RADIOLOGICAL SAFETY ASSESSMENT FOR INCIDENT-FREE TRANSPORTATION OF RADIOACTIVE DECONTAMINATION WASTE AFTER THE FUKUSHIMA NUCLEAR POWER PLANT ACCIDENT

by

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Radioactive decontamination waste generated by remediation following the Fukushima nuclear power plant accident was recently transported from its temporary storage sites to interim storage facilities as a pilot test. A transportation plan for the radioactive decontamination waste will be developed based on this pilot transportation experience and radiological safety assessment of pilot transportation. The objective of this study was to assess radiation doses to the public and crew workers released during incident-free pilot transportation. External dose rates around a transportation vehicle were calculated by using the Monte Carlo N-Particle code. Collective doses and maximally exposed individual doses to the public and effective doses to crew workers were calculated by using INTERTRAN. Two transportation routes, Asakawa-machi to Okuma-machi and Iwaki-shi to Okuma-machi, were considered. The maximum radioactivity concentration in the decontamination waste was calculated to be 660 kBqkg^{-1} which meets the value laid down by the guidelines of Japan's Ministry of the Environment. The collective doses to the public per shipment were 1.9 10^{-3} person-mSv for the Asakawa route and 2.2 10^{-4} person-mSv for the Iwaki route. Maximally exposed individual doses to the public were 9.6 10^{-7} mSv for the Asakawa route and 2.7 10^{-5} mSv for the Iwaki route. The total effective doses to crew workers were 0.27 mSv for the Asakawa route assuming five shipments per worker and 1.07 mSv for the Iwaki route assuming 45 shipments per worker. The radiation dose levels to the public and workers evaluated in this study were much lower than the annual dose limits for the general public and radiation workers. These study results can be used to develop transportation plans and guidelines for decontamination waste transportation.

Key words: Fukushima nuclear power plant accident, decontamination waste, interim storage facility, transportation, safety assessment

INTRODUCTION

Following the Fukushima nuclear power plant (NPP) accident radioactive materials were dispersed in the atmosphere and deposited onto the terrestrial environment. The Japanese government has continuously remediated the contaminated areas [1] and these remediation activities generated large volumes of decontamination waste, estimated at approximately 22 million m^3 [2]. According to the decontamination plan formulated by the Ministry of the Environment (MOE) of Japan, decontamination waste generated by remediation in the Fukushima Prefecture has been stored at temporary storage sites (TSS) [3]. Within the special decontamination area (SDA), for which Japanese government has assumed the responsibility to formulate and effect remediation plans, approximately 4.6 million m^3 of decontamination waste has been stored in approximately 250 TSS [4].

In September 2014, the governor of Fukushima approved the construction of interim storage facilities (ISF) in Okuma-machi and Futaba-machi to ensure safety and provide complete control over the decontamination waste until a disposal site would be available [2]. Since March 2015, pilot transportation of decontamination waste from TSS to ISF had been implemented for approximately one year in order to confirm safe and secure transportation [2, 5]. During pilot transportation, approximately 45 000 m^3 of decontamination waste was transported from 43 TSS during this period [6]. The MOE is preparing for future transportation by the implementation and review of this pilot transportation.

Radiological safety assessments for radioactive material transportation have been reported in references. The US Department of Energy (DOE) has de-

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veloped safety assessment tools, such as RADTRAN and RISKIND [7]. A study by Vieru evaluated the safety and risk of transportation of radioactive materials [8]. Weiner assessed radiological risk resulting from transportation of low-level radioactive waste (LLW) and naturally occurring radioactive material (NORM) under incident-free conditions [9]. Argonne National Laboratory (ANL) reported a transportation impact assessment for shipment of uranium hexafluoide (UF_6) cylinders [10]. The MOE assessed the radiation dose to the public from decontamination waste transportation [11].

Assessment of radiation doses to the public and workers is required for radiological safety assessment of decontamination waste transportation. A radiological safety assessment for transportation was performed by Japan's MOE [11]. However, it was a preliminary evaluation made for transportation planning. Therefore, MOE suggested that radiation dose assessment to pedestrians and workers should also be made during decontamination waste transportation. The objective of the present study was to assess radiological safety for the transportation of decontamination waste resulting from the Fukushima NPP accident. We calculated radiation doses to the public and crew workers released due to the pilot transportation of the waste. External dose rates around a transportation vehicle were evaluated by applying a radiation transport code. Radiation doses to the public and workers were calculated by using a safety assessment tool for radioactive waste transportation. This study was limited to incident-free transportation.

MATERIALS AND METHODS

Evaluation of external dose rates around a transportation vehicle

According to the decontamination waste transfer guidelines drawn up by MOE, the maximum external dose rate should not exceed 100 Svh^{-1} at the distance of 1 m from the back and sides of the vehicle and 20 Svh^{-1} at 1 m from the front of the vehicle. External dose rates around a transportation vehicle were evaluated to confirm that transportation follows the MOE guidelines. The radiation dose rates were evaluated by changing the radioactivity concentration in decontamination waste from 3 kBqkg^{-1} to 1 000 kBqkg^{-1}.

Input parameter values for the dose rate evaluation were collected by reviewing the available references and used for the evaluation. Decontamination waste made up more than 75 % of contaminated soil [12]. Therefore, decontamination waste was regarded as contaminated soil. Mass density and elemental composition of the contaminated soil were classified as soil type 1 defined by International Commission on Radiation Units and Measurements (ICRU) publication 53 [13]. The soil properties for radiation dose assessment are summarized in tab. 1. In most cases, a waterproof sandbag or a flexible container was used for packaging of the decontamination waste in TSS. The diameter and height of the sandbag and container were approximately 1.1 m fig. 1(a). The sandbag or container was only used to prevent dispersion, outflow, and leakage of the waste and thus had no radiation shielding effect [14]. The ratio of radioactivity concentrations between ^{134}Cs and ^{137}Cs in the decontamination waste was assumed to be 1 to 3 by considering the decay time after the Fukushima NPP accident. The transportation vehicle was assumed to be a 10-ton truck, which can be loaded with seven decontamination waste packages figs. 1(b) and 1(c).

External dose rates were calculated by using the Monte Carlo N-Particle (MCNP) code for simulating the contaminated soil and exposure condition. The external dose rates were calculated at the side and in the front of a transportation vehicle 1 m from the vehicle surface at the central line position of the side surface (P-1) and at the central line position of the front sur-

Table 1. Soil properties for radiation dose assessment of the public and crew workers

Property		Value
Density [gcm^{-3}]		2.0
Elemental composition [%]	H	2.20
	O	57.5
	Al	8.5
	Si	26.2
	Fe	5.60

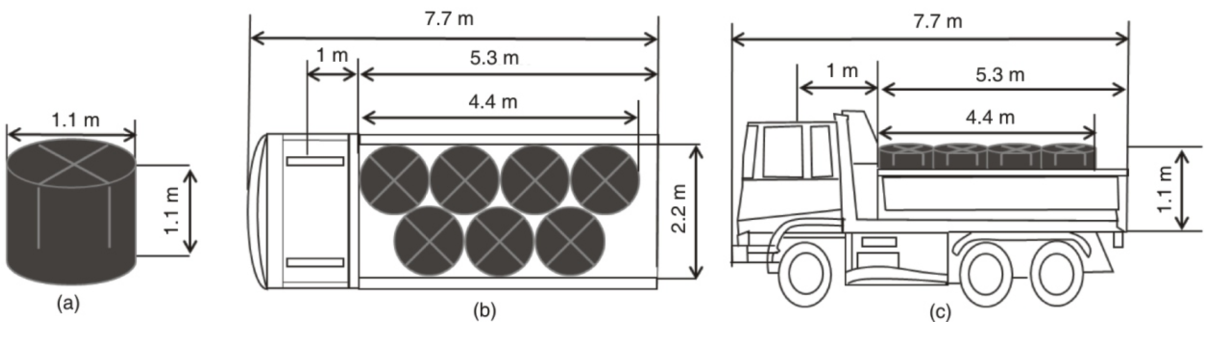

Figure 1. Geometric dimensions of decontamination waste packages and the transportation vehicle

face (P-2). Dose conversion coefficients from Publication 74 of the International Commission on Radiological Protection (ICRP) were used for dose calculation [15].

Assessment of radiation doses to the public and workers

Radiation doses emitted to the public and crew workers were assessed. For public exposure, collective doses and maximally exposed individual doses were calculated. For worker exposure, effective doses for each link and route were calculated. In addition, cumulative doses for each route were calculated considering multiple transportations. The INTERTRAN code was used to calculate the radiation doses from incident-free transportation. Radiation doses resulting from the waste transportation depended on the transportation route characteristics and exposure conditions. Therefore, such data were collected and used for dose assessment.

Two transportation routes were considered – Asakawa-machi to Okuma-machi and Iwaki-shi to Okuma-machi, fig. 2. Each route was subdivided into three links according to road type or region. The Asakawa route was subdivided into Asakawa TSS – Tamakawa IC (link 1), Tamakawa IC – Tomioka IC (link 2), and Tomioka IC – Okuma ISF (link 3) according to road type. The Iwaki route was subdivided into Iwaki TSS – Kawauchi-cho (link 4), Kawauchi-cho – Nogami-cho (link 5), and Nogami-cho – Okuma ISF (link 6) according to region.

The information on road type and route length was abstracted from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). According to road type Link 2 was a freeway and the others were non-freeway. The population density and vehicle density for each link were abstracted from the Statistics Bureau of the Ministry of Internal Affairs and Communication (MIC) and traffic information from Fukushima Prefecture. The volumes of decontamination waste transported through the Asakawa and Iwaki routes were approximately 100 m^3 and 1 000 m^3, re-

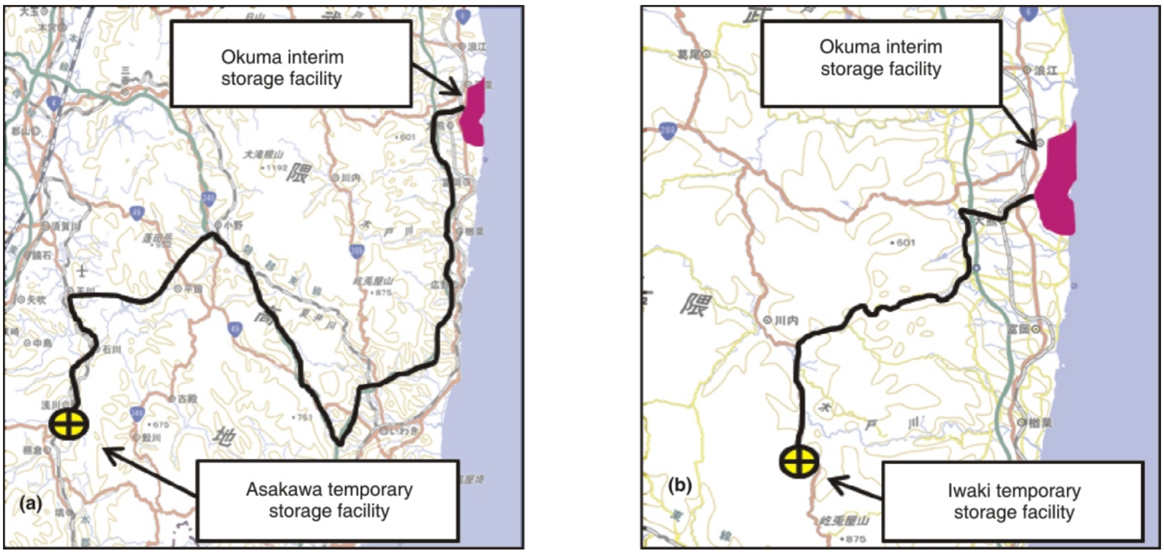

Figure 2. Transportation routes for decontamination waste: Asakawa-Okuma route (a) and Iwaki-Okuma route (b)

Table 2. Transportation route information, which affect radiation doses to the public and crew workers

Route	Link	Detail route	Road type	Route length [km]	Vehicle density (vehicle per hour)	Population density (person per km^2)	Number of shipments (average per worker)
Asakawa – Okuma	Link 1	Asakawa TSS – Tamakawa IC	Non-Freeway	21.2	758	181.8	15 (5 per worker)
	Link 2	Tamakawa IC – Tomioka IC	Freeway	108.0	72.5	93.8	
	Link 3	Tomioka IC – Okuma ISF	Non-Freeway	36.7	– [a]	– [a]	
Iwaki – Okuma	Link 4	Iwaki TSS – Kawauchi-cho	Non-Freeway	16.4	47.5	106.4	143 (45 per worker)
	Link 5	Kawauchi-cho – Nogami-cho	Non-Freeway	20.4	40.3	13.9	
	Link 6	Nogami-cho – Okuma ISF	Non-Freeway	10.0	– [a]	– [a]	

[a] Areas where it is anticipated that residents will not be able to return to for a long time

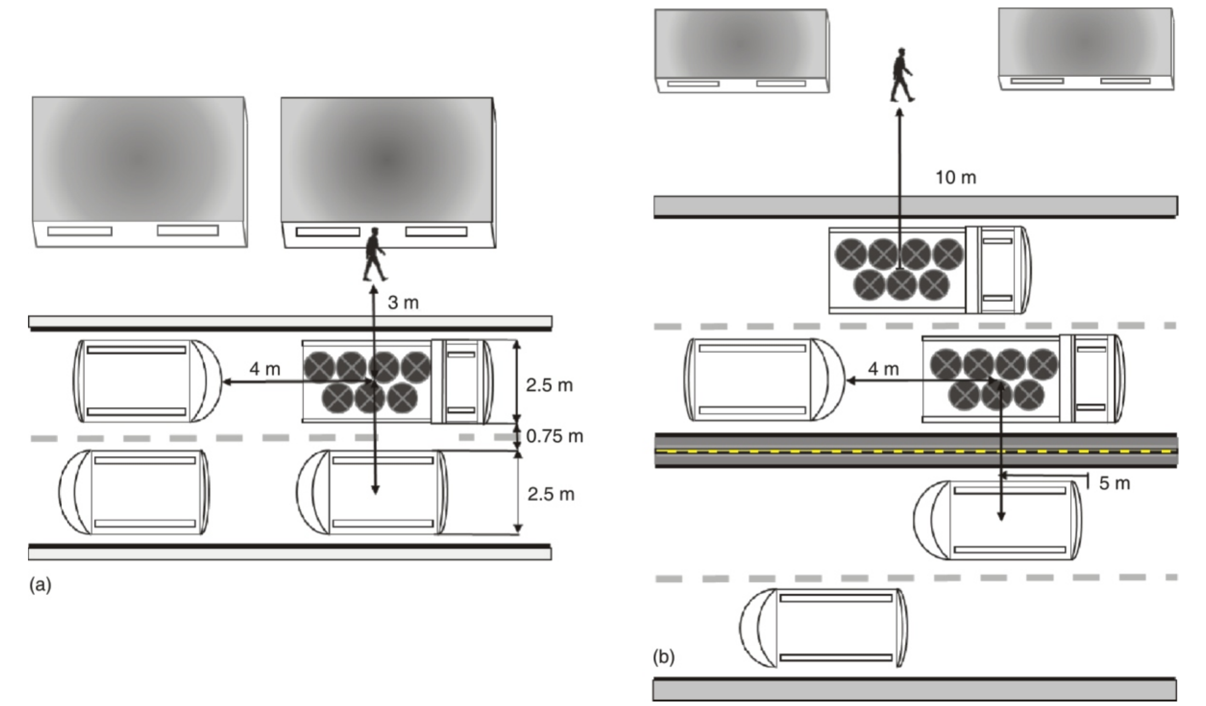

Figure 3. Exposure conditions for the public during decontamination transportation on non-freeway (a) and freeway (b) routes

spectively [16, 17]. The number of shipments was 15 for the Asakawa route and 143 for the Iwaki route. The average number of shipments per worker were five for the Asakawa route and 45 for the Iwaki route.

Members of the public around the transportation routes were subdivided into those along the route (off-link) and those sharing the route (on-link). The off-link population were all the persons living or working by each side of the transportation route. The on-link population were persons in all the vehicles that shared the transportation routes, and this group included persons traveling in both the same and the opposite directions as the shipment, as well as persons in vehicles passing by the shipment. The ratio of pedestrians to the residential population in off-link was assumed to be 1 to 3. The shielding factor was set as 0.4 considering that houses in Japan are wooden.

Figure 3 shows exposure conditions for the public during transportation on non-freeway and freeway routes. Exposure conditions for non-freeway and freeway routes were assumed based on H22 road information [12]. For the non-freeway route, it was assumed that the minimum distance between the side surface of the vehicle and residents along the street was 3 m. In addition, the minimum distance between vehicles travelling in the same direction was 4 m and the minimum distance between vehicles travelling in the opposite direction was 3.25 m. For the freeway route, the minimum distance between the side surface of the vehicle and residents along the street was 10 m considering the shoulder and the width of the street. In addition, the minimum distance between vehicles travelling in the same direction was 4 m and the minimum distance between vehicles travelling in the opposite direction was 5 m considering a median strip and the width of the road. The average speed of a vehicle on the non-freeway and freeway routes were assumed to be 30 kmh^{-1} and 70 kmh^{-1}, respectively.

Radiation doses to crew workers were also assessed. It was assumed that the crew worked on its own and did not work in shifts. The exposure condition of the crew workers was the same as the public exposure condition mentioned previously. The radiation dose per one shipment was evaluated by link and route. In addition, the cumulative dose for each route was calculated by considering the average number of shipments per crew worker.

RESULTS AND DISCUSSION

Radiation dose rates around a transportation vehicle

Table 3 shows the external dose rates at the distance of 1 m from the transportation vehicle surface. Assuming 3 kBqkg^{-1} of radioactivity concentration in the waste, dose rates were 0.17 Svh^{-1} at the central line position of the side surface and 0.09 Svh^{-1} at the central line position of the front surface. Increasing the radioactivity concentrations in the decontamination waste up to 1000 kBqkg^{-1}, the dose rates increased up to 56 Svh^{-1} at the side position and 29 Svh^{-1} at the front position. The study results were approximately 37%-60% lower than the preliminary results of MOE [11]. MOE assumed that the vehicle container was

Table 3. External dose rate around a transportation vehicle by radioactivity concentration in decontamination waste

Radioactivity concentration in decontamination waste [$kBqkg^{-1}$]	External dose rate [Svh^{-1}]			
	P-1 (side position)		P-2 (front position)	
	This study	MOE	This study	MOE
3	0.17	0.27	0.09	0.20
8	0.45	0.72	0.23	0.53
30	1.7	2.7	0.87	2.0
150	8.3	13	4.4	10
500	28	44	15	33
1.000	56	89	29	66

fully filled with decontamination waste, thus overestimating the radiation source and the resulting radiation doses. In fact, seven decontamination waste packages were loaded on to a vehicle for transportation. This study evaluated dose rates emitted from the vehicle carrying seven waste packages to simulate actual conditions, figs. 1 and 2.

The maximum radioactivity concentration in the decontamination waste was estimated to be approximately 660 $kBqkg^{-1}$ to meet the value laid down in the MOE guidelines (less than 100 Sv h-1 at the back and sides and 20 Svh^{-1} in the front of the vehicle). For the radioactivity concentration, dose rates were 37 $Sv h^{-1}$ at the side position and 20 Svh^{-1} in the front. No radiation shielding effect was considered in the dose rate calculation. A special transportation container with proper radiation shielding may need to be developed and used to transport decontamination waste at higher concentrations than the maximum concentration value mentioned above.

Radiation doses to the public

Figure 4 shows collective doses to the public from incident-free transportation. The collective dose per shipment was the highest for link 1 (1.1 10^{-3} person-mSv per shipment). The differences in collective doses could be attributed to transportation time (determined by route length and vehicle speed), population density, and road type. The transportation time of link 2 was 2.2 times higher than that of link 1 due to the route length and road type. However, the population density of link 1 was two times higher than that of link 2, and the distance between the road and the residents along the street of link 1 (non-freeway) was shorter than that of link 2 (freeway). Therefore, the collective dose for link 1 was the highest for the Asakawa route. Although the route length and vehicle density of link 4 was similar to those of link 5, the population density along link 4 was ten times higher than the one along link 5. Therefore, the collective dose for link 4 was the highest for the Iwaki route. For links 3 and 6, it was assumed that residents would not be able to return for a long time. Therefore, collective doses for these links were not calculated. The collective doses per shipment

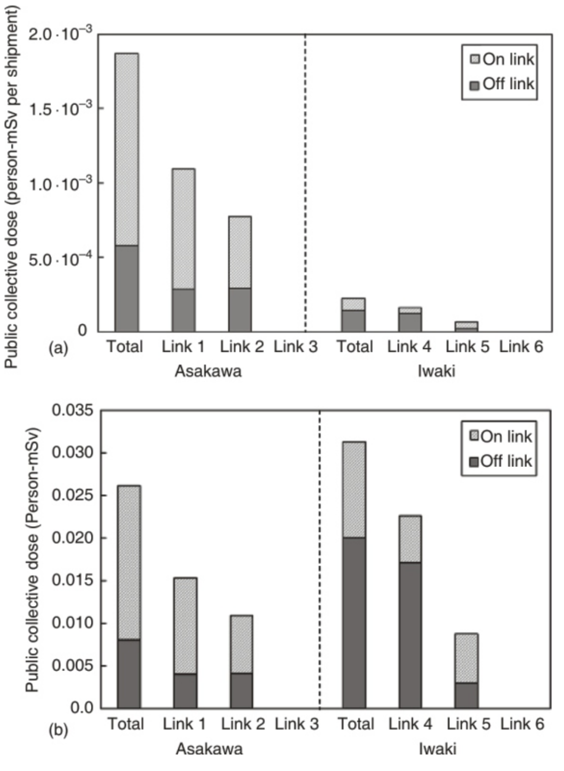

Figure 4. Collective doses to the public resulting from incident-free transportation; Radiation doses per shipment (a) and cumulative doses from multiple transportations (b). For the cumulative dose calculations, the total number of shipments for each route was considered

were 1.9 10^{-3} person-mSv for the Asakawa route and 2.2 10^{-4} person-mSv for the Iwaki route.

The collective doses for the off-link population on the Asakawa route were 4.3 10^{-3} person-mSv (26 %) for link 1 and 4.1 10^{-3} person-mSv (38 %) for link 2. In the case of the Iwaki route, collective doses for the off-link population were 1.7 10^{-2} person-mSv (76 %) for link 4 and 2.9 10^{-3} person-mSv (34 %) for link 5. The collective dose for off-link depended on the transportation time, population density, and exposure condition of the off-link population. Link 4 took up the highest proportion of collective dose for off-link because the population density relative to the vehicle density was much higher than for the other links.

The cumulative dose varied depending on the number of shipments, as well as the radiation dose per shipment. The cumulative doses were calculated by considering the total number of shipments for each route: 15 times for the Asakawa route and 143 times for the Iwaki route. The cumulative dose was higher for the Iwaki route due to the larger number of shipments. The cumulative doses were 0.27 mSv for the Asakawa route and 0.031 mSv for the Iwaki route.

Maximally exposed individual doses to the public were 9.6 10^{-7} mSv and 2.7 10^{-5} mSv at the distance of 3 m from the vehicle for the Asakawa route and the Iwaki route, respectively. The dose levels were much lower than the annual dose limit for the general public.

Radiation doses to crew workers

Figure 5 shows the effective doses to crew workers during incident-free transportation. Radiation doses to crew workers per shipment were the highest for link 2 (0.024 mSv per shipment) and the lowest for link 6 (0.005 mSv per shipment). The difference in effective doses to workers could be attributed to route length and vehicle speed, and therefore to transportation time. The transportation time of link 2 was approximately 1.5 hours, which was the longest time for the Asakawa route. In the case of the Iwaki route, the transportation time of link 5 was approximately 0.7 hours, which was the longest time for the route. The radiation doses per shipment were 0.053 mSv for the Asakawa route and 0.024 mSv for the Iwaki route.

The cumulative doses were calculated by considering the average number of shipments for each route. The total effective doses were 0.27 mSv and 1.07 mSv for the Asakawa route and the Iwaki route, respectively. The dose levels were much lower than the annual dose limit for radiation workers.

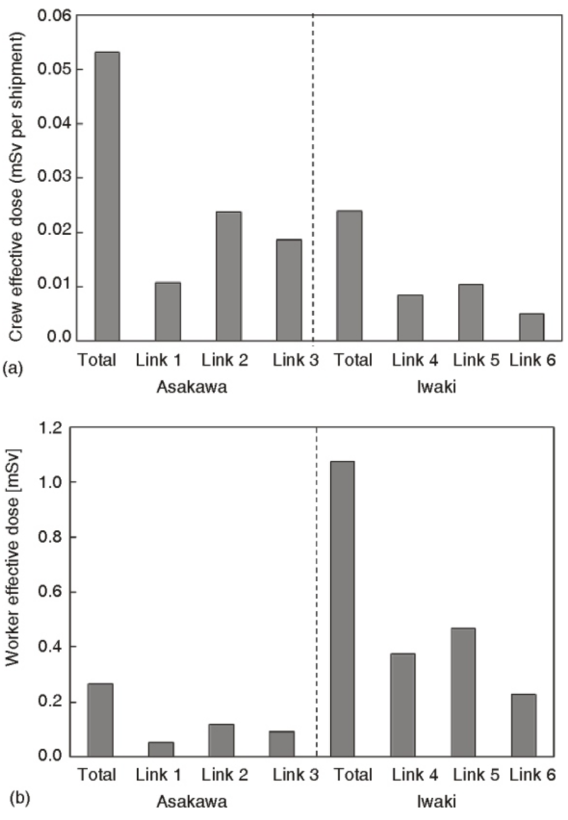

Figure 5. Effective dose to crew workers resulting from incident-free transportation: Radiation dose per shipment (left) and cumulative dose from multiple transportations (right). For the cumulative dose calculations, the average number of shipments per crew worker was considered for each route

CONCLUSIONS

Radiological safety assessment was made for pilot transportation of decontamination waste created by the Fukushima NPP accident. Radiation doses emitted to the public and crew workers resulting from transportation were assessed considering the transportation route. Decontamination waste properties, transportation route characteristics, and exposure conditions for each route were considered in the dose assessment.

External dose rates around a transportation vehicle were proportional to radioactivity concentrations in decontamination waste. Assuming 660 kBqkg^{-1} of radioactivity concentration in the waste, the external dose rates were 37 Svh^{-1} at the side position and 20 Svh^{-1} at the front position. The collective doses to the public per shipment were 1.9 10^{-3} person-mSv for the Asakawa route and 2.2 10^{-4} person-mSv for the Iwaki route. The maximally exposed individual doses to the public were 9.6 10^{-7} mSv for the Asakawa route and 2.7 10^{-5} mSv for the Iwaki route. The total effective doses to crew workers were 0.27 mSv for the Asakawa route and 1.07 mSv for the Iwaki route.

The maximum radioactivity concentration in the decontamination waste without waste package providing a shielding effect was 660 kBqkg^{-1} to meet the MOE guidelines. A special transportation container with proper radiation shielding may need to be developed and used to transport waste with a higher concentration than the maximum value. The dose levels to the public and workers were evaluated as being much lower than the annual dose limits for the general public and radiation workers. Therefore, it can be concluded that radiological safety was provided by this incident-free transportation. Further study for radiological safety assessment is necessary considering potential incidents during waste transportation. These study results can be used to develop transportation plans and guidelines for decontamination waste transportation. In addition, the safety assessment procedure can be used for emergency preparedness.

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AUTHORS' CONTRIBUTIONS

The manuscript was written by M. J. KIM, J. H. Park, J. O. Lee, and K. P. Kim. The MCNP simulations were done by M. J. Kim and J. Y. Song. Radiation dose assessments were done by J. H. Park, T. G. Do, and J. O. Lee. The scientific supervision was done by K. P. Kim. All authors analyzed and discussed the results and reviewed the manuscript.

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ПРОЦЕНА РАДИОЛОШКЕ СИГУРНОСТИ ТРАНСПОРТА БЕЗ ИНЦИДЕНТА ДЕКОНТАМИНАЦИОНОГ РАДИОАКТИВНОГ ОТПАДА НАКОН НЕСРЕЋЕ У НУКЛЕАРНОЈ ЕЛЕКТРАНИ ФУКУШИМА

Радиоактивни деконтаминациони отпад, настао ремедијацијом након нуклеарног акцидента у електрани Фукушима, недавно је превезен са привремених складишта до прелазних одлагалишта, као пилот тест. На основу овог искуства у пилот транспорту и процене раиолошке сигурности пилот превоза, биће развијен план транспорта радиоактивног деконтаминационог отпада. Циљ ове студије био је да се процене дозе зрачења којима су били изложени становништво и транспортне посаде приликом пилот превоза без инцидента. Спољашње јачине доза око транспортног возила израчунате су коришћењем MCNP кода. Колективне дозе, максимална излагања појединаца у популацији и ефективне дозе за раднике посада израчунате су помоћу INTERTRAN програма. Размотрена су два транспортна правца: Асакава-мачи до Окума-мачи и Иваки-ши до Окума-мачи. Максимална концентрација радиоактивности у деконтаминационом отпаду израчуната је на 660 $kBqkg^{-1}$, што задовољава вредности утврђену смерницама Министарства за околину Јапана. Колективне дозе за популацију по пошиљци биле су 1.9 10^{-3} mSv-човек за руту Асакава и 2.2 10^{-4} mSv-човек за руту Иваки. Максималне дозе изложености појединца, за популацију, биле су 9.6 10^{-7} mSv за Асакава руту и 2.7 10^{-5} mSv за Иваки руту. Укупне ефективне дозе за раднике у транспортним посадама износиле су 0.27 mSv за пут Асакаве уз пет пошиљки по раднику и 1.07 mSv за руту Иваки уз 45 пошиљки по раднику. Нивои дозе зрачења за популацију и раднике који су оцењени у овој студији били су много нижи од годишњих граница доза за популацију и раднике са радиоактивним материјалом. Ови резултати истраживања могу се користити за израду транспортних планова и смерница за транспорт деконтаминационог отпада.

Кључне речи: Фукушима акцидент, деконтаминациони отпад, постројење за прелазно одлагање, транспорт, оцена сигурности