Technical Note

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A Study of Immobilization Performance Requirements for Heterogeneous Radioactive Waste

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Highly radioactive waste is solidified to restrict leaching, retain its shape, and maintain its structural stability to prevent it from affecting humans and the environment as much as possible. This operation should be performed consistently regardless of whether the waste is homogeneous or heterogeneous. However, currently, there are no specific performance requirements for heterogeneous waste in Korea. This study reviewed domestic research results and the status of overseas applications, and proposed immobilization requirements for heterogeneous waste to be applied in Korea. IAEA safety standards, domestic laws, and waste acceptance criteria were reviewed. The status of heterogeneous waste immobilization in countries such as the United States, France, and Spain was reviewed. Most countries treat heterogeneous waste by encasing it in concrete, and impose immobilization requirements on this concrete. Based on these data, safety standards for the thickness, compressive strength, and diffusion limit of this concrete material were proposed as immobilization requirements for heterogeneous waste disposal in Korea. Quantitative values for the above requirements need to be derived through quantitative assessments based on the characteristics of domestic heterogeneous waste and disposal facilities.

Keywords: Heterogeneous waste, Immobilization, Performance requirement, Waste acceptance criteria, Concrete lining

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1. Introduction

All low- and intermediate-level radioactive waste (LILW) generated from nuclear facilities such as nuclear power plants, research institutes, hospitals, etc. are disposed of at disposal facilities to ensure that there is no impact on human health and the nature environment [1]. Typically, a disposal facility is formed of three representative barriers: waste package, repository, and disposal site. Each barrier plays a role in preventing, delaying, or restricting the release of radionuclides from the disposal facility to the nature environment, and is given proper performance requirements through the disposal facility safety assessment. The safety of a disposal facility is ultimately achieved by the organic and complementary integration of the above multiple barriers [2].

Currently, Korea has been operating a disposal facility in Gyeong-Ju since 2015 to safely dispose of LILW. The disposal facility can dispose of 100,000 drums of LILW and ensures safety by imposing proper performance requirements on multiple barriers such as waste package, disposal container, Silo, and disposal site. Among the barriers at the Gyeong-Ju disposal facility, the performances related to the waste package are described in the waste acceptance criteria (WAC) for the disposal facility. The generator must treat the waste to meet the applicable acceptance criteria and then deliver it to the disposal facility [3].

The representative performance requirement imposed on waste package is the solidification (immobilization) requirement. Legal regulations for solidification are described in Article 3, Sub-paragraph 7 and Article 11 of Nuclear Safety and Security Commission (NSSC) Notice No. 2021-26 [4]. Article 3, Sub-paragraph 7 describes the definitions of solidification (immobilization) and stipulates immobilization as a concept included in solidification. Article 11 stipulates three conditions for solidified waste. Since solid materials such as spent cartridge filters that are subject to immobilization are not fluid, the conditions applicable to immobilization are Sub-paragraph 2 restriction on the release of nuclides and Sub-paragraph 3 structural stability.

The solidification requirements in WAC for the disposal facility distinguish between solidification and immobilization. Solidification is applied to all fluid homogeneous wastes such as spent resin and concentrates waste, regardless of radioactivity, and performance requirements such as compressive strength and leaching rate are given to the solidified waste. On the other hand, immobilization is applied to solid heterogeneous waste with a total radioactivity concentration of 74,000 $Bq \cdot g^{-1}$ or more of nuclides with a half-life of more than 20 years, and no performance requirements are imposed on the immobilized waste.

Here, in the case of solidification, performance such as compressive strength and leaching rate is imposed on all homogeneous waste regardless of radioactivity, whereas in the case of immobilization, performance is not granted even though it targets only heterogeneous waste with high radioactivity. It is judged that there are contradictions in terms of safety. Since immobilization is a concept included in solidification in the law, it is judged that it makes sense that immobilization should be given similar performance to solidification, such as restriction on the release of nuclides and structural stability. Separately, the level or scale of performance required for immobilization may be different from solidification.

Accordingly, this study aims to investigate the status of immobilization performance application for heterogeneous waste in various foreign countries with extensive experience in operating disposal facilities and radioactive waste management, and to propose immobilization performance requirements for heterogeneous radioactive waste that can be applied in Korea.

2. Overseas Status

The status of immobilization performance for heterogeneous waste applied in 4 leading countries with extensive experience in disposal facility operation and radioactive

Table 1. Classification and definition of immobilization in IAEA

Term	Immobilization		
	Solidification	Embedding	Encapsulation
Definition	Immobilization of gaseous, liquid or liquid-like materials by conversion into a solid waste form	Immobilization of solid waste by surrounding it with a matrix material in order to produce a waste form (e.g., metallic materials)	Immobilization of dispersed solids by mixing them with a matrix material in order to produce a waste form (e.g., ash or powder)

waste management was investigated. The four overseas countries are the United States, France, Spain, and Japan. Prior to investigating overseas cases, IAEA publications related to immobilization were first reviewed.

2.1 IAEA

The IAEA uses immobilization as a term for the highest-level concept, as shown in Table 1 [5]. Immobilization is described as follows: “Immobilization is the conversion of waste into a waste form by solidification, embedding or encapsulation. The aim of it is to reduce the potential for migration or dispersion of radionuclides during handling, transport, storage and/or disposal”. Comparing IAEA and Korea, solidification is the same, and Korean solidification can be seen as a concept that includes IAEA’s embedding and encapsulation.

IAEA SSR-5 recommends that engineered barriers, including waste form, should be designed to provide containment of radionuclides in waste and waste form have to ensure the fulfilment of the safety functions with regard to safety in the long term [6].

2.2 United States

In the United States, 10CFR61.55 requires that if waste is classified as Class B or Class C depending on radioactivity concentration regardless of whether homogeneous or heterogeneous, the waste form must meet minimum and stability requirements. The above requirements for waste form are described in 10CFR61.56. The minimum requirements are prohibited items, packaging conditions, etc., and

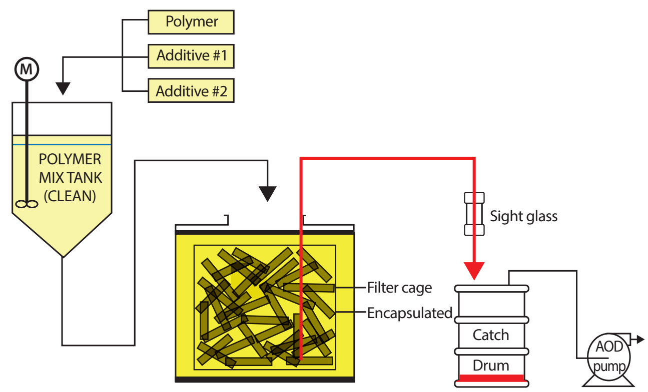

Fig. 1. The conceptual diagram for cartridge filter encapsulation.

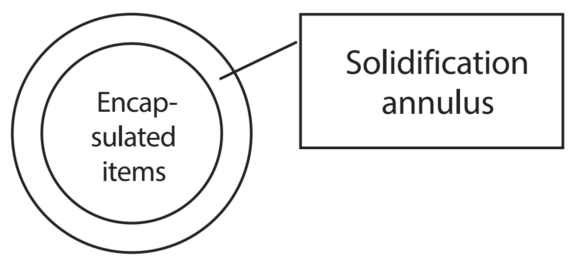

Fig. 2. The conceptual diagram of discrete item encapsulation.

the stability requirements are structural stability, free liquid, and void space restrictions [7].

The United States provides “Technical Position on Waste Form” guide on how to satisfy the structural stability specified in 10CFR61.56(b). This guide quantitatively provides performance requirements such as compressive strength and leaching rate for homogeneously solidified waste, but heterogeneous waste such as cartridge filter waste that is difficult to solidify requires demonstration to ensure stability. It also suggests the use of High Integrity Container (HIC) or

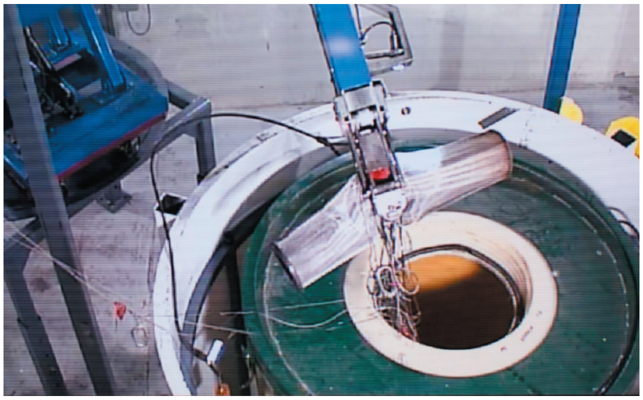

Fig. 3. Handling cartridge filter.

Fig. 4. Crushing cartridge filter.

encapsulation within a binder as acceptable alternatives for heterogeneous waste [8].

Encapsulation for heterogeneous waste is covered in the "Technical Position on Concentration Averaging and Encapsulation" guide. In this guide, encapsulation is defined as being different from solidification, which creates a physically homogeneous form of waste. The definition and advantages of encapsulation are as follows.

- (Definition) The process of surrounding discrete items of radioactive waste, such as sealed sources or cartridge filters, in a non-radioactive binding matrix, where the activity remains within the dimensions of the original item of waste.
- (Advantages) It can mitigate waste dispersion to the general environment after disposal, provide additional shielding to limit external radiation, and satisfy the stability requirements of 10CFR61.56(b) [9].

What performance was given to the encapsulation that satisfied the stability requirements could be found in the NRC technical evaluation report on the Class B, C cartridge filter encapsulation of Diversified Technologies. The conceptual diagram for encapsulation is shown in Fig. 1. To meet structural stability, the waste was surrounded by a 10 cm thickness concrete lining, and internal voids were evaluated [10]. In addition, the requirements for encapsulation were confirmed in WAC of Energy Solutions' Clive disposal facility. Liquid cartridge filters and other acceptable discrete items may be encapsulated, and discrete items must be encapsulated with a minimum 1-inch-thick lining on all sides within the packaging container. Fig. 2 shows a conceptual diagram of discrete item encapsulation [11]. Energy Solutions, which also performs treatment for cartridge filters, a representative heterogeneous waste, crushes and encapsulates Class A waste and encapsulates Class B waste in its original form, as shown in Figs. 3 and 4.

2.3 France (L'Aube Facility)

To ensure the safety of a disposal facility, France assigns performance to a waste package in three categories: mechanical aspect, containment aspect, and sustainability aspect. In addition, to meet the above performance, France divides a package into three components: waste matrix, internal cementitious lining-layer, and concrete container, and allocates performance to each component by selectively combining them. Fig. 5 shows a cross-section of an immobilized heterogeneous waste package (water filters) in France [12, 13].

First, the mechanical aspect is divided into the mechanical strength of the package and the mechanical performance requirements of each component. Basically, the mechanical strength given to the package was derived by considering the maximum load applied on the package

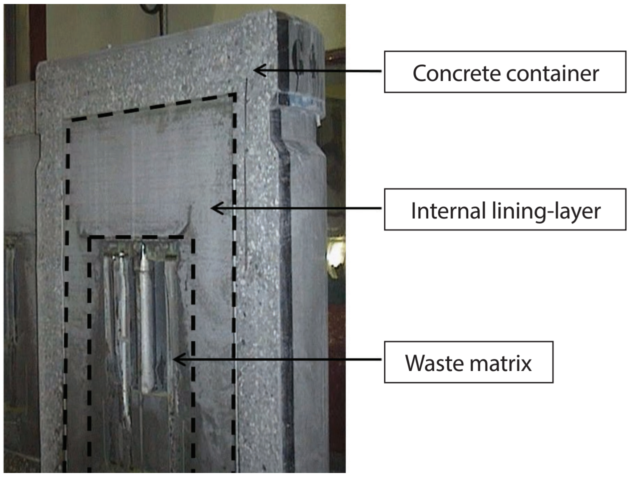

Fig. 5. Cross-section of an immobilized heterogeneous waste package.

during the lifetime of the disposal facility. French fundamental safety rules (RFS III.2.e) stipulate the mechanical strength limits of packages as shown in Table 2. To meet the strength limits set out in RFS III.2.e, ANDRA, a French waste management agency, has established various requirements for each component, including compressive strength, tensile strength, crack limit, thickness, porosity, density, thermal cycle, and irradiation. Here, in the case of a homogeneous waste matrix, the compressive strength of the matrix is applied, and in the case of a heterogeneous matrix, the compressive strength of the injection material is applied.

Table 2. Mechanical strength limits

Contents	Vertical strain rate	Compressive strength
Value	< 3%	> 0.35 MPa

Second, limits on containment performance for package are also specified in RFS III.2.e. The limits are as shown in Table 3, and the values are expressed as the annual fraction of activity released. Moreover, RFS III.2.e allows satisfying the performance limits by combining the performance of two or more components. ANDRA provides various requirements for each component of a package that can meet containment limits. Concrete containers have requirements such as porosity, thickness, and effective tritiated water diffusion coefficient, and the internal lining layer has requirements such as porosity, minimum value of thickness, and limits on the effective tritiated water diffusion coefficient. In the case of waste matrix, containment performance is assigned only to the homogeneous matrix and not to the heterogeneous matrix. ANDRA presents effective diffusion coefficient limits for each nuclide in a homogeneous matrix. The performance of a homogeneous matrix is determined based on the leaching rate.

Third, sustainability aspects are considered to ensure that the package maintains its mechanical strength and containment performance throughout the lifetime of the disposal facility. ANDRA considers the performance of concrete as a critical factor and sets the minimum degradable thickness requirements for concrete containers by evaluating the impact of environmental factors such as hydrolysis and corrosion of steel caused by chloride ions.

Table 3. Containment performance limits

Contents	Nuclide	Specific activity	Limit
Homogeneous package with containment performance	Each beta-gamma nuclide except tritium	$3.7 < SA < 37\ MBq \cdot kg^{-1}$	1.0×10^{-1} / yr
		$37\ MBq \cdot kg^{-1} < SA < 370\ MBq \cdot kg^{-1}$	2.8×10^{-2} / yr
		$SA > 370\ MBq \cdot kg^{-1}$	7.3×10^{-3} / yr
	Each alpha nuclide	-	2.0×10^{-4} / yr
Heterogeneous package with containment performance	Each beta-gamma nuclide except tritium	-	7.3×10^{-3} / yr
All package with containment performance	Tritium	-	5.0×10^{-2} / yr

Table 4. Specific activity limit

Contents	Target nuclide	Specific activity limit
Level 1	Total alpha	1.85×10^{2} Bq·g^{-1}
	Beta-gamma emitters with half-life > 5 y (tritium excepted) by isotope	1.85×10^{4} Bq·g^{-1}
	Total Beta-gamma activity for isotopes with half-life > 5 y	7.40×10^{4} Bq·g^{-1}
	Tritium	7.40×10^{3} Bq·g^{-1}
Level 2	Total alpha	3.70×10^{3} Bq·g^{-1}
	^{60}Co, ^{90}Sr, ^{137}Cs	3.70×10^{5} Bq·g^{-1}

Table 5. Performance requirements

Contents	Solidified homogeneous waste (Resins, sludge, evaporator concentrates)	Blocked waste (Cartridge filters, dried sludge, ashes)
Level 1	• Mechanical limits (Compression, tensile. Before and after immersion)	• Thickness of the mortar/concrete sleeve • Mechanical limits (compression) of the sleeve
Level 2	• Strongest mechanical limits (Compression, tensile. Before and after immersion, thermal cycles) • Leaching limits	• Thickness of the mortar/concrete blocking shield • Strongest mechanical limits (compression, and thermal cycles of the shield) • Diffusion limits

2.4 Spain (El Cabril Facility)

Unlike France, Spain places packages into concrete containers and disposes of them in concrete vaults. In addition, Spain classifies waste into level 1 and level 2 according to the specific activity limit of each nuclide as shown in Table 4 and imposes different performance requirements for each level as shown in Table 5. In terms of general waste classification, level 1 and level 2 can be roughly classified as low-level waste and intermediate-level waste, respectively [14, 15].

3. Proposal

Table 6 summarizes the immobilization performance requirements for heterogeneous waste in Korea and the three countries investigated. Similarly to the United States, Korea immobilizes only waste that exceeds a certain specific activity, but France and Spain immobilize all waste. In addition, with regard to performance requirements of immobilization, Korea only has safety of the immobilization material, while other countries have various requirements such as compressive strength, thickness, and tritium diffusion coefficient. On the other hand, due to its heterogeneous characteristics, all countries do not assign performance to the waste matrix itself, but to the internal lining and/or concrete container.

Based on the overseas application cases, immobilization performance requirements for heterogeneous waste applicable to Korea are proposed. According to the NSSC notice, since immobilization is a part of solidification, it must have performance such as restriction on the release of nuclides and structural stability. To correspond to these provisions, this study proposes a method applicable to Korea in which the immobilization performance for heterogeneous waste is achieved through internal lining as shown in Fig. 6. The performance requirements of this internal lining

Table 6. Summary of the immobilization performance requirements

Contents	Korea	United State	France	Spain
Criteria	Heterogeneous wastes exceeding a certain specific activity shall be immobilized.	All class B or C waste must meet the minimum and stability requirements in 10CFR61.55.	All waste is immobilized. Performance requirements depends on specific activity.	All waste is immobilized. Performance requirements depends on specific activity.
Method	Immobilization and/or HIC	Encapsulation and/or HIC	Internal lining and/or concrete container	Internal lining and disposal container
Performance requirements	Immobilization • Material safety	Encapsulation • Must demonstrate that stability is satisfied. • Compressive strength • Thickness • Porosity	Internal lining • Material safety • Compressive strength • Thickness • Tritiated water diffusion coefficient	Internal lining • Material safety • Compressive strength • Thickness • Diffusion limit

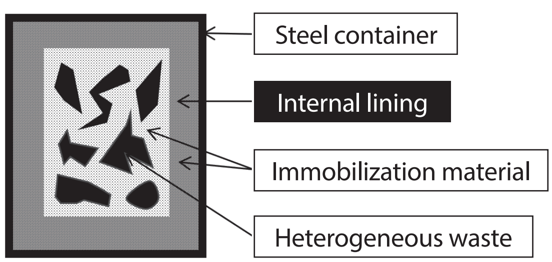

Fig. 6. Heterogeneous waste immobilized using internal lining.

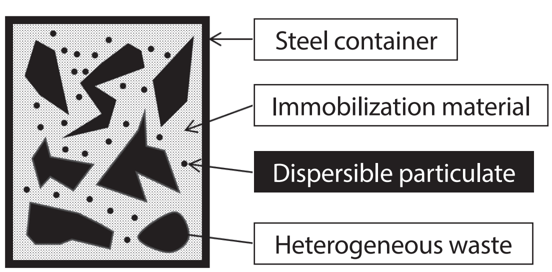

Fig. 7. Heterogeneous waste with dispersible particulates immobilized.

include compressive strength, thickness, and tritiated water diffusion coefficient. If the performance is achieved with HIC (or a concrete container with containment function), it can be immobilized without an internal lining. And it can be immobilized using a combination of internal lining and HIC (or a concrete container with containment function). Quantitative values for the above requirements of each components need to be derived through quantitative assessment based on the characteristics of domestic heterogeneous waste and disposal facilities. For reference, the immobilization method proposed in this study can be distinguished from the immobilization method without internal lining for heterogeneous waste containing dispersible particulates, as shown in Fig. 7, according to Korea's WAC. However, if the specific activity of this heterogeneous waste exceeds 74,000 $Bg \cdot g^{-1}$, the immobilization method proposed in this study should be applied.

4. Conclusions

This study reviewed domestic laws, WAC, and IAEA technical publications, and investigated cases of immobilization application to heterogeneous waste in three foreign countries such as the United States, France, and Spain, and proposed immobilization performance requirements for heterogeneous waste applicable to Korea through comparison with their cases. Currently, in Korea, there is no clear physical form for immobilization, and the only performance requirement is the safety of the immobilization material, it is necessary to specify the immobilization. On the other hand, in overseas cases, the immobilization was applied in a physical form with an internal lining, and immobilization performance requirements were imposed on the internal lining such as compressive strength, thickness, and tritiated water diffusion coefficient. The methods of immobilization by combining internal lining and HIC (or a concrete container with containment function) were also used. But they did not impose performance on the waste matrix due to its heterogeneous nature. Based on the above overseas cases, physical form for immobilization with internal lining, and performance requirements such as compressive strength, thickness, diffusion limit were proposed as a method applicable to Korea.

This study will improve the understanding of stakeholders such as waste generators and repository operators by specifying the immobilization type and performance requirements for domestic heterogeneous waste. Furthermore, it is expected to contribute to improving the safety of disposal facilities by providing performance to immobilized heterogeneous waste packages.

Further research should be conducted in the future to derive quantitative values for the immobilization performance requirements proposed in this study through realistic and quantitative assessments using domestic heterogeneous waste and disposal facility characteristics.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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