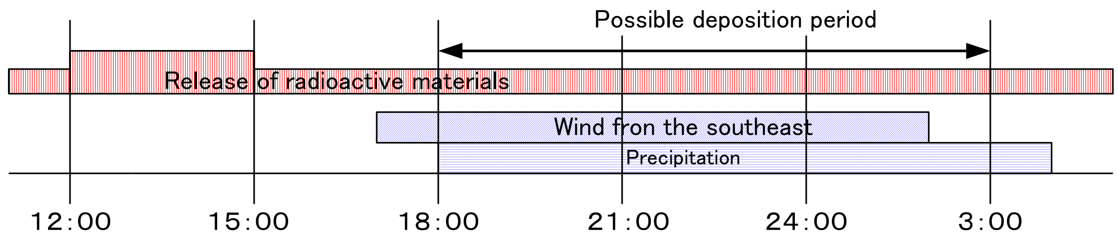

Figure 1. Time diagram to show the possible contamination period from March 15 to March 16 caused by the nuclear accident in Fukushima No.1 nuclear power station.

It is said that the maximum released rate (almost 10^{16} Bqh^{-1}) might be occurred in the morning on March 15 and had lasted till about 15:00 pm in the afternoon. After 15:00 pm, relatively small amounts of radioactive materials were released continuously for long time. The release rate of the radioactive material reduced rapidly after March 16 (10^{15} ～ 10^{14} Bqh^{-1}). From the Meteorological Agency data[4], precipitation started at about 18:00 pm on March 15 and stopped at about 4:00 am on March 16 and the southeast wind started at about 17:00 pm and changed its direction at about 2:00 am on March 16. From the time chart shown in figure 1, it is assumed here that the radioactive materials released from the nuclear power plants were mainly deposited on the surface during 9 hours in the period of rainfall.

２．２ Estimation of ground surface radioactivity

Variations of the radioactivity in the soil and the exposure dose rate at Iidate-mura nagadoro are shown in figure 2. The values on March 15 were extrapolated from the measured data by assuming half-life of I-131, Cs-134 and Cs-137, respectively. The half life of I-131 derived from the fitted line was a little longer than the theoretical one because of continuous deposition of I-131 after March 16. So the extrapolated values shown in the second line in table 1 would contain errors by a factor of about 2.

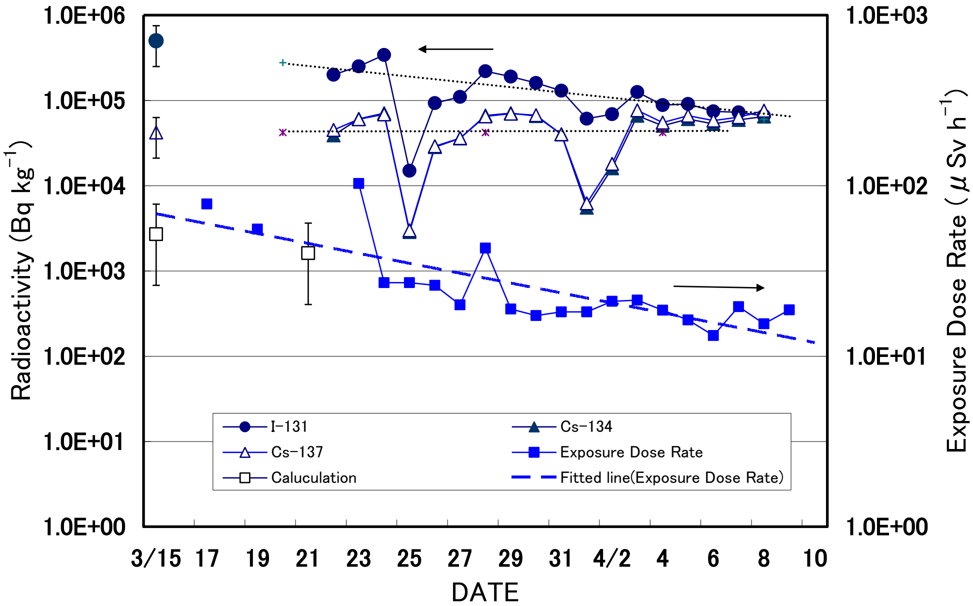

Figure 2. Variation of I-131, Cs-134, Cs-137 in the soil and exposure dose rates monitored at Iidate-mura nagadoro.

The ground surface radioactivities shown in the third line of table 1 were estimated on the assumption that the soil sample stated above had a surface width of 100 cm^2 where the radioactive materials in the air were deposited.

Table 1. Radioactivities of soil, ground surface and exposure dose rate extrapolated to March 15.

	I-131 $\left(T_{\frac{1}{2}}=8.04d\right)$	Cs-134 $\left(T_{\frac{1}{2}}=2.06y\right)$	Cs-137 $\left(T_{\frac{1}{2}}=30.2y\right)$
soil($Bqkg^{-3}$)	5.0×10^5	4.2×10^4	4.2×10^4
ground surface($Bqcm^{-2}$)	5.0×10^3	4.2×10^2	4.2×10^2
exposure dose rate($\mu Sv\ h^{-1}$)	2.0×10^1	2.3×10^1	9.1×10^0

For assessment of the validity of the surface radioactivity, exposure dose rate around the sampling point were estimated by using following formula,

$$\phi_i = k_i \cdot \frac{S_A}{2}\left[E_1(b_1) - E_1(b_1 \sec\theta)\right] \qquad b_1 = \mu_l\, t \quad (t = 1m, \sec\theta = 100)$$

$$D_i = \Gamma_i \cdot \left(\frac{\phi_i}{7.96 \cdot k_i}\right)$$

Here,

φ_i : particle flux density for i-th radionuclide ($cm^{-2}s^{-1}$)

S_A : specific strength of surface source($cm^{-2}s^{-1}$)

$En(b_1)$: exponential integral functions (n=1)

b_1 : shield thickness expressed in mean free path lengths

Γ_i : H*(10) rate constant for i-th rdionuclide ($\mu Svm^2Bq^{-1}h^{-1}$)

k_i : conversion constants

The exposure dose rates expected on March 15 are shown in the last line in table 1 and the sum of all dose rate components is shown by the left side open square in the figure 2. Exposure rate on March 21, which is also shown by the open square, was calculated by taking into consideration of the half life of I-131 and Cs-134 and Cs-137. As shown in the figure, the calculated exposure dose rates are very close to the fitted line of the measured ones. The difference between the calculated values from the fitted line was within 50 % of the predicted ones from the line.

２．３　Comparison with the SPEEDI calculation

Dispersion of the radioactive materials around Fukushima No.1 nuclear power site was calculated by the SPEEDI or by the WSPEEDI (Worldwide version of SPEEDI) on the assumption that the release of radioactive material with unit release rate ($1Bqh^{-1}$) started at 13:00 pm and continued till 3:00 am of March 16[3]. From the calculation it was shown that the relatively high concentration of I-131 arrived at Iidate-mura nagadoro at about 19:00 pm and deposited during 8 hours with the deposition rate of 5×10^{-11}～1×10^{-9} Bqm^{-2} h^{-1}. Based on these deposition rates, the total amount of I-131 deposited was estimated as approximately 3.0×10^{-9} Bqm^{-2} on the ground surface. On the other hand, the highest release rate of I-131 observed on March 15 was considered to be about $10^{16}Bqh^{-1}$ and it would become rapidly smaller after 15:00 pm of March 15. So the total amount of I-131 on the ground surface could be estimated as 7.5×10^{7} Bqm^{-2} by assuming 3×10^{16} Bq of I-131 release during 8 hours. The deposited I-131 estimated here is relatively in good agreement with the value determined by using the monitored data since it was inferred that the radioactivity estimated here would contain errors by a factor of 2 or 3.

３． Results and Discussion

３．1　Intake of radioactive materials in the air

Radioactivities in the air was estimated on the basis of the surface I-131, Cs-134 and Cs-137 extrapolated to those on March 15 on the assumption that they were distributed uniformly in the air up to a height of about 500 m and washed out with washing ratio of 0.53 h^{-1}. The results are shown in table 2 together with the respiration rates and the amount of inhalation intake by 1 hour respiration. The numbers in parentheses of the radioactivity column of table 2 shows the radioactivities in the air calculated on the assumption that it did not rain on March 15, that is, there occurred no precipitation washout of the radioactive material.

Table 2. Rdioactivities in the air and the amount of inhalation intake during 1 hour respiration.

	I-131		Cs-134 or Cs-137		Respiration ratio (m^3 h^{-1})
	Radioactivity (Bqm^{-3})	Intake (Bqh^{-1})	Radioactivity (Bqm^{-3})	Intake (Bqh^{-1})	
adults	9.9×10^3	9.2×10^3	8.5×10^2	7.9×10^3	9.3×10^{-1}
children(1)	(2.1×10^4)	3.6×10^3	(1.8×10^3)	3.1×10^2	3.6×10^{-1}

Radioactive airborne dust in the air monitored by the MEXT (Ministry of Education, Culture, Sports, Science and Technology) showed that more than hundreds or thousands Bq m^{-3} of I-131 were observed in Iidate-mura or Hirono-machi after March 21 when the radioactive material was continuously released from the nuclear power plants with almost 2 orders of magnitude smaller release rate than that observed on March 15. By taking into consideration of the difference of the release rates of the radioactive material I-131 in the air shown in parentheses in table 2 seems not to be so different from the realistic one. And this discussion was also true for Cs-134 and Cs-137.

３．２ Estimation of internal doses of the people

Internal exposure dose rates by 1 hour inhalation of I-131, Cs-134 and Cs-137[5] are shown in table 3. From table 3, in the early stage of the radiological disaster, adults and children thyroids received equivalent doses of 2.6 mSv and 5.0 mSv per 1 hour respiration, respectively. And effective doses by I-131 were about 0.14mSv for adults and 0.25 mSv for children per 1 hour respiration. On the other hand, effective doses by both Cs-134 and Cs-137 were 0.05 mSv for adults and children per 1 hour respiration.

By taking into consideration of the life style of the people in winter, that is, assuming that the people stayed outdoors for 1 hour and stayed in house for 8 hours, equivalent doses by I-131 were 6.8 mSv for adults and 13 mSv for children and effective doses by I-131 were 0.36mSv for adults and 0.65 mSv for children. Effective doses by both Cs-134 and Cs137 were 0.12mSv～0.13 mSv for adults and children. Here, radioactivity reduction coefficient of a house was assumed to be 0.2.

The equivalent doses or effective doses in table 3 were the most probable ones obtained under the exposure condition that almost a half of the radioactive materials flowed from the nuclear power station were staying in the air. This means it would be quite possible that the internal exposure doses varied depending on the efficiency of the precipitation washout and on the stay in-house time. So, the doses in table 3 would vary by a factor of 2 of the evaluated values if the washing ratio was varied from 0.3 to 0.7. And they would also become two times larger than those in table 3 if the people stayed outdoors for more than 3 hours.

Table 3. Internal doses of adults and children by I-137, Cs-134 and Cs-137 in the air on March 15.

	I-131		Cs-134	Cs-137
	Equivalent dose (mSv/9h)	Effective Dose (mSv/9h)	Effective dose (mSv/9h)	Effective dose (mSv/9h)
adults	6.8×10^{0}	3.6×10^{-1}	4.2×10^{-2}	8.0×10^{-2}
children	1.3×10^{1}	6.5×10^{-1}	5.2×10^{-2}	8.0×10^{-2}

Though the results shown in table 3 were simply internal doses during 9 hours from March 15 to March 16, determination of the internal exposure in the early stage of nuclear disaster would be important for examination of the radiation effects of the people because these doses were caused by the largest release rate of the radioactive material after the Fukushima nuclear accident. It seemed possible from the discussion stated above that the equivalent doses by inhalation intake of I-131 would be less than 20 mSv and effective doses by inhalation intake of I-131, Cs-134 and Cs137 would be less than 1 mSv in the early stage of nuclear disaster by taking into consideration of the total amount of radioactive material released from the power plants and the probability distribution of the wind direction from the power station.

４． Conclusions

From the discussion stated above, conclusions are as follows;

1. I-131, Cs-134 and Cs-137 in the air from 18:00 pm on March 15 to 3:00 am on March 16 were estimated on the basis of the soil radioactivities extrapolated from the data monitored after March 21 and 9.9×10^{3} Bqm^{-3} for I-131 and 8.5×10^{2} Bqm^{-3} for each Cs-134 and Cs-137 was obtained.
2. In the early stage of the radiological disaster, adults and children thyroids received equivalent doses of 2.6 mSv and 5.0 mSv per 1 hour respiration, respectively. And effective doses by I-131 were about 0.14mSv for adults and 0.25 mSv for children and those by both Cs-134 and Cs-137 were 0.05 mSv for adults and children per 1 hour respiration.

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