Technical Paper
https://doi.org/10.7733/jnfcwt.2022.039

Evaluation of Exposure Dose and Working Hours for Near Surface Disposal Facility

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(Received August 9, 2022 / Revised September 6, 2022 / Approved October 13, 2022)

Decommissioning of nuclear power plants generates a large amount of radioactive waste in a short period. Moreover, Radioactive waste has various forms including a large volumes of metal, concrete, and solid waste. The disposal of decommissioning waste using 200 L drums is inefficient in terms of economics, work efficiency, and radiation safety. Therefore, The Korea Radioactive Waste Agency is developing large containers for the packaging, transportation, and disposal of decommissioning waste. Assessing disposability considering the characteristics of the radioactive waste and facility, convenience of operation, and safety of workers is necessary. In this study, the exposure dose rate of workers during the disposal of new containers was evaluated using Monte Carlo N-Particle Transport code. Six normal and four abnormal scenarios were derived for the assessment of the dose rate in a near surface disposal facility operation. The results showed that the calculated dose rates in all normal scenarios were lower than the direct exposure dose limitation of workers in the safety analysis report. In abnormal scenarios, the work hours with dose rates below 20 $mSv \cdot y^{-1}$ were calculated. The results of this study will be useful in establishing the optimal radiation work conditions.

Keywords: Decommissioning radioactive waste, Radiation worker, Disposal container, Exposure dose, Working hours, Near surface disposal facility

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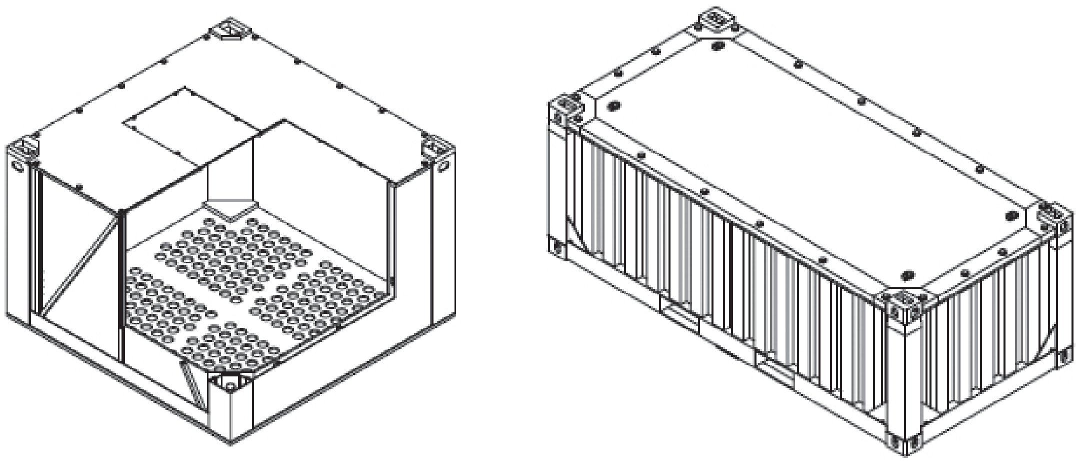


(a) P2B (b) PT1

Fig. 1. Containers configuration.

1. Introduction

At the Gyeong-ju intermediate and low-level radioactive waste disposal facility, the first-phase disposal facility with a capacity of 100,000 drums of radioactive waste has been in operation since 2015, and the construction of the second-phase near surface disposal facility to dispose of 125,000 drums is being prepared. There are only three types of disposal containers used in the disposal facility: two types of concrete box containers that can hold 200 L drum and 320 L drum, and HIC. However, when operating the disposal facilities, these containers are not appropriate to dispose decommissioning radioactive waste. Decommissioning radioactive waste has various shapes, sizes, and radiation levels, and is expected to be generated in large quantities in a short period.

To dispose of the decommissioning waste, the Korea Radioactive Waste Agency (KORAD) is developing new packaging, transportation, and disposal containers in consideration of radiological characteristics, characteristics of disposal facilities, operational convenience, and safety of disposal for the efficient and safe management of decommissioning waste [1].

But, 200 L and 320 L drums and HIC are planned to be disposed of in the near surface disposal facility according to the Safety Analysis Report (SAR). To use the new containers, the disposal facility operator must evaluate the radiation dose for workers and the general public. And the doses should be lower than the regulatory limit while operating the disposal facility using the new containers. Also, an adequate radiation protection plan must be provided to satisfy ALARA guidelines [2].

In this study, the exposure dose rate of the worker was evaluated using the MCNP code assuming several scenarios of the new container disposal in the near surface disposal facility. It was checked whether the evaluated dose rate in normal scenarios satisfies the dose constraint suggested in the SAR. And the work hours that satisfy the regulatory exposure dose limit of 20 $mSv \cdot y^{-1}$, and the annual KORAD self-managed dose limit of 4 $mSv \cdot y^{-1}$ were calculated under abnormal conditions to derive appropriate radiation work conditions [3].

2. Characteristics of Packages

In this study, two types of containers in Fig. 1 and 200 L drums were selected for exposure dose evaluation among

Table 1. Detail specifications of P2B, PT1 containers and 200 L drum

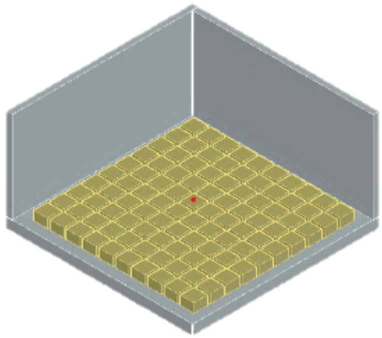
Container	(mm)			Volume (cm^3)	Density ($g \cdot cm^{-3}$)	Weight (ton)	^{60}Co specific activity ($Bq \cdot g^{-1}$)	^{60}Co total activity (Bq)
	Width/ Radius (W)/(R)	Length (L)	Height (H)					
P2B	1,452	1,452	950	2,002,889	7.85	12.52	5.80×10^3	6.39×10^{10}
Waste (RV)	1,350	1,350	770	1,403,325	7.85	11.02		
PT1	1,600	3,400	1,200	6,528,000	7.85	36.56	4.40×10^3	6.80×10^{10}
Waste (Ingot)	1,442	3,242	939	4,389,791	7.85	34.46		
200 L drum	308.5	-	884	264,175	7.85	0.235	4.88×10^4	5.75×10^8
Waste (Solid)	307.5	-	882	261,872	0.9			

Table 2. Flux to dose conversion factor (ICRP-74)

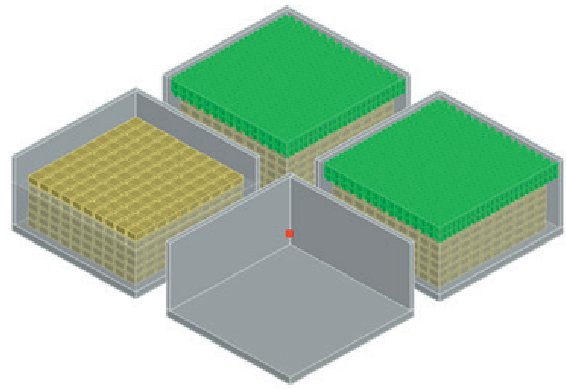
Energy (MeV)	Conversion Factors (mSv/hr/($cm^2 \cdot$sec))	Energy (MeV)	Conversion Factors (mSv/hr/($cm^2 \cdot$sec))
0.01	2.20×10^{-7}	0.5	1.06×10^{-5}
0.015	2.99×10^{-6}	0.6	1.24×10^{-5}
0.02	3.78×10^{-6}	0.8	1.58×10^{-5}
0.03	2.92×10^{-6}	1	1.87×10^{-5}
0.04	2.30×10^{-6}	1.5	2.48×10^{-5}
0.05	1.98×10^{-6}	2	3.10×10^{-5}
0.06	1.84×10^{-6}	3	4.00×10^{-5}
0.08	1.91×10^{-6}	4	4.82×10^{-5}
0.1	2.20×10^{-6}	5	5.58×10^{-5}
0.15	3.20×10^{-6}	6	6.34×10^{-5}
0.2	4.32×10^{-6}	8	7.78×10^{-5}
0.3	6.48×10^{-6}	10	9.22×10^{-5}
0.4	8.57×10^{-6}	-	-

the disposal containers for decommissioning waste. Table 1 shows the specifications of each container and the 200 L drum. In the case of the P2B container, cuttings from RVs or large NPP equipment will be disposed of, and in the case of PT1, metals or concrete and soil waste will be disposed of, and in the case of the 200 L drum, solid waste will be disposed of. The filling fraction was assumed to be 100% in every package. The empty space was poured with concrete grouting.

The radiation source term should be derived through chemical analysis of radioactive waste data. But it is difficult to derive the exact radiation source term for decommissioning radioactive waste. So the radiation source terms derived from the previous study were applied [4]. In this



(a) one vault modeling



(b) four vaults modeling

Fig. 2. Vault modeling configuration.

Table 3. Containers stacking information in disposal vault

Container	Arrangement in vault	Grouting thickness (vertical side thickness / horizontal side thickness / upper side thickness)	Number of 200 L drums disposed on the extra upper space
P2B	10×10×6	30 cm / 30 cm / 10 cm	1,430
PT1	5×8×6	30 cm / 44 cm / 10 cm	715

study, only ^{60}Co evaluated among radionuclides constituting metal waste because the beta-ray-emitting nuclide and low-energy gamma-emitting daughter nuclide have minimal radiation effect on the external radiation dose rate. ^{60}Co emits two gamma rays with energies of 1.172 MeV and 1.332 MeV during one decay. As shown in table 1, the P2B container is a container for packaging/disposal, and the maximum specific activity of ^{60}Co is 5.80×10^{3} Bq·g^{-1}, which satisfies the surface radiation dose rate of 2 mSv·h^{-1}. And the weight of the waste contents is 11.02 tons. So the total gamma activity multiplied by weight and specific activity is 6.39×10^{10} Bq. The PT1 container is a container for packaging/disposal/transport, and the maximum specific activity of ^{60}Co, 4.40×10^{3} Bq·g^{-1} and the weight of the contents is 34.46 tons. So the total gamma activity is 6.80×10^{10} Bq. Also, maximum specific activity of the 200 L drum is 4.88×10^{4} Bq·g^{-1}. And the total gamma activity is 5.75×10^{8} Bq.

3. MCNP Modeling

In this evaluation, the Monte Carlo N-Particle Transport Code (MCNP) was used. MCPLIB84 based on ENDF/B-VI library was applied to the cross-section library. For the flux to dose conversion factor, the data in Table 2 reported in ICRP-74 was used [5]. MCNP is a statistical code using the Monte Carlo method, and uncertainty is included in the result value, which is expressed as the concept of a relative error obtained by dividing the standard deviation of the mean by the mean.

The reliability of the calculation results was ensured by adjusting the number of particles. So the relative error of each total dose rate calculation result was less than 10% at most [6].

In the case of near surface phase disposal facility, there are a total of 20 disposal vaults, but for the efficiency of exposure calculation, One or four disposal vaults were modeled and evaluated as shown in Fig. 2. A 20×20×20 cm cubic F4 tally was set in the appropriate tally location or A mesh tally was set to find conservative tally position. As shown in Table 3, The number of containers that can be disposed of in one vault varies depending on the specifications of the containers. In addition, after stacking the new containers, 200 L drums were stacked on the extra upper space of the disposal vault. The separation distance between each container was evaluated through computational analysis to ensure structural safety [7]. The separation distance between containers is shown filled with concrete grouting. And the grouting thickness of each direction is shown in Table 3.

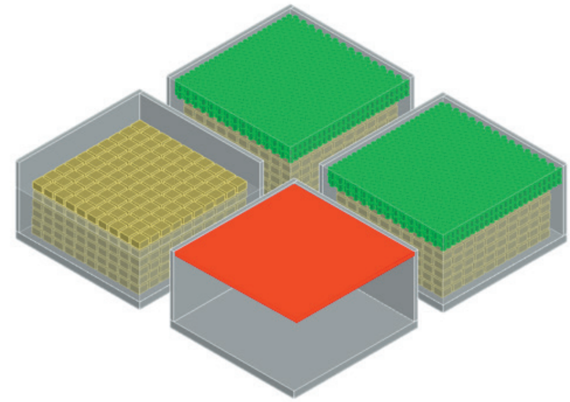


Fig. 3. Normal scenario 1 configuration (Crane Operators).

4. Exposure Scenarios and Dose Limits

To evaluate the exposure dose rate of radiation workers according to various situations, 10 scenarios were composed for each container and the exposure dose rate was evaluated [8]. The 10 scenarios were divided into 6 normal scenarios to evaluate disposal safety by applying the direct dose constraints of the SAR, and 4 abnormal scenarios to evaluate work hours in abnormal exposure situations. The assessment was carried out by modeling the situation of the disposal vault according to each scenario and setting the appropriate tally location.

In the case of a normal scenario, radioactive waste disposal at the facility is carried out using cranes, forklifts, and transport vehicles. Therefore, a normal scenario was established to evaluate the exposure dose rate of crane workers, truck drivers, and slab construction workers.

In normal scenario, the dose constraint suggested in the SAR should be satisfied. The dose constraint is as follows.

□ Direct exposure constraints by gamma radiation (SAR Section 6.3.1.2.3 Safety evaluation during operation).

- Less than 0.02 mSv·h^{-1} exposure dose to crane operators for stacking radioactive waste containers, grouting workers and workers pouring concrete slabs at the top of the vault.
- Less than 0.003 mSv·h^{-1} exposure dose to underground inspection road maintenance worker 0.003 mSv·h^{-1} (drainage pipe).
- Less than 0.001 mSv·h^{-1} exposure dose to workers near the sealed vault.

The situation in which a worker enters a disposal facility in progress due to unexpected events was set as the abnormal scenario and the exposure dose rate in the scenarios is evaluated. In the case of an abnormal scenario, the dose constraints suggested in the SAR cannot be applied, so we tried to evaluate the work hours using the dose limit for the management of annual radiation workers' dose. The calculated work hours satisfy the annual regulatory dose limit of 20 mSv and 4 mSv, the annual KORAD dose limit for radiation workers.

4.1 Normal Scenarios

1) Normal Scenario 1: exposure scenario for crane operator stacking radioactive waste containers.

In normal scenario 1, four disposal vaults are modeled. The two disposal vaults on the right have been sealed, and the disposal is in progress in the upper left vault. In the lower left, the crane operator is working at the position

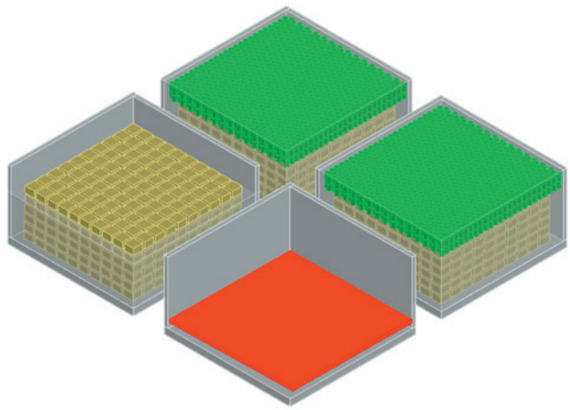


Fig. 4. Normal scenario 2 configuration (Truck Operators).

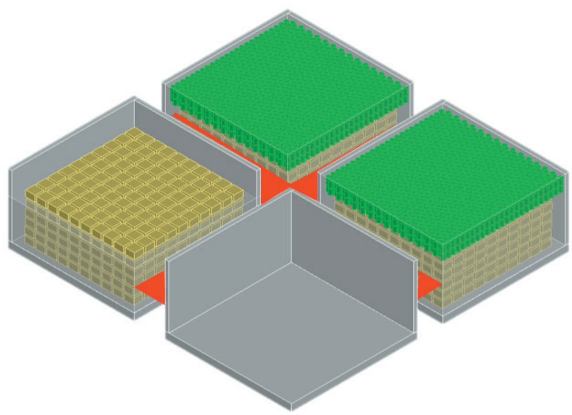


Fig. 5. Normal scenario 3 configuration (between two sealed Repositories and one Repository in progress).

of the red box shown in Fig. 3. As shown in Fig. 3, a F4 tally is on the top of the lower left disposal vault.

2) Normal Scenario 2: exposure scenario for the truck driver transporting radioactive waste containers.
   The vaults modeling is the same as normal scenario 1, but the truck driver works on the bottom of the vault. As shown in Fig. 4, the position of the tally changes to a position 120 cm above the bottom surface of the lower left vault.
3) Normal Scenario 3: exposure scenario when working between two sealed vaults and one open vault.
   In normal scenario 3, work proceeds between two sealed vaults and one open vault. And disposal in the open vault

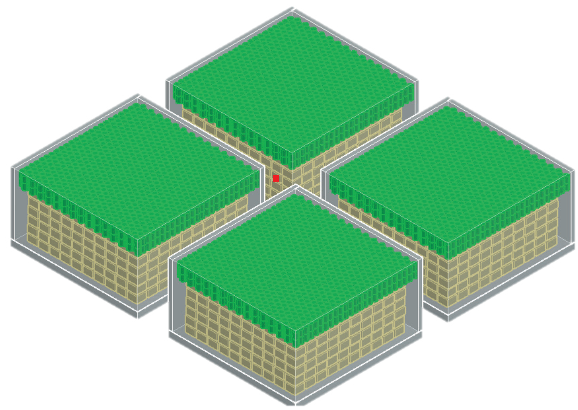


Fig. 6. Normal scenario 4 configuration (between 4 Sealed Repositories).

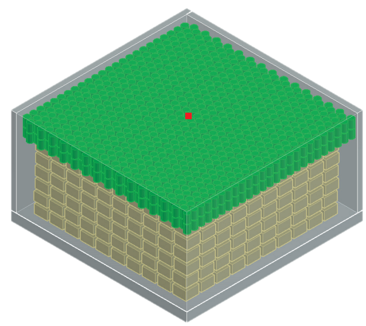


Fig. 7. Normal scenario 5 configuration (on a Slab).

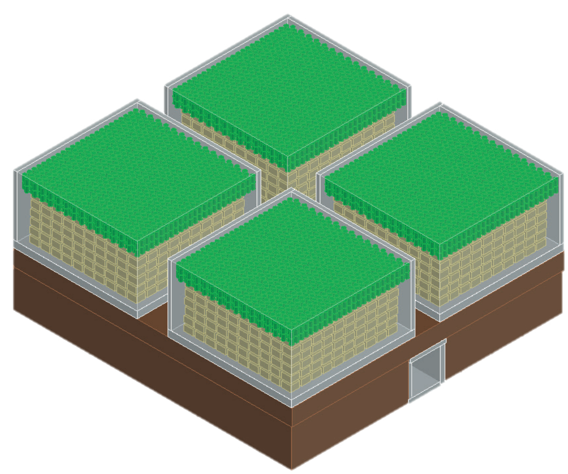


Fig. 8. Normal scenario 6 configuration (underground inspection road maintenance).

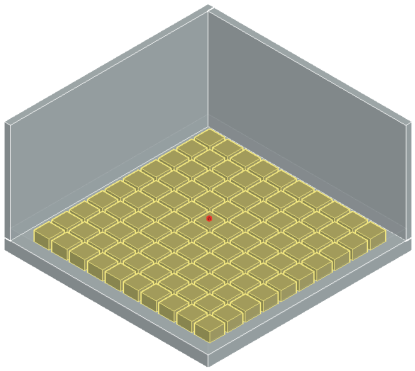


Fig. 9. Abnormal scenario 1 configuration (1st stack disposal is completed).

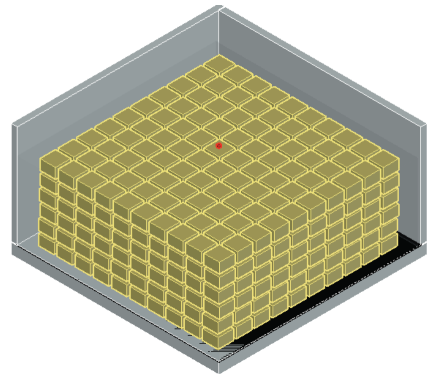


Fig. 10. Abnormal scenario 2 configuration (6th stack disposal is completed).

is in progress. The disposal facility works performed near sealed vaults satisfy the dose constraint of 0.001 $mSv \cdot h^{-1}$. The vaults modeling is the same as normal Scenario 1. but tally position is different, as shown in Fig. 5, F4 tally was 120 cm above the ground in the center between the four disposal vaults.

4) Normal Scenario 4: exposure scenario near four sealed vaults.

In normal scenario 4, work proceeds near four sealed vaults. And scenario 4 also satisfies the dose constraint of 0.001 $mSv \cdot h^{-1}$. Scenario 4 was modeled as shown in Fig. 6. F4 tally was 120 cm above the ground in the center between the four sealed vaults.

5) Normal Scenario 5: operator exposure scenario on the slab of one sealed disposal vault.

The operator is working on the disposal vault slab after the disposal and concrete grouting were completed. At this time, since the operator works in the center of the slab as shown in Fig. 7, F4 tally was 120 cm above the slab.

6) Normal Scenario 6: exposure scenario during underground inspection passage maintenance.

As shown in Fig. 8, four disposal vaults are sealed. At this time, it was assumed that the operator was performing maintenance work at the center of the underground inspection passage located in the center between the four disposal vaults. And F4 tally was 120 cm above the ground of the center of inspection passage.

4.2 Abnormal Scenarios

In the SAR, disposal facility operators work remotely, so the cases when workers have to work inside the unsealed disposal vault is abnormal exposure situation, and the dose constraints for the abnormal cases are not suggested in the SAR. However, in unexpected accidents such as a fire in vault or container drop accident in vaults, workers may have to work in vaults. At this time, it is necessary to evaluate the working hours so as not to exceed the annual dose limit of radiation worker suggested by the nuclear safety act. In this study, to evaluate the work hours that satisfy the individual dose limit even in the case of such abnormal exposure, the scenario assuming an abnormal exposure situation was set up as follows.

1) Abnormal Scenario 1: exposure scenario inside the disposal vault after 1st stack disposal is completed.

As shown in Fig. 9, one disposal vault is modeled. The worker is working inside the disposal vault after 1st stack disposal is completed. At this time, the operator is working in the center of the vault. So, F4 tally was 120 cm above the disposed 1st stack container.

2) Abnormal Scenario 2: exposure scenario inside the disposal vault after the 6th stack disposal is completed.

As shown in Fig. 10, the worker is working inside the disposal vault after the 6th stack disposal is completed,

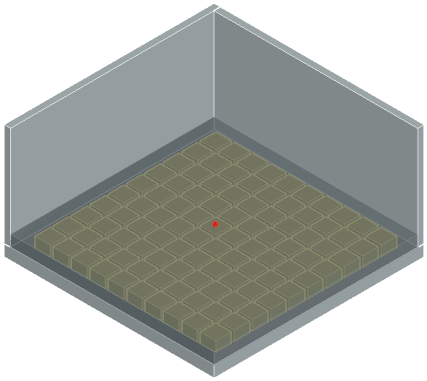


Fig. 11. Abnormal scenario 3 configuration (1st stack disposal and grouting is completed).

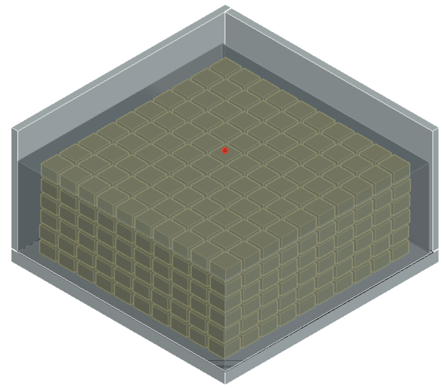


Fig. 12. Abnormal scenario 4 configuration (6th stack disposal and grouting is completed).

Table 4. Exposure dose results and constraints for each scenario (P2B)

Container	Scenario	Explanation	Dose value ($mSv \cdot hr^{-1}$)	Dose constraint ($mSv \cdot hr^{-1}$)
P2B	Normal Scenario 1	Crane Operators	2.9213×10^{-4}	2.00×10^{-2}
	Normal Scenario 2	Truck Operators	1.0152×10^{-3}	2.00×10^{-2}
	Normal Scenario 3	between two sealed Vaults and one Vault in progress	7.4837×10^{-5}	1.00×10^{-3}
	Normal Scenario 4	between 4 Sealed Vaults	1.1771×10^{-8}	1.00×10^{-3}
	Normal Scenario 5	on a Slab	1.8191×10^{-4}	1.00×10^{-3}
	Normal Scenario 6	underground inspection road maintenance	2.5646×10^{-6}	3.00×10^{-3}
	Abnormal Scenario 1	1st stack disposal is completed	2.0502×10^{-1}	-
	Abnormal Scenario 2	6th stack disposal is completed	2.0141×10^{-1}	-
	Abnormal Scenario 3	1st stack disposal and grouting is completed	7.4302×10^{-2}	-
	Abnormal Scenario 4	6th stack disposal and grouting is completed	7.4200×10^{-2}	-

and F4 tally was 120 cm above the disposed 6th stack container.

3) Abnormal Scenario 3: exposure scenario inside the disposal vault after the 1st stack disposal and grouting is completed.

In this scenario, the worker is working inside the vault after the 1st stack disposal and the 1st stack grouting are completed. So, F4 tally was 120 cm above the 1st stack grouting.

4) Abnormal Scenario 4: exposure scenario inside the disposal vault after the 6th stack disposal and grouting is completed.

In this scenario, the worker is working inside the vault after the 6th stack disposal and the 6th stack grouting are completed.

5. Results

The exposure dose rate evaluated through the normal scenarios is shown in Tables 4 and 5. The disposal suitability in terms of shielding was evaluated by comparing

Table 5. Exposure dose results and constraints for each scenario (PT1)

Container	Scenario	Explanation	Dose value ($mSv\cdot hr^{-1}$)	Dose constraint ($mSv\cdot hr^{-1}$)
PT1	Normal Scenario 1	Crane Operators	1.6800×10^{-4}	2.00×10^{-2}
	Normal Scenario 2	Truck Operators	5.7222×10^{-4}	2.00×10^{-2}
	Normal Scenario 3	between two sealed Vaults and one Vault in progress	3.2319×10^{-5}	1.00×10^{-3}
	Normal Scenario 4	between 4 Sealed Vaults	3.8978×10^{-7}	1.00×10^{-3}
	Normal Scenario 5	on a Slab	1.0192×10^{-4}	1.00×10^{-3}
	Normal Scenario 6	underground inspection road maintenance	1.6515×10^{-6}	3.00×10^{-3}
	Abnormal Scenario 1	1st stack disposal is completed	1.5400×10^{-1}	-
	Abnormal Scenario 2	6th stack disposal is completed	1.5584×10^{-1}	-
	Abnormal Scenario 3	1st stack disposal and grouting is completed	4.5150×10^{-2}	-
	Abnormal Scenario 4	6th stack disposal and grouting is completed	4.6470×10^{-2}	-

Table 6. Exposure dose (mSv) in case of disposal and sealing of one disposal vault

P2B	Time (hr/work)	Number of works	Total work time (hr)	Dose rate ($mSv\cdot hr^{-1}$)	Total dose of each work (mSv)
Unloading container (in crane)	0.5	2,030	1,015	2.92×10^{-4}	2.97×10^{-1}
Vault grouting (in crane)	2	6	12	2.92×10^{-4}	3.51×10^{-3}
Slab pouring (in crane)	2	1	2	1.82×10^{-4}	3.64×10^{-4}
Underground inspection road maintenance	2	12	24	2.56×10^{-6}	6.16×10^{-5}
Total dose (mSv)					**3.00×10^{-1}**
PT1	Time (hr/work)	Number of works	Total work time (hr)	Dose rate ($mSv\cdot hr^{-1}$)	Total dose of each work (mSv)
Unloading container (in crane)	0.5	955	477.5	1.68×10^{-4}	8.02×10^{-2}
Vault grouting (in crane)	2	6	12	1.68×10^{-4}	2.02×10^{-3}
Slab pouring (in crane)	2	1	2	1.02×10^{-4}	2.04×10^{-4}
Underground inspection road maintenance	2	12	24	1.65×10^{-6}	3.96×10^{-5}
Total dose (mSv)					**8.25×10^{-2}**

these dose rates with the dose constraints of SAR. The dose rate of the normal scenario 1 to 6 was evaluated to be low compared to the exposure dose constraint, and even in the case of normal scenario 5, which has the highest dose rate compared to the constraint, has an exposure dose rate of 1/5 of the constraint. In particular, the exposure dose rate of workers on the slab was evaluated to be very low. The value is 0.001771 $\mu Sv\cdot hr^{-1}$ for P2B and 0.038978 $\mu Sv\cdot hr^{-1}$

Table 7. Calculation results of work hours for each scenario (P2B)

Container	Scenario	Explanation	Dose value ($mSv·hr^{-1}$)	Work hours based on 20 $mSv·y^{-1}$ (hr)	Work hours based on 4 $mSv·y^{-1}$ (hr)
P2B	Abnormal Scenario 1	1st stack disposal is completed	$1.5400×10^{-1}$	98	20
	Abnormal Scenario 2	6th stack disposal is completed	$1.5584×10^{-1}$	99	20
	Abnormal Scenario 3	1st stack disposal and grouting is completed	$4.5150×10^{-2}$	269	54
	Abnormal Scenario 4	6th stack disposal and grouting is completed	$4.6470×10^{-2}$	270	54

Table 8. Calculation results of work hours for each scenario (PT1)

Container	Scenario	Explanation	Dose value ($mSv·hr^{-1}$)	Work hours based on 20 $mSv·y^{-1}$ (hr)	Work hours based on 4 $mSv·y^{-1}$ (hr)
PT1	Abnormal Scenario 1	1st stack disposal is completed	$2.0502×10^{-1}$	98	20
	Abnormal Scenario 2	6th stack disposal is completed	$2.0141×10^{-1}$	99	20
	Abnormal Scenario 3	1st stack disposal and grouting is completed	$7.4302×10^{-2}$	269	54
	Abnormal Scenario 4	6th stack disposal and grouting is completed	$7.4200×10^{-2}$	270	54

for PT1. As a result of the dose sensitivity according to the number of container stacks, the difference did not appear significantly due to the shielding effect by grouting. But, due to the shielding effect of grouting, there was a large difference in the exposure dose rate before grouting and after grouting.

With normal scenario results of P2B, we calculated the exposure dose in case of disposal and sealing of one disposal vault as shown in Table 6. When the container disposal is proceeding, unloading container, vault grouting, slab pouring, and underground inspection road maintenance are performed and the time required for each work and the required number of works is suggested in SAR. The total exposure dose calculated by multiplying time by dose rate is 0.3 mSv. And in the case of PT1, the total exposure dose is 0.0825 mSv. The dose result is very low compared to the dose limit of 20 and 4 mSv. So, remote work with new containers is important to ensure worker safety.

In the case of an abnormal scenario, the dose constraints presented in the SAR cannot be applied, the exposure of workers during radiation work was managed by evaluating the work hours that satisfy the annual dose limit of the radiation dose of 20 mSv and the annual KORAD dose limit of 4 mSv. Table 7 shows the work hours for each scenario of the P2B container, and Table 8 shows the work hours of the PT1 container. As the results of the dose evaluation, even if the number of container stacks changes, the work hours do not change significantly. However, depending on whether grouting is done or not, there are large differences. If the worker proceeds to work in the disposal vault after loading the P2B container at the 1st or 6th stacks, it is possible to work for about 98 hours based on 20 $mSv·hr^{-1}$ and about 20 hours based on 4 $mSv·hr^{-1}$. In the case of PT1 container in 1st or 6th stacks, it is possible to work for about 130 hours based on 20 $mSv \cdot hr^{-1}$ and about 26 hours based on 4 $mSv \cdot hr^{-1}$.

6. Conclusions

As mentioned in the introduction, it is important to evaluate whether the disposal safety of the near surface facility is safe even if disposing of new large containers. In this study, Scenarios of normal and abnormal situations were constructed, and the exposure dose rate of workers for each scenario was evaluated. The evaluation is based on the virtual source term information of wastes derived in the previous study. As a result of the dose rate evaluation, the exposure dose rate of workers in the normal scenario was evaluated to be lower than the direct exposure dose constraints of the SAR during disposal facility operation. The total exposure dose calculated by normal scenario results is lower than the annual dose limit of 20 mSv and 4 mSv. All of the normal scenarios are based on remote operation. So remote work with the new container is important to ensure the radiation safety of workers.

The abnormal scenarios have high exposure dose rates. So the work hours not to exceed 20 mSv and 4 mSv were suggested so that it can help manage the annual exposure dose of workers. However, the source terms of decommissioning waste have not yet been accurately analyzed, if the optimal radiation work conditions are derived by utilizing the source terms and characteristics of the decommissioning radioactive waste based on actual measurements, it is possible to establish a safe and efficient disposal process for decommissioning radioactive waste.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP Project No. 2021151010040) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea.

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