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Transport Risk Assessment for On-Road/Sea Transport of Decommissioning Waste of Kori Unit 1

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Compared to operational wastes, nuclear power plant (NPP) decommissioning wastes are generated in larger quantities within a short time and include diverse types with a wider range of radiation characteristics. Currently used 200 L drums and IP-2 type transport containers are inefficient and restrictive in packaging and transporting decommissioning wastes. Therefore, new packaging and transport containers with greater size, loading weight, and shielding performance have been developed. When transporting radioactive materials, radiological safety should be assessed by reflecting parameters such as the type and quantity of the package, transport route, and transport environment. Thus far, safety evaluations of radioactive waste transport have mainly targeted operational wastes, that have less radioactivity and a smaller amount per transport than decommissioning wastes. Therefore, in this study, the possible radiation effects during the transport from NPP to disposal facilities were evaluated to reflect the characteristics of the newly developed containers and decommissioning wastes. According to the evaluation results, the exposure dose to transport workers, handling workers, and the public was lower than the domestic regulatory limit. In addition, all exposure dose results were confirmed, through sensitivity analysis, to satisfy the evaluation criteria even under circumstances when radioactive materials were released 100% from the container.

Keywords: Decommissioning radioactive waste, RADTRAN, Transport risk assessment, LILW disposal facility, Annual dose limit

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1. Introduction

On contrary to the operational waste, which tend to have a consistent generation rate and limited variety in the waste types, the radioactive wastes generated during the decommissioning of the NPP, such as facilities and structures within the NPP, demolition and decontamination equipment, work clothes, and miscellaneous goods used for a wide range of decommissioning works, have a wide variety of waste types, sizes, and radiation characteristics (clearance to intermediate level). Furthermore, these decommissioning wastes tend to be generated in large quantities within a short period of time [1].

Due to such differences between operational and decommissioning wastes, 200 L or 320 L drums, and IP-2 type transport containers may be inefficient or impossible to be used for packaging and transporting decommissioning wastes. Hence, through the study of “Development of Waste Package, Transport, and Disposal Containers for Decommissioning Wastes of Nuclear Power Plant”, decommissioning wastes are categorized according to waste type, size, weight, and radiation characteristics, then containers, which consider characteristics of each waste group, are under development.

These containers are designed to be of larger sizes and higher design weights compared to the 200 L, and IP-2 type transport containers. Therefore, current transported system (handling equipment, transport vehicles, and transport vessels), which are tailored to the transport of the operational waste, is required to be changed or redesigned considering the characteristics of the container under development. Likewise, transport strategy, such as transport schedule, frequency, and route, should be established according to the generation characteristics of decommissioning wastes.

Meanwhile, in the process of transporting the radioactive waste, the public and the workers are likely to be exposed to the radiation emitted from the radioactive materials. If radioactive materials are released out of the package due to accidents, such as collisions, rollovers, and fire, more people may be affected by radiation in the broader environment. Therefore, when considering the transport of radioactive materials, it is necessary to evaluate the transport safety of the radioactive materials in advance, considering of the type of radioactive material, the transport route, and the transport environment.

So far, the safety evaluation of radioactive waste transport has focused mainly on the transport of operational waste. However, for the decommissioning waste, the safety evaluation is only under the conditions when on-road transport and existing transport containers are considered, excluding the characteristics and the transport strategies of the decommissioning wastes. The decommissioning wastes have relatively high activity levels compared to operational wastes and are transported in a large amount at once using the developed containers. Furthermore, both on-road and sea routes may be considered according to the transport strategy for decommissioning wastes. In this study, such conditions, which were previously excluded, are reflected in the safety evaluation by considering various types of waste, new containers, transport routes of both land and sea, etc.

The transport route is from the Kori NPP to the Gyeongju disposal facility, and the evaluation targets are the transport workers, the handling (loading and unloading of radioactive material package) workers, and the public near the transport route. For the evaluation, the RADTRAN 6 code, which is the most widely used code for transport risk assessment, was used.

Then, the evaluation result expressed as exposure dose and risk on the workers and public during the transport of the radioactive material is compared with the domestic regulatory limit to confirm the transport safety of the decommissioning wastes. Additionally, the sensitivity analysis was performed to evaluate the change in exposure dose according to the change in the release rate of radioactive materials after the accident.

2. Assessment Input Data and Assumption

The input parameters required for the transport risk assessment consist of seven basic items and detailed items as shown in Tables 1 and 2 [2].

2.1 On-Road Transport

On-road transport route is through which radioactive waste is transported by vehicle to national roads and highways.

2.1.1 Characteristics of the Transport Container and Package

In this study, transport risk on 7 types of packages including different contents, shown in Table 3, were evaluated. Realistically, the surface dose rate of the package would be lower than the transport regulation radiation level limit of 2 mSv·h^{-1} [3], depending on the activity concentration in the package. However, for conservative evaluation, the surface dose rate of all packages is assumed to be 2 mSv·h^{-1}. In addition, the radiation dose rate (0.658 mSv·h^{-1}) at a point 1 m away from the package was calculated using the microshield computer code. Since there was no nuclide that emits neutrons in the wastes to be transported, the neutron fraction was set to 0%.

2.1.2 Transport Route

The input parameters related to the transport route are distance, vehicle speed, population density, and accident rate of each link that is a route segment. The transport route was set as shown in Table 4, considering the transport time, population density, and accident possibility to minimize the exposure dose. The transport link was divided into 16 sections according to administrative districts based on eup, myeon, and dong. The population and area of each section were calculated using Statistical Geographic Information Service (SGIS) [4] and website information for each administrative district. The total transport distance is 77.2 km (14.2 km on national roads and 63 km on highways), and the speed of the vehicle was assumed to be 60 km·h^{-1} on highways and 30 km·h^{-1} on national roads. The accident rate was calculated by dividing the number of accidents by the vehicle traffic and distance according to the calculation formula [5]. The information on accidents and vehicle traffic was obtained from the Traffic Accident Analysis System (TAAS) [6] and the Korean Statistical Information Service (KOSIS), respectively [7, 8].

$$[Accident\ Rate]_i = \frac{[Number\ of\ Accidents]_i}{[Number\ of\ Vehicles]_i \times [Length]_i} \qquad (1)$$

$[\text{Accident Rate}]_i$: Accident rate in section i [Number of accidents/vehicle·km]
$[\text{Number of Accidents}]_i$: Average number of accidents per day in section i [Number of accidents/days]
$[\text{Number of Vehicles}]_i$: Average daily vehicle traffic in section i [Vehicles/day]
$[\text{Length}]_i$: The length of section i [km]

2.1.3 Transport Vehicle

Each transport vehicle is loaded with only one package, therefore the dose at 1m from the vehicle and gamma/neutron fraction was set to be the same value as the package. The number of vehicle occupants was set to two (the driver and radiation safety manager). The vehicle shielding factor was applied with a value (0.03) corresponding to the dose limit of 0.02 mSv·h^{-1} at the occupant position [9].

2.1.4 Stop

If a transport vehicle stops for any reasons (eg. Crew change, passenger transfer, crew meals, refueling, storage, and inspection, etc.), then persons at or near the stop point can be exposed to external radiation from the shipment [10]. In this evaluation, it was expected that there will be no stopping during transport due to the short transport distance, but for a conservative evaluation, only one stop during a transport is assumed. The stop time was set as 1 hour, and the stop location was set to Nam-gu, Mugeo-dong, which had

Table 1. Assessment input parameter (normal)

Basic item	Detailed items	Description
Vehicle	Transport mode	Transport route type
	Exclusive use	Indicate whether the vehicle is exclusive use or not.
	Size (CD) (m)	Largest dimension of vehicle
	Dose rate at 1 m (mrem·hr^{-1})	Dose rate at 1 m from the package
	Gamma fraction	Fraction of gamma rays to the total external package dose
	Neutron fraction	Fraction of neutron rays to the total external package dose
	Crew size	The number of crew members in the vehicle
	Crew distance (m)	Average distance between the package and the crew members
	Width facing crew (m)	Largest dimension of the package that faces toward the crew
	Crew shielding factor	Fraction of shielding to the crew members from external package dose
	Number of shipments	The number of transports
Link	Mode	Road type
	Length (km)	Distance traveled on this link
	Speed (km·hr^{-1})	Average speed the vehicle travels on this link
	Adjacent vehicle occupants	Average number of people in other vehicles
	Population density (people·km^{-2})	Population density surrounding the link
	Traffic (vehicles·hr^{-1})	The number of vehicles traveling on this link per hour
	Accident per km	Probability of a vehicle accident per kilometer on this link
	Deaths per accident	Average number of fatalities from a vehicle accident
	Population type	Population type
	Farm fraction if rural	Fraction of agricultural area surrounding the link
Stop	Population density (people·km^{-2})	Population density near the stop
	Inner radius (m)	Inner boundary of stop area
	Outer radius (m)	Outer boundary of stop area
	Shielding factor	Fraction of shielding to people near the stop area from external package dose
	Duration (hr)	Duration of the stop, in hours
Handling	Persons	The number of handling workers
	Distance (m)	Average distance of the handlers from the package
	Duration (hr)	Duration of the handling, in hours
Package	Largest dimension (m)	Largest dimension of the package
	Dose rate at 1 m from surface (mrem·hr^{-1})	Dose rate at 1 m from the package
	Gamma fraction	Fraction of gamma rays to total external package dose
	Neutron fraction	Fraction of neutron rays to total external package dose
	Number of package	The number of packages

Table 2. Assessment input parameter (accident)

Basic item	Detailed items		Description
Accident	Severity probabilities		Probabilities of different types of vehicle crash
	Release group	Release fraction	Fraction of radioactive material's escapes from the package containment
		Aerosol fraction	Fraction of aerosolization of released radioactive material
		Respirable fraction	Fraction of the aerosolized material that consist of particles small enough to enter the lung
		Deposition velocity ($m \cdot s^{-1}$)	Fraction of the aerosolizing material move to the ground
	Weather		Weather information that affects dispersion
	Dispersion areas		Properties of the regions surrounding an accidental release
Radionuclide	Radionuclide		Assign radionuclides to each package
	Inventory (Ci)		Inventory of radionuclides

Table 3. Package specification

No	Packaging (transport container)			Contents	
	Code	Purpose	Size (m, W × L × H)	Inner package	Waste type
1	T1	Transport	2.44 × 6.06 × 1.40	P1 × 2 EA	Incompressible dry active waste, Spent filter
2	T2	Transport	1.60 × 3.40 × 1.30	P2A × 2 EA	RVI
3	T2	Transport	1.60 × 3.40 × 1.30	P2B × 2 EA	RV, Metal ingot
4	T3	Transport	1.60 × 3.40 × 1.30	P3 × 1 EA	Insulation waste, Dry active waste, Metal
5	T3	Transport	1.60 × 3.40 × 1.30	P4B × 6 EA	Soil, Concrete
6	T4	Transport	2.44 × 6.06 × 1.30	P4A × 8 EA	Soil, Concrete, Dry active waste
7	PT1	Package/Transport/ Disposal	1.60 × 3.40 × 1.40	PT1	Insulation waste, Dry active waste, Metal

the highest population density among the transport links. In addition, the range of the exposed target was assumed to be the public within a radius of 800 m (default) [2].

2.1.5 Handling

The handling workers are likely to be heavily affected by radiation because they handle a container with radioactive materials at adjacent distances. In this study, it is assumed that 6 workers are involved in loading/unloading per vehicle for 1 hour at 1 m from the package.

2.1.6 Accident Condition

The fraction of radionuclides in the package that could be released in an accident, was assumed to be 0.1% as suggested in NUREG/CR-4370 [11]. For a conservative assessment, it was assumed that all the radionuclides released into the atmosphere due to an accident are aerosolized and the respirable fraction value is 1.0. The deposition velocity of all nuclides except gaseous nuclides (^{3}H, ^{14}C) was set to 0.01 $m \cdot s^{-1}$, the recommended value of code [12]. Weather conditions are classified from strong instability A grade to strong stability F grade according to the atmospheric stability grade. The Pasquill Category D section (ambient lapse rate is the same as the adiabatic lapse rate) with the fastest wind speed at 10 m ground was applied to the evaluation [13].

2.1.7 Radionuclide Inventory

Table 5 shows the radionuclide inventory date for each

Table 4. Transport route (on-road transport)

Link number	Link section	Administrative district	Length (km)	Pop.density (people·km^{-2})	Traffic (vehicles·hr^{-1})	Accidents per km	Population type
1	Kori NPP~ Jangan IC	Gijang-gun, Jangan-eup	7.1	175.44	14,184	1.36×10^{-7}	Suburban
2	Jangan IC~ Onyang IC	Gijang-gun, Jangan-eup	7.4	175.44	53,408	9.24×10^{-9}	Suburban
3	Jangan IC~ Onyang IC	Ulju-gun, Onyang-eup	3.7	451.2	53,408	1.39×10^{-8}	Suburban
4	Onyang IC~ Cheongnyang IC	Ulju-gun, Onyang-eup	5.9	451.2	44,403	-	Suburban
5	Onyang IC~ Cheongnyang IC	Ulju-gun, Cheongnyang-eup	2	321.98	44,403	6.17×10^{-8}	Suburban
6	Cheongnyang IC~ Munsu IC	Ulju-gun, Cheongnyang-eup	5.2	321.98	31,387	5.60×10^{-8}	Suburban
7	Munsu IC~Ulsan JCT	Ulju-gun, Cheongnyang-eup	2.1	321.98	30,951	-	Suburban
8	Munsu IC~Ulsan JCT	Nam-gu, Mugeo-dong	0.7	9,567.82	30,951	-	urban
9	Ulsan JCT~ Beomseo IC	Ulju-gun, Beomseo-eup	0.9	926.21	23,144	4.54×10^{-8}	Suburban
10	Ulsan JCT~ Beomseo IC	Jung-gu, Daun-dong	3.2	2,691.29	23,144	1.23×10^{-8}	urban
11	Ulsan JCT~ Beomseo IC	Ulju-gun, Beomseo-eup	3.8	926.21	23,144	-	Suburban
12	Beomseo IC~ South Gyeongju IC	Ulju-gun, Beomseo-eup	3.8	926.21	21,730	1.11×10^{-8}	Suburban
13	Beomseo IC~ South Gyeongju IC	Gyeongju-si, Oedong-eup	11.1	169.08	21,730	1.14×10^{-8}	Suburban
14	South Gyeongju IC~ East Gyeongju IC	Gyeongju-si, Oedong-eup	4.5	169.08	20,108	1.01×10^{-8}	Suburban
15	South Gyeongju IC~ East Gyeongju IC	Gyeongju-si, Munmudaewang-myeon	8.7	36.97	20,108	1.04×10^{-8}	Rural
16	East Gyeongju IC~ KORAD disposal facility	Gyeongju-si, Munmudaewang-myeon	7.1	36.97	798	3.22×10^{-7}	Rural

package used in the evaluation [14].

2.2 Sea Transport

Sea transport is a route from the Kori NPP lighter's wharf to the Wolsung NPP lighters wharf (hereinafter referred to as wharf) using an exclusive ship. On-road transports from the waste storage facility to the Kori wharf, and from the Wolsung wharf to the disposal facility were not evaluated as the transports are carried out within the boundaries of the exclusive area of Kori NPP, and the distance is short.

Table 5. Radionuclide inventory

Radionuclide	Transport container (inner package, contents)						
	PT1 (PT1)	T1 (P1)	T2 (P2A)	T2 (P2B)	T3 (P3)	T3 (P4B)	T4 (P4A)
^{3}H	-	4.55×10^{8}	1.50×10^{8}	2.33×10^{9}	-	7.82×10^{9}	1.56×10^{10}
^{14}C	-	6.88×10^{9}	6.11×10^{7}	8.57×10^{7}	-	2.85×10^{8}	5.71×10^{8}
^{55}Fe	6.86×10^{8}	9.50×10^{10}	2.76×10^{12}	3.01×10^{13}	8.08×10^{10}	-	-
^{59}Fe	6.07×10^{8}	-	-	-	7.15×10^{8}	-	-
^{58}Co	2.52×10^{10}	3.47×10^{9}	-	-	2.97×10^{10}	-	-
^{59}Ni	-	7.51×10^{8}	3.60×10^{10}	1.79×10^{10}	-	-	-
^{60}Co	2.67×10^{10}	1.34×10^{10}	1.83×10^{11}	7.86×10^{10}	3.14×10^{10}	1.13×10^{10}	2.26×10^{10}
^{63}Ni	2.36×10^{10}	4.61×10^{10}	3.56×10^{12}	1.77×10^{12}	2.78×10^{10}	3.60×10^{9}	7.19×10^{9}
^{90}Sr	-	6.91×10^{6}	2.14×10^{-3}	7.26×10^{-3}	-	5.71×10^{7}	1.14×10^{8}
^{94}Nb	-	2.33×10^{6}	1.42×10^{6}	2.26×10^{6}	-	-	-
^{99}Tc	-	3.17×10^{7}	5.76×10^{5}	9.33×10^{2}	-	-	-
^{129}I	-	5.82×10^{3}	2.41×10^{-10}	3.93×10^{-10}	-	-	-
^{134}Cs	-	-	-	-	-	1.72×10^{10}	3.45×10^{10}
^{137}Cs	7.49×10^{9}	6.49×10^{7}	1.97×10^{-3}	1.38×10^{-3}	8.82×10^{9}	1.54×10^{10}	3.08×10^{10}
^{144}Ce	-	1.52×10^{6}	-	-	-	-	-
^{93}Mo	-	-	-	6.55×10^{3}	-	-	-
^{152}Eu	-	-	-	-	-	2.61×10^{10}	5.23×10^{10}
^{154}Eu	-	-	4.75×10^{6}	5.24×10^{7}	-	2.91×10^{9}	5.82×10^{9}
^{156}Eu	-	-	-	-	-	2.63×10^{9}	5.25×10^{9}
^{54}Mn	9.77×10^{6}	-	-	1.94×10^{10}	1.15×10^{7}	-	-
Total	1.52×10^{11}	1.66×10^{11}	6.54×10^{12}	3.20×10^{13}	1.79×10^{11}	8.74×10^{10}	1.75×10^{11}

Table 6. Package loaded per shipment

Packaging	Inner package	No. Packages				
		A	B	C	D	E
T1	P1×2 EA	-	-	-	-	1
T2	P2A×2 EA	-	25	-	-	-
	P2B×2 EA	-	6	4	-	-
T3	P3×1 EA	5	-	3	5	4
	P4B×6 EA	4	-	2	3	3
T4	P4A×8 EA	2	-	2	2	-
PT1	PT1	21	-	20	21	21
Total		32	31	31	31	29

Table 7. Transport route (sea transport)

Link number	Link section	Administrative district	Length (km)	Pop.density (people·km^{-2})	Traffic (vehicles·hr^{-1})	Accidents per km	Population type
1	Kori NPP~1 km	Gijang-gun, Jangan-eup	1	175.44	0	2.55×10^{-3}	Suburban
2	Jangan IC~Onyang IC	Dong-gu, Jangan-eup	64.5	6,746.93	0	2.55×10^{-3}	Suburban
3	KORAD disposal facility~1 km	Gyeongju-si, Munmu-daewang-myeon	1	36.97	0	2.55×10^{-3}	Rural

2.2.1 Characteristics of the Transport Container and Package

In this study, the number of packages loaded per shipment was assumed as shown in Table 6 and five types (A to E) of transport risk assessments were performed.

2.2.2 Transport Route

As shown in Table 7, the sea transport distance from the Kori wharf to the Wolsung wharf is about 73.2 km and links were classified into three sections. The average speed of the shipment is about 22.2 km·h^{-1}, and the accident rate was referred to in the data presented in the 2020 Marine Accident Statistical Data published by the Ministry of Oceans and Fisheries [15]. The accident rate was calculated as 2.55×10^{-3} and applied equally regardless of the link section.

2.2.3 Transport Vehicle

The transport ship "Cheong Jeong Nuri" is used to transport radioactive waste in Korea, which is a 2,600-ton ship with a length of 78 m and a width of 15 m. The ship's passengers are a total of 20 persons that consist of 17 crew members, 1 transport manager, and 2 radiation safety managers.

The radiation dose in the work area is limited to 0.0075 mSv·h^{-1} according to the technical standards [16]. Therefore, the shielding factor of the transport ship was applied with a value (0.84) corresponding to reducing the surface dose of 2 mSv·h^{-1} of the package to 0.0075 mSv·h^{-1} at the work position.

2.2.4 Handling

In sea transport, the distance between the package and the worker was set to 10 m because a crane and a lifting device are used for loading and unloading works. It was also assumed that 10 workers and 10 hours of working time are required.

2.2.5 Accident Condition

If a marine accident caused by a collision with other ships or obstacles, severe weather, and ship failure occurs, the normal operation of the ship becomes impossible. In this evaluation, it was assumed that radioactive materials are released outside of the ship after the ship is stranded in the near port due to collision or inability to operate. Other accident-related input data is the same as on-road transport accident conditions.

3. Transport Scenario

Transport scenarios can be divided into a normal transport condition and an accident transport condition, depending on whether radioactive materials are released or not.

3.1 Normal Condition

Normal transport (incident-free) is defined as "transport during which no accident, packaging, or handling abnormality or malevolent attack occurs" and radioactive materials leakage does not occur during routine, incident-free

Table 8. Dose limit

Classification	Effective dose limit
Radiation worker	100 mSv for five years within the scope not exceeding 50 $mSv{\cdot}y^{-1}$
Persons engaging in transport	6 $mSv{\cdot}y^{-1}$
Public	1 $mSv{\cdot}y^{-1}$

transport and during accidents when there is no breach of containment. Therefore, in normal conditions, the contents of the radioactive materials package do not matter; only the external dose is important [10].

The evaluation considered only external exposure caused due to the radiation emitted by radioactive materials loaded inside the container. Evaluation targets were the public residing on the transport route, the persons in vehicles sharing the transport link, the transport workers (operators and safety managers), and the handling workers. The exposure range was set to a radius of 800 m from the transport vehicle.

3.2 Accident Condition

Accident transport condition is in which radioactive materials are leaked out of the container and spread around the accident locations. The evaluation targets were the public living within 10 km from the point of accident and the five exposure pathways (inhalation, ground shine, cloud shine, ingestion, and resuspension) were considered as sources of internal and external exposures to the public during an accident [17].

3.3 Assessment Criteria

The assessment criteria for results are the dose limits for the public, the radiation workers, and the persons engaging in transport. The dose limit means the upper limit of the amount of radiation exposed which is the sum of the external and internal doses, and each level is suggested in the enforcement decree of the nuclear safety act [18].

As shown in Table 8, the cumulative radiation level limits are 100 mSv for five years within the scope of not exceeding 50 $mSv{\cdot}y^{-1}$ for the radiation worker, 6 $mSv{\cdot}y^{-1}$ for the transport worker, and 1 $mSv{\cdot}y^{-1}$ for the public. For a conservative evaluation, the assessment criterion of the radiation worker is set as 20 $mSv{\cdot}y^{-1}$ which is the annual average for the five-year.

4. Results

4.1 On-Road Transport

4.1.1 Normal Condition

Tables 9 and 10 show the evaluation results for the collective exposure dose and the individual exposure dose for the on-road transport under normal conditions, respectively. According to the evaluation results, the collective exposure dose of the transport worker, the handling worker, and the public is 0.25 mSv to 0.35 mSv, 11.7 mSv to 14.7 mSv, and $4.12{\times}10^{-2}$ mSv to 3.67 mSv, respectively. Also, the individual exposure dose is 0.123 mSv to 0.178 mSv, 1.95 mSv to 2.45 mSv, and $5.07{\times}10^{-7}$ mSv to $1.91{\times}10^{-4}$ mSv, respectively. The results are between $1.69{\times}10^{-7}$% to $9.23{\times}10^{-5}$% of the national standard, and all the results satisfies the requirement that the exposure dose evaluated should be below the legal dose limit.

4.1.2 Accident Condition

Tables 11 and 12 show the evaluation results for the collective dose risk and the individual dose risk of the on-road transport under accident conditions, respectively. According to the evaluation results, the collective dose risk

Table 9. On-Road-Normal collective dose (mSv)

Classification		PT1	T1-P1	T2-P2A	T2-P2B	T3-P3	T3-P4B	T4-P4A
Transport worker		0.246	0.355	0.253	0.253	0.253	0.253	0.348
General public	Off road	0.041	0.042	0.042	0.042	0.042	0.065	7.91×10^{-7}
	On road	0.206	0.209	0.209	0.209	0.209	0.325	1.07×10^{-4}
	Stop	2.330	2.360	2.360	2.360	2.360	3.670	1.91×10^{-4}
Radiation worker		11.70	14.70	11.80	11.80	11.80	11.80	14.70

Table 10. On-Road-Normal individual dose (mSv)

Classification		PT1	T1-P1	T2-P2A	T2-P2B	T3-P3	T3-P4B	T4-P4A	Annual limit ($mSv\cdot y^{-1}$)
Transport worker		0.123	0.178	0.127	0.127	0.127	0.127	0.174	6
General public	Off road	5.02×10^{-7}	7.94×10^{-7}	5.10×10^{-7}	5.10×10^{-7}	5.10×10^{-7}	5.10×10^{-7}	7.91×10^{-7}	1
	On road	6.81×10^{-5}	1.08×10^{-4}	6.91×10^{-5}	6.91×10^{-5}	6.91×10^{-5}	6.91×10^{-5}	1.07×10^{-4}	1
	Stop	1.21×10^{-4}	1.91×10^{-4}	1.23×10^{-4}	1.23×10^{-4}	1.23×10^{-4}	1.23×10^{-4}	1.91×10^{-4}	1
Radiation worker		1.95	2.45	1.97	1.97	1.97	1.97	2.45	20
Assessment result		Satisfaction	Satisfaction	Satisfaction	Satisfaction	Satisfaction	Satisfaction	Satisfaction	-

Table 11. On-Road-Accident collective dose (mSv)

Link no.	PT1	T1-P1	T2-P2A	T2-P2B	T3-P3	T3-P4B	T4-P4A
Link 1	2.00×10^{-9}	8.94×10^{-10}	1.82×10^{-8}	4.53×10^{-8}	2.35×10^{-9}	6.27×10^{-9}	1.25×10^{-8}
Link 2	1.42×10^{-10}	6.33×10^{-11}	1.29×10^{-9}	3.21×10^{-9}	1.67×10^{-10}	4.44×10^{-10}	8.86×10^{-10}
Link 3	2.73×10^{-10}	1.22×10^{-10}	2.49×10^{-9}	6.19×10^{-9}	3.21×10^{-10}	8.56×10^{-10}	1.71×10^{-9}
Link 4	-	-	-	-	-	-	-
Link 5	4.69×10^{-10}	2.10×10^{-10}	4.27×10^{-9}	1.06×10^{-8}	5.52×10^{-10}	1.47×10^{-9}	2.93×10^{-9}
Link 6	1.10×10^{-9}	4.94×10^{-10}	1.01×10^{-8}	2.51×10^{-8}	1.30×10^{-9}	3.47×10^{-9}	6.92×10^{-9}
Link 7	-	-	-	-	-	-	-
Link 8	-	-	-	-	-	-	-
Link 9	4.31×10^{-10}	1.93×10^{-10}	3.93×10^{-9}	9.78×10^{-9}	5.08×10^{-10}	1.35×10^{-9}	2.70×10^{-9}
Link 10	8.08×10^{-10}	3.61×10^{-10}	7.37×10^{-9}	1.83×10^{-8}	9.52×10^{-10}	2.53×10^{-9}	5.06×10^{-9}
Link 11	-	-	-	-	-	-	-
Link 12	4.59×10^{-10}	2.05×10^{-10}	4.19×10^{-9}	1.04×10^{-8}	5.41×10^{-10}	1.44×10^{-9}	2.88×10^{-9}
Link 13	2.51×10^{-10}	1.12×10^{-10}	2.29×10^{-9}	5.71×10^{-9}	2.96×10^{-10}	7.89×10^{-10}	1.57×10^{-9}
Link 14	9.06×10^{-11}	4.05×10^{-11}	8.26×10^{-10}	2.05×10^{-9}	1.07×10^{-10}	2.84×10^{-10}	5.67×10^{-10}
Link 15	3.96×10^{-11}	1.77×10^{-11}	3.61×10^{-10}	8.99×10^{-10}	4.67×10^{-11}	1.24×10^{-10}	2.48×10^{-10}
Link 16	9.98×10^{-10}	4.46×10^{-10}	9.10×10^{-9}	2.27×10^{-8}	1.18×10^{-9}	3.13×10^{-9}	6.25×10^{-9}

Table 12. On-Road-Accident individual dose (mSv)

Link no.	PT1	T1-P1	T2-P2A	T2-P2B	T3-P3	T3-P4B	T4-P4A
Link 1	8.13×10^{-15}	3.63×10^{-15}	7.40×10^{-14}	1.84×10^{-13}	9.55×10^{-15}	2.55×10^{-14}	5.08×10^{-14}
Link 2	5.77×10^{-16}	2.57×10^{-16}	5.24×10^{-15}	1.30×10^{-14}	6.79×10^{-16}	1.80×10^{-15}	3.60×10^{-15}
Link 3	4.32×10^{-16}	1.93×10^{-16}	3.94×10^{-15}	9.79×10^{-15}	5.08×10^{-16}	1.35×10^{-15}	2.71×10^{-15}
Link 4	-	-	-	-	-	-	-
Link 5	1.04×10^{-15}	4.66×10^{-16}	9.47×10^{-15}	2.35×10^{-14}	1.22×10^{-15}	3.26×10^{-15}	6.50×10^{-15}
Link 6	2.44×10^{-15}	1.10×10^{-15}	2.24×10^{-14}	5.57×10^{-14}	2.88×10^{-15}	7.69×10^{-15}	1.53×10^{-14}
Link 7	-	-	-	-	-	-	-
Link 8	-	-	-	-	-	-	-
Link 9	3.32×10^{-16}	1.48×10^{-16}	3.02×10^{-15}	7.52×10^{-15}	3.91×10^{-16}	1.04×10^{-15}	2.08×10^{-15}
Link 10	2.14×10^{-16}	9.58×10^{-17}	1.95×10^{-15}	4.85×10^{-15}	2.53×10^{-16}	6.71×10^{-16}	1.34×10^{-15}
Link 11	-	-	-	-	-	-	-
Link 12	3.53×10^{-16}	1.58×10^{-16}	3.22×10^{-15}	8.00×10^{-15}	4.16×10^{-16}	1.11×10^{-15}	2.22×10^{-15}
Link 13	1.06×10^{-15}	4.73×10^{-16}	9.66×10^{-15}	2.41×10^{-14}	1.25×10^{-15}	3.33×10^{-15}	6.62×10^{-15}
Link 14	3.82×10^{-16}	1.71×10^{-16}	3.49×10^{-15}	8.65×10^{-15}	4.51×10^{-16}	1.20×10^{-15}	2.39×10^{-15}
Link 15	7.64×10^{-16}	3.42×10^{-16}	6.97×10^{-15}	1.74×10^{-14}	9.02×10^{-16}	2.39×10^{-15}	4.79×10^{-15}
Link 16	1.93×10^{-14}	8.61×10^{-15}	1.76×10^{-13}	4.38×10^{-13}	2.28×10^{-14}	6.04×10^{-14}	1.21×10^{-13}
Assessment result	Satisfaction	Satisfaction	Satisfaction	Satisfaction	Satisfaction	Satisfaction	Satisfaction

was evaluated as 1.77×10^{-11} mSv to 4.53×10^{-8} mSv, and the individual dose risk was evaluated as 9.58×10^{-17} mSv to 4.38×10^{-13} mSv. Among the transport links, the highest risk appeared in section 16, because the accident rate is higher than in other sections. The results, which all met the does limit, are evaluated to be between 9.58×10^{-15}% to 4.38×10^{-11}% of the national standard.

4.2 Sea Transport

4.2.1 Normal Condition

Tables 13 and 14 show the evaluation results for the collective exposure dose and the individual exposure dose on the sea transport under normal conditions, respectively. According to the evaluation results, the collective exposure doses for the transport worker, the handling worker, and the public are 5.94×10^{-3} mSv, 5.86 mSv to 20.3 mSv, and 5.81×10^{-3} mSv, respectively. Also, the individual exposure doses are 2.97×10^{-3} mSv, 0.586 mSv to 2.03 mSv, and 9.75×10^{-6} mSv, respectively. All the evaluation results satisfied the legal dose limit.

The reasons why the dose values of the transport worker and the public were equal in all shipments (A to E) are as follows:

- The external radiation dose is calculated from the transport packages which are the radiation source for normal conditions.
- The stowage of the ship loaded large numbers of transport containers was assumed to be a single transport package.
- Regardless of the number of transport containers (A−E), the evaluation was inputted with the same package information, so the same evaluation result was derived.

Table 13. Sea-Normal collective dose (mSv)

Classification		A shipment	B shipment	C shipment	D shipment	E shipment	Annual limit ($mSv·y^{-1}$)
Transport worker		$5.94×10^{-3}$	$5.94×10^{-3}$	$5.94×10^{-3}$	$5.94×10^{-3}$	$5.94×10^{-3}$	6
General public	Off road	$5.81×10^{-3}$	$5.81×10^{-3}$	$5.81×10^{-3}$	$5.81×10^{-3}$	$5.81×10^{-3}$	1
Radiation worker		7.00	20.3	7.03	6.81	5.86	20
Assessment result		Satisfaction	Satisfaction	Satisfaction	Satisfaction	Satisfaction	-

Table 14. Sea-Normal individual dose (mSv)

Classification		A shipment	B shipment	C shipment	D shipment	E shipment	Annual limit ($mSv·y^{-1}$)
Transport worker		$2.97×10^{-3}$	$2.97×10^{-3}$	$2.97×10^{-3}$	$2.97×10^{-3}$	$2.97×10^{-3}$	6
General public	Off road	$9.75×10^{-6}$	$9.75×10^{-6}$	$9.75×10^{-6}$	$9.75×10^{-6}$	$9.75×10^{-6}$	1
Radiation worker		0.70	2.03	0.70	0.68	0.58	20
Assessment result		Satisfaction	Satisfaction	Satisfaction	Satisfaction	Satisfaction	-

Table 15. Sea-Accident collective dose (mSv)

Link no.	A shipment	B shipment	C shipment	D shipment	E shipment
Link 1	$2.74×10^{-4}$	$1.92×10^{-3}$	$7.03×10^{-4}$	$2.58×10^{-4}$	$1.88×10^{-4}$
Link 2	0.681	4.77	1.74	0.640	0.466
Link 3	$5.78×10^{-5}$	$4.05×10^{-4}$	$1.48×10^{-4}$	$5.43×10^{-5}$	$3.96×10^{-5}$

Table 16. Sea-Accident collective dose (mSv)

Link no.	A shipment	B shipment	C shipment	D shipment	E shipment
Link 1	$1.11×10^{-9}$	$7.80×10^{-9}$	$2.86×10^{-9}$	$1.05×10^{-9}$	$7.64×10^{-10}$
Link 2	$7.21×10^{-8}$	$5.05×10^{-7}$	$1.84×10^{-7}$	$6.77×10^{-8}$	$4.93×10^{-8}$
Link 3	$1.12×10^{-9}$	$7.82×10^{-9}$	$2.86×10^{-9}$	$1.05×10^{-9}$	$7.64×10^{-10}$

In addition, the exposure doses about the on-link and the stop were not evaluated because it was assumed there are no other ships moving adjacent to the transport route, and the transport ship does not stop during sea transport.

4.2.2 Accident Condition

Tables 15 and 16 show the evaluation results for the collective dose risk and the individual dose risk of the sea transport under accident conditions, respectively. According to the evaluation results, the collective dose risk was evaluated as $3.96×10^{-5}$ mSv to 4.77 mSv and the individual dose risk was evaluated as $7.64×10^{-10}$ mSv to $5.05×10^{-7}$ mSv. The results are between $7.64×10^{-8}$% to $5.05×10^{-5}$% of the national standard, thus satisfying the dose limit.

5. Sensitivity Analysis

Sensitivity analysis was performed to confirm the amount of change in exposure dose according to the increasing ratio of radioactive materials released out of the packages from 0.1% to 100% under accident conditions.

The analysis for the on-road transport was performed in section 16 where the highest exposure dose was evaluated among the transport links. The analysis results are shown in Fig. 1 and the highest individual dose risk among the results is 4.38×10^{-10} mSv, which is the case when releasing 100% of the contents from the T2-P2B package.

In the case of sea transport, sensitivity analysis was performed for section 2, and the results are shown in Fig. 2. As a result of the evaluation, the individual dose risk was the highest at 5.05×10^{-4} mSv, which is the case when releasing 100% of the contents from the package of shipment of B.

Through the sensitivity analysis, it was confirmed that the dose risk increased proportionally with the amount of release of radioactive materials, and even though the contents were released 100%, the evaluation result was still significantly lower than the legal limit.

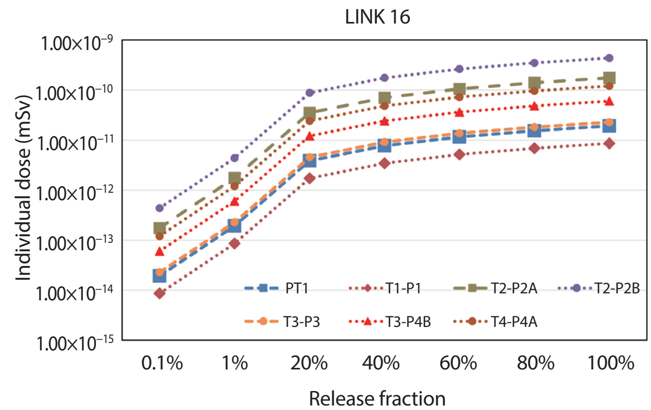

Fig. 1. Sensitivity analysis results-On-Road-Transport in Link 16 (mSv).

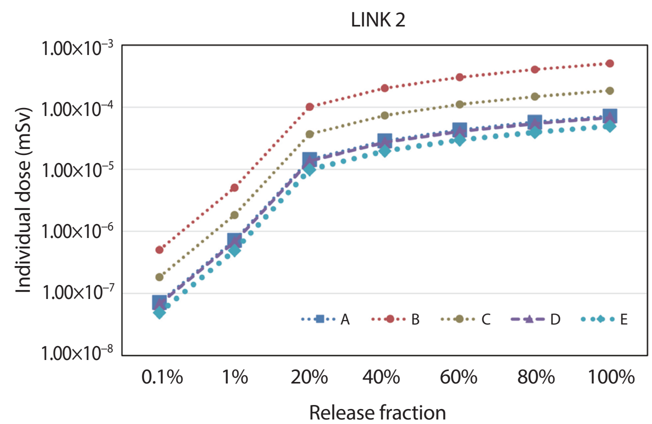

Fig. 2. Sensitivity analysis results-Sea-Transport in Link 2 (mSv).

6. Conclusion

In this study, the risk assessment of the transport of the decommissioning wastes of Kori Unit 1 to disposal facilities was evaluated. The transport scenarios were divided into a normal condition and an accident condition, and the transport route was divided into on-road transport and sea transport. Also, the evaluation result expressed as dose and risk value on the public and the workers was compared with the domestic regulatory limit to confirm the safety of the transport.

As a result of the on-road transport, the exposure dose of the transport workers, the public, and the handling workers in the normal transport condition was evaluated as 2.97%, 7.94×10^{-5}%, and 12.25% of the legal dose limit, respectively. Also, the dose risk of the public in the accident transport condition was evaluated as 4.38×10^{-11}% of the legal dose limit.

As a result of the sea transport, the exposure dose of the transport workers, the public, and the handling workers in the normal transport condition was evaluated as 4.95×10^{-2}%, 9.75×10^{-4}%, and 10.15% of the legal dose limit, respectively, and the dose risk of the public in the accident transport condition was evaluated as 5.05×10^{-5}% of the legal limit.

Additionally, sensitivity analysis was performed to confirm the amount of change in exposure dose according to the increasing ratio of radioactive materials released out from the packages from 0.1% to 100% under accident conditions. As a result of the evaluation, when radioactive materials were released 100% during the on-road transport and the sea transport, the exposure dose was evaluated at 4.38×10^{-8}% and 5.05×10^{-2}% of the dose limit, respectively.

In summary, all the evaluation results satisfied the requirement, which states that the dose of the public and the workers received during the transport of radioactive materials should not exceed the legal dose limit. However, unlike the other results, the exposure dose of the handling workers was evaluated to be relatively high, and it may exceed the dose limit depending on the working distance and the time. Therefore, it is necessary to prepare appropriate handling systems and a working environment, which can lower the exposure dose of the workers.

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