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Preliminary Assessment of Radiation Effects for Transport of Spent Nuclear Fuel to Interim Storage Facility

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Abstract Spent fuel is stored in the on-site storage of the nuclear power plant, but there is currently no disposal site for high-level waste, and the on-site storage facility of Hanbit NPPs is expected to be saturated in 2031. The construction of an interim storage facility is planned because it is difficult to expand the storage facility. However, since road transportation is impossible under the Road Traffic Act, a preliminary assessment of the radiological effects was conducted for sea transportation that can transfer a large amount of spent fuel. Since SF was not transported by sea in Korea, overseas cases were investigated, and the exposure doses of transport crews and the general public during normal transport were compared with the legal standard for KORAD-21 containers that had undergone land transport safety evaluation using RADTRAN. In addition, the individual dose according to the route of the general public at the time of an accident was compared. It was confirmed that the expected exposure dose under the conditions set in this study was below the legal limit.

Key words: Spent fuel (SF), KORAD-21, RADTRAN, Transportation

1. INTRODUCTION

SF (Spent Fuel) has been continuously generated for 43 years since commercial nuclear power generation began in 1978. SF is stored in wet storage in each NPP (Nuclear Power Plant). The saturation rates of the spent fuel storage at the Kori NPP, Hanbit NPP, and Hanul NPP are 83.3%, 74.2%, and 80.8% as of the fourth quarter of 2021 shown in Table 1.

Wet storage is a technology which has been used for a long time since the 1950s and has proven safety. Since it is cooled with water, the cooling efficiency is very high, so the SF taken from the NPP can be stored immediately. However, there is a disadvantage in that the operation and management of the facility is relatively complicated, resulting in high cost.

The Kori and Hanbit NPPs are expected to be saturated in 2031, and the Hanul NPP is expected to be saturated in 2032. In order to add and expand the limited capacity of the wet storage, the estimated year of storage tank saturation is delayed through the installation of dense storage racks and transfer between units. However, it only delays the expected saturation period but does not solve the fundamental problem. Therefore, it is urgent to construct an interim storage facility or final disposal facility to store the SF stored inside the NPP. Accordingly, the Korea government decided to operate ISFSI (Independent Spent Fuel Storage Facility) on the site of the NPP, and is planning to construct an interim storage facility and a permanent disposal facility after selecting the site. It is expected 20 years for the construction of an interim storage facility, 37 years for the construction of a permanent disposal facility, and 37 years for the construction of an interim storage facility [2]. In principle, the SF from the interim storage facility such as independent SF storage installation

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Table 1. SF amount of Kori, Hanbit and Hanul NPP [1]

Reactor	Headquarters	Unit	Storage (Assembly)	Storage capacity (Assembly)	Saturation rate (%)
PWR	Kori	1	485	485	100.00
		2	712	712	100.00
		3	2013	2103	95.72
		4	2042	2105	97.01
	Hanbit	1	1769	2105	84.04
		2	1489	2100	70.90
		3	908	1125	72.07
		4	824	1125	66.58
		5	850	1281	61.10
		6	851	1281	55.61
	Hanul	1	862	957	50.12
		2	881	905	44.63
		3	1202	1321	39.14
		4	1195	1321	33.66
		5	1103	1281	28.17
		6	1099	1281	22.68

(ISFSI) on the site should be taken out without delay after the construction of the interim storage facility.

2. SF TRANSPORT STATUS AT DOMESTIC AND OVERSEAS

2.1. SF Transportation of Domestic

SF is stored in wet storage in each NPP, and domestic transport has been carried out only nearby units in the same headquarter. The history of SF transport between units for the last three years is shown in Table 2. Most of the transport was done to create free space in the wet storage. In the beginning, it was transported using KSC-4 (4 assemblies) casks, but recently, KN-12 (12 assemblies) casks are used for inter-unit transport.

2.2. SF Transportation of Overseas

2.2.1. US

In the case of the United States, 93 NPPs are in operation in 55 regions, accounting for about 19% of electricity generation in the United States. After the TMI (Three Mile Island accident) occurred in 1979, the proportion of nuclear power generation decreased. However, it is recovering through the flow of SMR (Small Module Reactor) and carbon neutrality, etc. Nowadays, there is no final disposal site for storage of SF in the US. SF is stored in a storage container and collected in ISFSI.

SF shipments approved by the NRC (United States Nuclear Regulatory Commission) are reported to be 1524 times. Transportation of SF is mainly carried out by land transportation. 84% of SF transportation is used by highway and 16% is by rail [3]. Shipping using expressways in the United States peaked at 254 cases in 1984, and then showed a decreasing trend until 1990 [3].

2.2.2. Japan

An NPP supplies about 30% of the electricity produced in Japan. Japan has a history of transporting SF generated in its own country to reprocessing facilities in the UK and France more than 160 times from 1969 to the 1990s. The amount of SF transported by vessels is shown in Table 3 and 4. A total SF of 10 Japanese power companies was transported by signing SF reprocessing contracts with Areva NC (Nuclear Cycle) of France and BNFL (British Nuclear Fuels Limited) of the UK [4]. 4200 tons of SF were transported to the UK, and 2940 tons of SF were transported to France. Of the 12 shipments of vitrified High-Level Waste (HLW), the first was from France to Japan in 1995, the last

Table 2. History of the SF transport in domestic

Year	Quarter	Transport route	Assemblies	Changed storage (assemblies)	
				Before	After
2019	1	Kori #2 → Shinkori #2	36	724 → 688	590 → 626
	1	Hanul #2 → Hanul #5	24	884 → 860	893 → 917
	2	Kori #2 → Shinkori #2	36	688 → 652	626 → 662
	2	Hanul #1 → Hanul #6	60	929 → 869	751 → 811
	2	Hanul #2 → Hanul #5	48	860 → 812	917 → 965
	3	Hanul #4 → Hanul #6	36	1090 → 1054	811 → 847
2020	1	Hanbit #4 → Hanbit #2	18	914 → 896	1335 → 1353
	2	Kori #4 → Shinkori #2	96	2062 → 1966	564 → 660
	2	Hanbit #4 → Hanbit #2	72	896 → 824	1353 → 1425
	2	Hanul #3 → Hanul #6	54	1187 → 1133	847 → 901
	3	Kori #4 → Shinkori #1	84	1966 → 1882	660 → 744
2021	1	Kori #3 → Saeul #2	84	2045 → 1961	1882 → 1966
	1	Hanul #2 → Hanul #6	60	844 → 817	967 → 1027
	2	Kori #3 → Kori #4	12	1961 → 1949	1966 → 1978
	4	Hanul #1 → Hanul #6	72	934 → 862	1027 → 1099

Table 3. Number of HLW canisters from France [4]

Year of shipment	Number of HLW canisters from France
1995	28
1997	40
1998	60
1999	40 + 104
2000	192
2001	152
2003	144
2004	132
2005	124
2006	164
2007	130
Total (12 Shipments)	1310

Table 4. Number of HLW canisters from the UK [4]

Year of shipment	Number of HLW canisters from the UK
2010	28
2011	76
2013	28
2014	132
2015	124
2016	132
Total (6 shipments)	520

in 2007.

2.2.3. Sweden

All SF and radioactive wastes generated in Sweden are transported by SKB (Swedish Nuclear Fuel and Waste Management Company). In addition to the LILW (Low and Intermediate - Level Waste) repository and the SF site, CLAB (Central Interim Storage Facility for Spent Fuel) is being operated. After cooling for a certain period, SF withdrawn from each NPP is transported to CLAB and stored for 30 to 40 years. Subsequently, when the final disposal facility is built around 2025, the SF stored in the CLAB will be subtracted and transported to the final disposal facility [5]. Since most of Sweden's NPPs are located on the coast, they are carried out by sea transport using ships, except for loading, unloading, and in-situ transport to the CLAB wharf. This characteristic is similar to Korea.

2.2.4. France

There are currently 53 NPPs in operation in France, producing 63 GW per year, with one under construction.

Table 5. Class of INF ship [6]

Ship class	Standard
INF-1	Vessels certified for the carriage of substances with a total radioactivity of 4,000 TBq or less.
INF-2	Ships which are certified to carry irradiated nuclear fuel or high-level radioactive wastes with an aggregate activity less than 2×10^6 TBq and ships which are certified to carry plutonium with an aggregate activity less than 2×10^5 TBq.
INF-3	Vessels certified for transport of radioactive fuel or high-level radioactive waste and vessels certified for transport of plutonium without limitation on the total radioactivity of the material.

Table 6. Specification of SF transport ship

Country	Name	Built (year)	INF	Length (m)	No. cask	Ship. capacity (t)	Purpose
U.K.	Pacific Heron	2008	3	103.9	20	4850	SF/HLW/MOX
U.K.	Pacific Egret	2010	3	103.9	20	4408	SF/HLW/MOX
U.K.	Pacific Grebe	2010	3	103.9	20	4916	SF/HLW/MOX
Sweden	M/S Sigrid	2013	3	99.5	12	1600	SF/ILW
Japan	Roduei maru	1987	3	100	20	3000	SF
Japan	Kaiei maru	1985	3	SF 100	12	3000	SF

About 1,150 MTU of SF has generated annually. France is implementing a circular fuel cycle policy, and the 'La Hague' reprocessing facility converts plutonium and uranium into MOX (mixed oxide fuel) and UOX (uranium oxide fuel). The La Hague reprocessing facility reprocesses SF from several countries in the Europe and Japan as well as in France. SF originating in Germany and Sweden is transported to Vallognes by rail, and SF generated in Belgium and the Netherlands is transported by truck. The SF was produced in Japan and transported by sea through the Japan-Europe ocean crossing.

3. STATUS AND REGULATIONS RELATED TO DOMESTIC AND FOREIGN SF TRANSPORT SYSTEMS

3.1. Transport Ship and Cask

3.1.1. Transport Ship

Since Korean NPPs are located nearby the coast and the load limit on general roads is 25 tons according to the Road Traffic Act, sea transport of SF is judged to have advantage. Currently, there are no ships for transporting SF in Korea, but only there is a ship for radioactive waste called the Chungjung Nuri for a LILW. The total weight of the Chungjung Nuri is 2,600 tons, and it has dimensions of 78.6 m in length, 15.8 m in width, and 7.3 m in depth. However, because it is not suitable for transporting a large amount of SF, the radiological assessment was conducted with reference to overseas SF transport vessels.

A vessel of INF-2 or INF-3 class is required for sea transport. As shown in Table 5, in the case of an INF-2 ship, plutonium with a total radioactivity of 2×10^5 TBq or less can be transported. In the case of an INF-3 ship, many containers can be transported at one time as there is no radiation restriction, but the price is higher than that of an INF-2 ship.

Representative INF-3 vessels include Pacific Heron, Pacific Grebe, and Pacific Egret of PNTL in the UK and Roduei maru, Kaiei maru, and M/S Sigrid in Sweden in Japan. The number, weight, and use of each ship's loadable casks are summarized in Table 6.

Radiological assessment was conducted based on the specifications of the Pacific Grebe vessel, which is a vessel capable of loading the largest number of casks in the Table 6. The specific specifications of Pacific Grebe are presented in Table 7 and the shape of Pacific Grebe is shown in Fig. 1.

3.1.2. Transport Cask

SF casks can be divided into transport casks, storage casks, and dual-purpose casks for both transport and stor-

age. Transport and storage are carried out by inserting a canister loaded with SF inside the SF cask. The canister is cooled by using natural convection in the space inside the cask and is closed by sealing or welding. Metal casks are mainly used for transportation, and for storage and dual-purpose casks, there are metal cask and concrete cask (silo, horizontal or vertical method). The dual or multiple-purpose cask reduces exposure by reducing the frequency of SF handling when transported to storage or disposal facilities.

Various casks are used to transport SF in various countries. In Korea, as the demand for a storage facilities increased from the 1990s, a metal cask that can be used for both transport and storage was developed. Moreover, it provided a technical basis for the development of concrete casks using canisters. Tables 8 and 9 summarized the internationally commercialized casks.

Table 7. Specification of Pacific Grebe [7]

Item	Value
Length overall	103.92 m
Breadth	17.25 m
Draft	6.75 m
Number of holds	4
Capacity	20 casks
Designed speed	14 knots
Deadweight (max)	4916 ton
Principle cargo carried	High-level wastes / compacted waste

Also, casks developed or used in Korea are shown in Table 10. The KSC-4 can be transported with 4 SF assemblies loaded, and the KN-12 can be transported with 12 SF assemblies loaded. These casks have a history of being used for inter-unit transport operations in the NPP. Containers such as DSS-21, DSS-24, and DPC-24 have not yet been commercialized in Korea and are casks for both transport and storage. In the case of KORAD-21, it was developed by KORAD (Korea Radioactive Waste Agency). KAERI (Korea Atomic Energy Research Institute) conducted a safety assessment for land transport in 2020. Therefore, in this study, the radiological assessment was evaluated using the specifications of KORAD-21.

3.2. Transport Route and Maritime Transport Accident Probability Analysis

3.2.1. SF Transport Route

For the transport route, only sea transport was considered, excluding land transport. The starting point was designated as a Hanbit NPP and the arrival point was selected as an arbitrary point near the East Sea. The sea distance and transport time were measured using the sea distance program provided by the National Oceanic and Atmospheric Administration website. For the transport route, the maritime transport route for LILW and the oil tanker navigation route were considered. In the Fig. 2, green line is the prohibited area for oil tankers, thus the transport route was set based on the red line. The moving distance and time were obtained

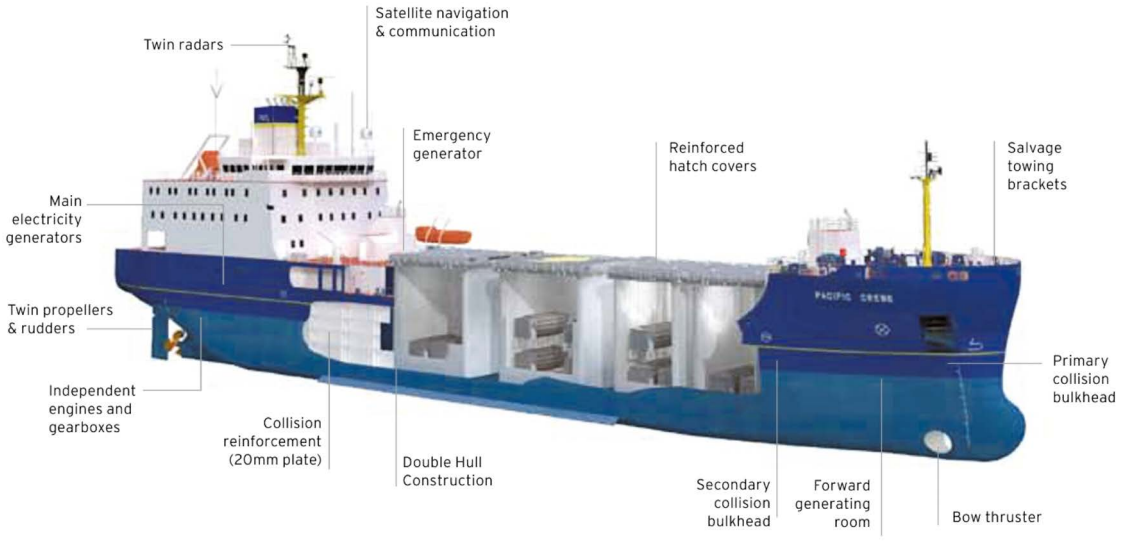


Fig. 1. INF 3 Vessel of Pacific Grebe [7].

Table 8. Commercially available SF casks for transport (LWR) [8]

Reactor type	Casks		Technical requirements		
	Owner	Model	Capacity (assemblies)	Thermal load (kW)	Total Wt. (Mt)
LWR	BNG	NTL-3M	7P	30	54
		NTL-3MA	10B	10	53
		NTL-9	7B	25	36
		NTL-11	7P	20	78
		NTL-14	5P	45	85
		NTL-15	10B	9	25
		EXCELLOX-6	6P	20	95
	GA	GA-4	4P	2.47	27.5
		GA-9	9B	2.12	27
	GE	IF-3000	7P/16B	68-70	60.7
	GNS	CASTOR-S1	6P/17B	30	79~82
	H-Z	NH-25	1P/2B	7	29
	Lehrer	LK-80	12P	100	100
		LK-100	12P/24P	30	72
	MHI	MSF-1	1P	6.7	45
	NAC	NAC-LWT	1P/2B	11.5	25.6
		NLI-1/2	1P/2B	10.6	23.1
		NLI-10/24	10P/24B	70	97
	NFT	NFT-10P	10P	25	83
		NFT-14P	14P	54	115
		NFT-12B	12B	15	23
		NFT-22B	22B	25	97
		NFT-32B	32B	22	106
		NFT-38B	38B	26	119
	OCL	HZ-75T	7P/17B	40	82
	PNTL	EXCELLOX-3			
		EXCELLOX-3A	5P/14B	30	72
		EXCELLOX-3B	14B	24	74
		EXCELLOX-4	7P	40	92
		EXCELLOX-7	17B	20	89
		EXL-4MOX	8M	8	92
	ACL (formal TN)	TN-8	3P	35.5	38
		TN-9	7B	24.5	39
		TN-10			
		TN-12	12P/32P	51.6/64	100/105
		TN-12/2(A/B)	12P	93/70	102/104
		TN-13	12P/32P	64	105/115
		TN-17	7P/17B	25(35)	78
		TN-17/2	7P	43	81

Table 9. Commercially available casks for transport (VVER, CANDU) [8]

Reactor type	Casks		Technical requirements		
	Owner	Model	Capacity (assemblies)	Thermal load (kW)	Total Wt. (Mt)
WWER (VVER)	GNS	CASTOR-84			
	BIZ	C-30	30/48 W440	9.21	120
	Izhora	TK-6	30 W440	15	92
		TK-10B	6 W1000	13	94.4
		TK-13	12 W1000	20	116
		TK-8	9 RBMK	NA	NA
		TK-11	51/102	12	105
		TK-104	57/114	5	120
		TK-109	72/114	6.3	126
		TK-11BN	35 BN600	10.7	90
CANDU	AECL	NOD-F1	2C	NA	12
	OPG	IFTC	192C	1.5	39
		DSCTP	364C	3	100
	DAE	DAE India	220C	70	63

Table 10. SF transport and Storage casks in Korea

Model	Company	Capacity (Bundle)	Weight (ton)	Purpose
KSC-1	KAERI	1 PWR	28	Transport
KSC-4	KAERI	4 PWR	37	Transport
KN-12	KHNP	12 PWR	75	Transport
KN-18	KHNP	14 PWR	104.4	Transport
KORAD-21	KORAD	21 PWR/WH	120.5	Transport & Storage
HI-STAR	KHNP	63 PHWR	21.5	Transport
DSS-21	Doosan	21 PWR/WH	120	Transport & Storage
DSS-24	Doosan	24 PWR/WH	120	Transport & Storage
DSS-32	Doosan	32 WH	130	Transport & Storage
DPC-24	Doosan	24 PWR/WH	114	Transport & Storage

using the sea distance program. The speed of the ship was set 13 knots (24 km h^{-1}), which is smaller than the 14 knots of the maximum moving speed of Pacific Grebe. Carrying distance was set to 757.8 km. As a result, the time required for transportation was found to be 31 hours and 29 minutes.

3.2.2. Transport Accident Probability Analysis

There are no exclusive SF vessels in Korea yet. Only Chung-Jung nuri, a LILW vessel, is in operation. There have been no accidents that occurred while transporting radioactive waste in domestic sea. Therefore, the accident status of general ships which occurred in the domestic sea was analyzed and used as a transport safety assessment in this study. For general maritime accident data of various ships, data from 2017 to 2021 is compiled by applying statistical data from the national statistical portal [11]. Marine accident types are summarized in the subsection. Using the general ship data, the probability of total loss by a collision, overturning, or sinking accident was calculated.

In order to damage the SF cask as a result of an accident

during transport, a strong impact must be applied from the outside, not when the ship is stopped like an engine failure. Consequently, the probability of total loss in case of collision, overturning, and sinking of the SF vessel was calculated using the equation 1, assuming that collision, overturning and sinking accidents occurred in the number of cases when each accident occurred.

$$X = A/B \times C \times D \times (E + F + G) \quad (1)$$

X = Probability of total loss by collision, overturn, and sinking
A = Number of maritime accidents
B = Number of registered vessels
C = Accdients rate on the shipping route
D = Probability of ship accident corresponding to weight of shipment
E = Probability of being overall destroyed by a collision
F = Probability of being overall destroyed by overturn
G = Probability of being overall destroyed by sinking

Table 11. Specification of KORAD-21 [9]

Name	KORAD-21
Capacity	21 PWR fuel assembly (WH & CE)
Burn up	45,000 MWD/MTU
Enrichment	4.5 wt % ^{235}U
Cooling time (yr)	10 yr
Decay heat	16.8 kW/canister
Dimension (canister)	1686 mm O.D × 4880 mm L
Dimension (cask)	2216 mm O.D × 5285 mm L
Weight (cansiter)	33.0 ton
Weight (cansk)	104.7 ton
Material (cask)	forged carbon steel
Material (canister)	stainless steel, BORAL (B4C + AL) or Metamic

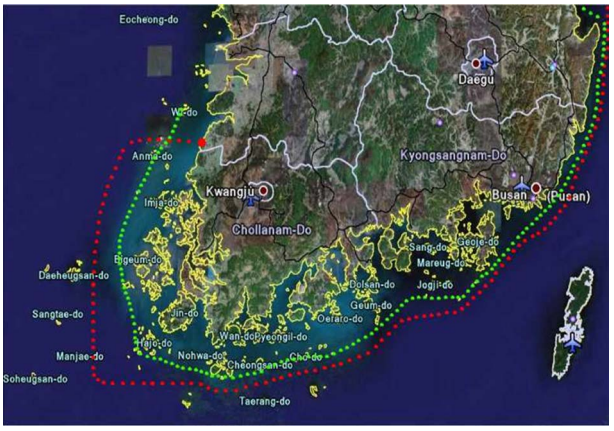
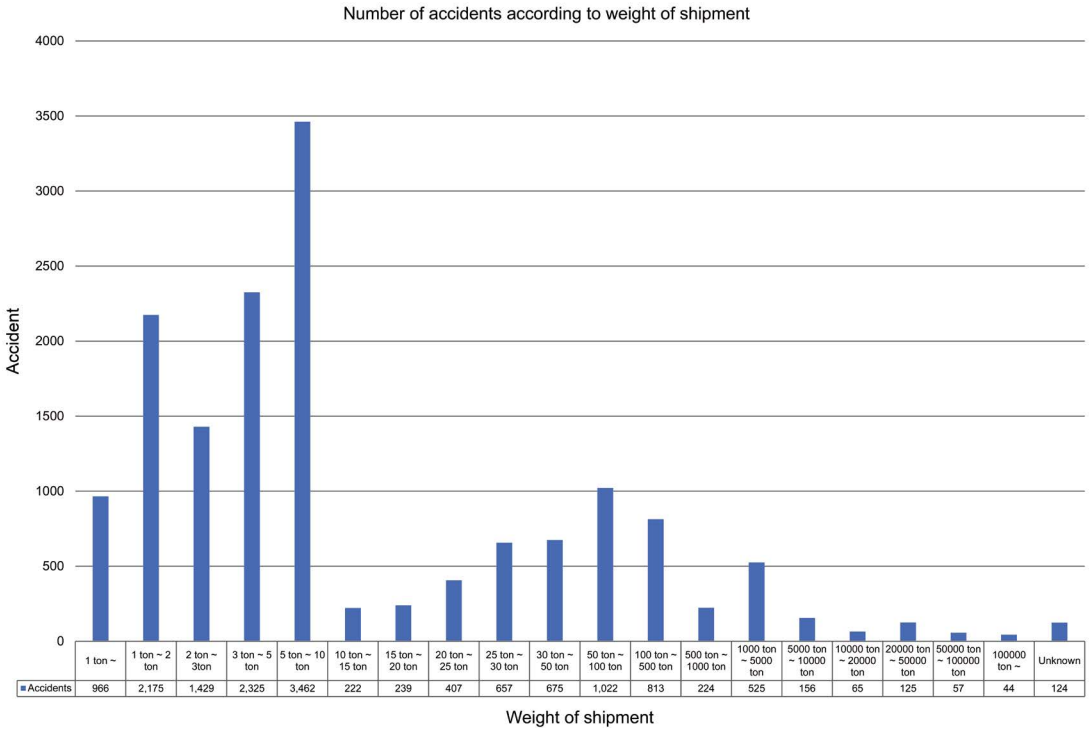


Fig. 2. Sea transport route setting[10].

Table 12. Accidents rate for number of registered vessels (A) and maritime accidents (B)

	Year	Fishing boat	Non-fishing boat						Total
			Ferry	Cargo ship	Oil tanker	Tugboat	Water leisure	Others	Subtotal	
Number of maritime accidents (A)	2017	66736	326	691	757	1243	19494	6062	28573	95309
	2018	65906	330	672	760	1213	21403	6010	30388	96294
	2019	65835	328	654	753	1194	22923	5936	31788	97623
	2020	65744	328	657	784	1196	31503	5915	40383	106127
	2021	–	326	657	766	1162	–	5653	–	–
Number of registered vessels (B)	2017	1939	46	127	73	91	472	134	943	2882
	2018	2013	44	112	89	111	469	130	955	2968
	2019	2134	53	111	93	94	586	203	1140	3274
	2020	2331	47	139	83	112	647	176	1204	3535
	2021	1971	36	110	85	119	597	135	1082	3053
Accident rate (A/B)	2017	2.91%	14.11%	18.38%	9.64%	7.32%	2.42%	2.21%	3.30%	3.02%
	2018	3.05%	13.33%	16.67%	11.71%	9.15%	2.19%	2.16%	3.14%	3.08%
	2019	3.24%	16.16%	16.97%	12.35%	7.87%	2.56%	3.42%	3.59%	3.24%
	2020	3.55%	14.30%	21.16%	10.59%	9.36%	2.05%	2.98%	2.98%	3.33%
	2021	–	11.04%	16.74%	11.10%	10.24%	–	2.39%	–	–



	1 ton ~	1 ton ~ 2 ton	2 ton ~ 3ton	3 ton ~ 5 ton	5 ton ~ 10 ton	10 ton ~ 15 ton	15 ton ~ 20 ton	20 ton ~ 25 ton	25 ton ~ 30 ton	30 ton ~ 50 ton	50 ton ~ 100 ton	100 ton ~ 500 ton	500 ton ~ 1000 ton	1000 ton ~ 5000 ton	5000 ton ~ 10000 ton	10000 ton ~ 20000 ton	20000 ton ~ 50000 ton	50000 ton ~ 100000 ton	100000 ton ~	Unknown
Accidents	966	2,175	1,429	2,325	3,462	222	239	407	657	675	1,022	813	224	525	156	65	125	57	44	124

Fig. 3. Number of accidents according to the weight of shipment.

3.2.2.1. Marine Accidents Compared to the Number of Registered Ships

Table 12 shows the number of accidents and their ratios compared to the number of registered ships among marine accidents occurring in domestic seas.

From 2017 to 2020, the incidence rate shows an increasing trend from 3.02% to 3.33%.

3.2.2.2. Probability of Accidents along Transport Routes

The NPP to be transported by SF is the Hanbit NPP, which is located in Yeongwang on the west coast. Since the interim storage was set to an arbitrary point on the East Sea, the probability of the main trading port along the route was calculated. Major ports are Mokpo, Yeosu, Gunsan, Samcheonpo, Masan, Okpo, Busan, and Ulsan ports. The accident rate from Mokpo Port to Ulsan Port is 6.79% of the total maritime accident rate by trade port.

3.2.2.3. Current Status of Marine Accidents by Total Tonnage by Ship Use

The weight of the SF vessel (Pacific Grebe) is about 9,800 tons when the SF is loaded to the maximum. Therefore, the accident rate of ships with a weight of 5,000 ton to 10,000 ton is the subject as shown in Fig. 3. The accident rate is 0.99% of all accidents.

3.2.2.4. Status of Marine Accidents by Accident Type and Damage

When looking at the status of marine accidents by accident type, most of the marine accidents are light loss among total loss, medium loss, light loss, and no damage. Most of these accidents are caused by collisions and engine damage, as shown in Table 13. Large accidents such as overturning, fire, explosion and sinking cause total damage to the vessel, but minor accidents such as a contact show that the damage level and a number of occurrences are small. Based on this, by substituting each value in Equation 1, the probability of occurrence of an accident during SF transport was calculated, and the value was 3.152E-10.

4. RADIOLOGICAL ASSESSMENTS FOR TRANSPORT SCENARIOS

4.1. RADTRAN Code Analysis

RADTRAN code is a program developed by SNL (Sandia National Laboratories) and used to calculate risk assess-

Table 13. Ratio of accidents and loss type

Accident	Total loss	Middle	Light loss	Without loss	Total accidents	Ratio (%)
Collision	49	95	1812	560	2516	21.69
Overturn	82	109	199	31	421	3.63
Sinking	161	42	44	4	251	2.16
Fire and explosion	104	101	443	29	677	5.84
Contact	1	4	114	58	177	1.53
Downgrading	31	69	484	174	758	6.53
Engine damage	2	104	3757	309	4172	35.97
Others	35	158	2124	311	2628	22.66
Total	465	682	8977	1476	11600	100
Ratio (%)	4.01	5.88	77.39	12.72	100.00	

ment during the transport of radioactive waste [12]. The initial version of RADTRAN I and II was developed to prepare NUREG-0170 (ML12192A282 and ML022590370, 1977)[13], the first environmental impact assessment report on the transport of radioactive waste. Since then, several updates have been made, and the latest version, NRC-RADTRAN v1.0. This program is currently being distributed by the RAMP (Radiation Protection Computer Code Analysis and Maintenance Program). In RAMP, not only RADTRAN, but also programs such as RASCAL, RESRAD, PAVAN and DanD can be downloaded. In order to download these programs, it is possible to obtain approval after applying for the program to RAMP.

A variety of radioactive materials is transported annually in each country and internationally. There are several shipment modes which are truck, rail, maritime vessels, and aircraft. Workers and persons who are sharing links could be exposed to radiation when radioactive materials are transported. NRC-RADTRAN focus on the risks and consequences of various exposure. RADTRAN can assess risk for both incident-free and accident conditions. The evaluation procedure diagram is shown in Fig. 4. Trucks, trains, and ships can be selected as means of transport. External exposure doses and risks to residents, workers, and carriers can be evaluated.

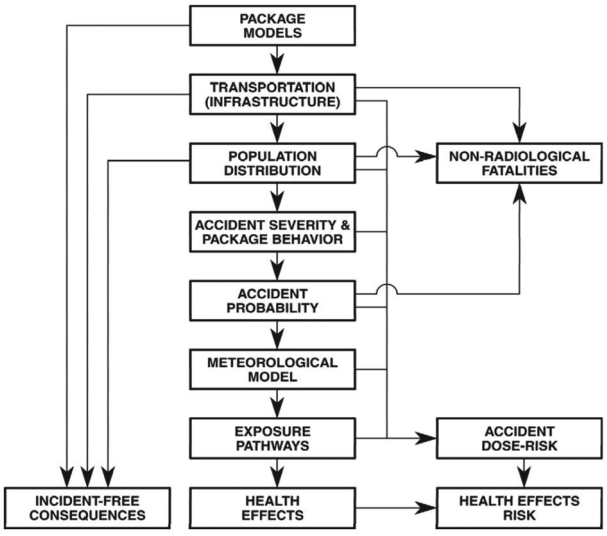


Fig. 4. RADTRAN evaluation procedure diagram [14].

4.1.2. RADTRAN Input Factors

4.1.2.1. Selection of Source Term

The geometric structure, size, weight, cooling period, burn-up, radiation source, decay heat, and radioactive material concentration of SF are basic data for SF transport impact analysis, so a reference SF should be selected. In the case of Hanbit NPP, which is to be transported, currently CE 16×16 PLUS7 nuclear fuel is loaded the most. According to the generation trend consistent with the fuel characteristics of PWR, from 2015, the generation of CE type 16×16 exceeds that of WH 17×17. It is predicted that the majority of SF that has been cooled for more than 10 years, which can be transported to interim storage facilities, WH-type will be dominant after 2070 [8]. Therefore, for a conservative evaluation, it was expected that it would be appropriate to target SF with an initial concentration of 4.5wt.%, a burnout of 45,000 MWd/MTU, and a cooling period of 5 years.

Based on this, a source term was selected for the evaluation of sinking accidents during sea transportation. The

Table 14. RADTRAN input and output item [15]

	Incident free transport scenario	Accident transport scenario
Input	• Package dimensions • Package external dose rate • Vehicle dimensions • Vehicle speeds • Vehicle external dose rate • Route characteristics • Population densities • Stop characteristics • Urban building density	• Radionuclide inventory • Accident rate (route characteristic) • Conditional probability of accident severity • Release, aerosol, respirable fractions Particle settling velocity • Meteorological parameters · Population densities • Fraction of land in agriculture
Output	• Collective external dose to residents along route • Collective external dose to public at stops • Collective external dose to urban non-residents • Collective dose to occupants of vehicles sharing route • Occupational external doses • MEI external doses	• Collective "dose risks:" inhalation, resuspension, groundshine, cloudshine, ingestion • Collective doses MEI doses and dose risks • Doses and dose risks per radionuclide • Critical group doses and dose risks • Doses and dose risks from loss of lead shielding

Table 15. Source term for radiological assessment [8]

Radionuclides	10 years [Ci]	Type	Radionuclides	10 years [Ci]	Type
^{210}Pb	2.21×10^{-8}	Particle	^{239}Pu	3.87×10^{2}	Particle
^{210}Bi	2.21×10^{-8}	Particle	^{240}Pu	5.90×10^{2}	Particle
^{210}Po	1.92×10^{-8}	Particle	^{241}Pu	1.32×10^{5}	Particle
^{225}Ra	2.60×10^{-7}	Particle	^{242}Pu	2.63	Particle
^{226}Ra	2.08×10^{-7}	Particle	^{241}Am	1.39×10^{3}	Particle
^{225}Ac	2.60×10^{-7}	Particle	^{243}Am	3.33×10^{1}	Particle
^{229}Th	2.60×10^{-7}	Particle	^{85}Kr	9.53×10^{3}	Gas
^{230}Th	1.07×10^{-4}	Particle	^{90}Y	9.19×10^{4}	Particle
^{234}Th	3.11×10^{-1}	Particle	^{93}Zr	2.44	Particle
^{233}Pa	4.77×10^{-1}	Particle	^{99}Tc	1.81×10^{1}	Particle
^{233}U	4.04×10^{-5}	Particle	^{106}Ru	2.02×10^{4}	Ruthenllum
^{234}U	1.40	Particle	^{134}Cs	3.94×10^{4}	Cesium
^{236}U	3.89×10^{-1}	Particle	^{135}Cs	6.54×10^{-1}	Cesium
^{238}U	3.11×10^{-1}	Particle	^{137}Cs	1.28×10^{5}	Cesium
^{237}Np	4.77×10^{-1}	Particle	^{144}Ce	1.45×10^{4}	Particle
^{239}Np	3.33×10^{1}	Particle	^{147}Pm	5.27×10^{4}	Particle
^{238}Pu	4.66×10^{3}	Particle			

nuclides in the RADTRAN nuclide library were entered as targets. For nuclides not included in the library, DCF (Dose Conversion Factor) was entered by referring to ICRP-119 [16], but there were some nuclides with no DCF for cloudshine and groundshine, so these were excluded due to inducing an error in the derivation of the result value. The mechanism for calculating the exposure dose in case of an accident calculates the exposure dose to personnel within the range as the radioactive material diffuses according to the weather conditions.

4.1.2.2. Isotope Release Fraction

In the 'Accidents' tab of RADTRAN, you can set the severity level when an accident occurs and set the conditional

probability that an accident at each level will occur. As SF transport in Korea was carried out only within the on-site, data from the US DOE [17] and NRC were referred to. The Probability tab allows you to specify the conditional probability of an accident of a particular severity, given that an accident happens. The conditional probabilities should include all possible accidents; references that may be used for Type B packages are NRC, 2013 and DOE, 2002 [14]. The most likely accidents are those in which there is neither a release of radioactive material nor a loss of gamma shielding.

4.2. Incident-free Scenario

During incident-free transportation, the transport cask is not damaged, and the external exposure by gamma rays and neutron rays is considered as the potential exposure to be considered. The ratio of gamma rays and neutron rays was set to 0.6 and 0.4 [12]. The exposure targets on the transport route were set to the general public and the transportation workers within a radius of 800 m from the transport ship [18]. And there are 5 man who handle SF cask loading and unloading. The duration of loading and unloading is 2 hours.

Table 16. Severity and release fractions for uncanistered PWR SF (NRC, 2013) [14]

Index	Conditional probability	Gas	Volatiles	Particulates	CRUD
0	0.99993	0	0	0	0
1	5.96E-12	0.80	0.50	0.70	0.001
2	3.57E-11	0.80	0.50	0.70	0.001
3	1.79E-11	0.80	0.50	0.70	0.001
4	1.79E-11	0.80	0.50	0.70	0.001
5	3.4E-10	0.80	0.50	0.70	0.001
6	3.4E-10	0.80	0.50	0.70	0.001
7	1.13E-10	0.80	0.64	0.45	0.001

4.3. Accident Scenario

In the case of the accident scenario, a case in which a ship is completely damaged in a collision, overturn, or sinking accident, resulting in damage to the transport cask and waste, is considered. Accidents occur on each path. The exposure targets were set as transport workers and the general public, and it was assumed that the radiation exposure of the exposed targets was measured from internal exposure by respiration of radioactive materials emitted in the form of aerosols and radioactive materials re-suspended or suspended in the air [18].

The evacuation period of the general public around the accident site after the accident occurred was set to 24 hours after the accident occurred.

5. RESULTS OF RADIATION ASSESSMENT

5.1. Incident-free Scenario

The result of the RADTRAN program is expressed as a collective dose. It was converted into individual dose by referring to the calculation formula of the RADTRAN technical manual. In all routes, the individual dose to the crew

Table 17. Input data for incident-free scenarios

Link	Length (km)	Speed (km h^{-1})	Popular density	Accidents km^{-1}	Death per accidents
YG	69.4	24	475	3.15E-10	0.242
HSD	1205	24	72.18	3.15E-10	0.242
HN1	34.2	24	66	3.15E-10	0.242
HN2	108.3	24	66	3.15E-10	0.242
GH	59	24	77	3.15E-10	0.242
SCHP	64.2	24	276	3.15E-10	0.242
CHW	201.3	24	1375	3.15E-10	0.242
PS	63.5	24	3604	3.15E-10	0.242
US	65	24	1502	3.15E-10	0.242
PH1	71.5	24	445	3.15E-10	0.242
PH2	21.4	24	445	3.15E-10	0.242
PH3	18.5	24	445	3.15E-10	0.242

member was 5.25×10^{-4} mSv yr^{-1} and the individual dose to the general public was 4.92×10^{-6} mSv yr^{-1}, which was significantly lower than the annual dose limit for persons who engaging in transport of 6 mSv. And results of individual dose to handlers are shown in Table 18 and Fig. 5. The slope changes at a distance of more than 15 m. This is because, in the calculation of RADTRAN, when the distance exceeds 10 m, the line source is changed to the point line source.

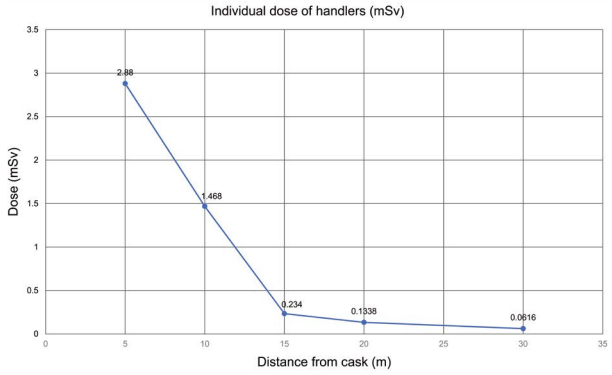


Fig. 5. Individual dose to handlers.

Table 18. Individual dose to handlers

Distance (m)	Individual dose (mSv)
5	2.88
10	1.47
15	0.234
20	0.0134
30	0.00616

5.2. Accident Scenario

The exposure dose due to the radioactive material leaked from the transport cask in the event of a transport accident was calculated. In the RADTRAN program, the resulting value is expressed as 'Population risk (man-Sv)', so it must be converted into an exposure dose. The individual dose can be obtained from equation 2 and 3.

Table 19. Individual dose to crew and general public at incident-free condition [unit: mSv]

Link	CREW (mSv)	Off link (mSV)
YG	1.84×10^{-5}	4.10×10^{-7}
HSD	3.20×10^{-4}	4.10×10^{-7}
HN1	9.05×10^{-6}	4.10×10^{-7}
HN2	2.87×10^{-5}	4.09×10^{-7}
GH	1.57×10^{-5}	4.10×10^{-7}
SCHP	1.70×10^{-5}	4.10×10^{-7}
CHW	5.35×10^{-5}	4.10×10^{-7}
PS	1.69×10^{-5}	4.10×10^{-7}
US	1.73×10^{-5}	4.10×10^{-7}
PH1	1.90×10^{-5}	4.09×10^{-7}
PH2	5.65×10^{-6}	4.10×10^{-7}
PH3	4.91×10^{-6}	4.10×10^{-7}
Total	5.25×10^{-4}	4.92×10^{-5}

Table 20. Individual dose to general public at accident condition

Link	P-risk (Sv) [A]	Population [B]	Accidents Probability [C]	Individual dose (mSv)
YG	5.35E-11	6.41E+05	2.19E-08	3.82×10^{-6}
HSD	1.41E-10	9.74E+04	3.80E-07	3.81×10^{-6}
HN1	3.66E-12	8.91E+04	1.08E-08	3.81×10^{-6}
HN2	1.16E-11	8.91E+04	3.41E-08	3.81×10^{-6}
GH	7.37E-12	1.04E+05	1.86E-08	3.81×10^{-6}
SCHP	2.88E-11	3.73E+05	2.02E-08	3.82×10^{-6}
CHW	4.49E-10	1.86E+06	6.34E-08	3.80×10^{-6}
PS	3.71E-10	4.87E+06	2.00E-08	3.81×10^{-6}
US	1.58E-10	2.03E+06	2.05E-08	3.80×10^{-6}
PH1	5.16E-11	6.01E+05	2.25E-08	3.81×10^{-6}
PH2	1.55E-11	6.01E+05	6.74E-09	3.82×10^{-6}
PH3	1.34E-11	6.01E+05	5.83E-09	3.82×10^{-6}
Total	1.30E-09	1.20E+07		4.57×10^{-5}

$$\text{Population risk} = [\text{Individual dose (Sv)}] \times [\text{Population}] \times [\text{Accidents Probability}] \quad (2)$$

$$\text{Accidents probability} = [\text{Accidents rate of each Link}] \times [\text{Conditional probability of occurrence of an accident's severity level}] \times [\text{Distance (km)}] \quad (3)$$

As a result, the annual individual dose to the general public along the route was estimated to be 4.57×10^{-5} mSv. When carrying 5, 10, and 15 casks, it was evaluated as 1.14×10^{-5} mSv, 2.29×10^{-5} mSv, and 3.43×10^{-5} mSv. The paths with the highest exposure dose were evaluated to be the Yeongwang-Hansando route, which has a relatively high population density, and the vicinity of Pohang Port.

6. CONCLUSIONS

In this study, a preliminary evaluation of the effects of radiation on the transport of SF using ships was conducted. When transported normally without an accident, the individual dose of transport workers was estimated to be 5.25×10^{-4} mSv, and the individual dose to the general public was evaluated as 4.92×10^{-5} mSv. This is significantly smaller than the annual dose limit of 1 mSv for the general public and annual dose limit for persons who engaging in transport of 6 mSv.

The individual dose in the transport accident condition was estimated to be 4.57×10^{-5} mSv when 20 casks were transported. When 5, 10, and 15 casks were transported, 1.14×10^{-5} mSv, 2.29×10^{-5} mSv, and 3.43×10^{-5} mSv were shown, respectively.

Safe transport of SF is a very important issue now that the on-site storage facility is approaching saturation point. It is essential to establish an optimal transport scenario that considers not only safety, but also technology and economic feasibility. In this study, the status of SF transport at home and abroad was examined, and transport casks and ships were investigated. For data such as the release rate of radioactive material in the case of SF maritime transport accidents, there is no data on sea transport, so the release rate at the time of land transport and drop accidents was referred to. However, in the case of sea transport, a relatively conservative value was used to reduce the error because the complex movement of ocean currents and the effect on the marine ecosystem must also be considered.

In a future study, a scenario of transporting SF generated from Kori, Shin-Kori, and Hanul NPP as well as from Hanbit NPP to an arbitrary storage facility would be developed to minimize time and cost, and a preliminary evaluation of the radiation effect during transport needs to be conducted.

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REFERENCES

1. KHNP, Status of spent nuclear fuel storage by nuclear power plant Quarter 4, 2021.
2. The 2nd Basic Plan for High-Level Radioactive Waste Management in 2021.12.
3. Public Information Circular for shipments of Irradiated Reactor Fuel, NUREG-0725 Rev.1.
4. Shipments of Nuclear Materials Between Europe and Japan, BNFL Brief 4 1996.12.
5. Clab-Central Interim Storage Facility for Spent Nuclear Fuel, SKB homepage, Accessed Sep. 28 2022, Available from: https://www.skb.com/our-operations/clab/
6. IMO, Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes in Flasks on Board Ships, 1994.
7. PNTL, Our Fleet - Fact sheets about Pacific Grebe, PNTL homepage, Accessed 24 July 2022, Available from: https://www.pntl.co.uk/wp-content/uploads/2012/09/PNTL_Grebe_01.pdf
8. Nuclear Safety Foundation, Risk assessment of spent nuclear fuel transport and storage facilities and final report on development of degradation characteristics for long-term wet storage on site, Nuclear Safety Research Project 5th Year Final Report, R&D/1505032-0517-SB120, page 37-158, 31 July 2018.
9. Baeg C-Y and Cho C-H. 2018. 'Development Status for Commercialization of Spent Nuclear Fuel Transportation and Dry Storage System Technology', *JNFCWT* **16**(2):271-279.
10. Ministry of Knowledge Economy, Development of cost estimation system for nuclear power plant post-treatment business, pp. 280-282, 2009.
11. KOSIS, Marine Accidents, KOSIS (Korean Statistical Information Service) homepage, Accessed 04 April 2022, Available from: https://kosis.kr/search/search.do?query=%ED%95%B4%EC%96%91%EC%82%AC%EA%B3%A0

12. Seo M, Dho H-S, Hong S-W and Park JB. 2017. Preliminary Assessment of Radiological Impact on the Domestic Railroad Transport of High Level Radioactive Waste. *J. Nucl. Fuel Cycle Waste Technol.* **15**(4):381-390.
13. RAMP, Codes: NRC-RADTRAN overview "Doses from routine and accident scenarios of transporting radioactive material", RAMP website, Accessed 07 March 2022, Available from: https://ramp.nrc-gateway.gov/codes/nrc-radtran
14. Risk Assessment of Transportation of Radioactive Materials Using RADTRAN, Futh F. Weiner, Sandia National Laboratories
15. NRC, RADTRAN 6/RadCat 6 User Guide, SAND2013-8095
16. Eckerman K, Harrison J, Menzel H-G and Clement CH. 2012. Compendium of Dose Coefficients based on ICRP Publication 60, ICRP, 26-58 and 72-123.
17. DOE, A Resource Handbook on DOE Transportation Risk Assessment, DOE/EM/NTp/HB-01, 119-128, 2002.
18. Seo M, Hong S-W and Park JB. 2016. Radiological Impact Assessment for the Domestic On-road Transportation of Radioactive Isotope Wastes. *J. Nucl. Fuel cycle Waste Technol.* **14**(3):279-287.