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고준위 원자핵폐기물 처분용기의 선형정적 구조해석
Linear Static Structural Analysis of Spent Nuclear Fuel Disposal Canister

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ABSTRACT

This paper presents the results of a structural analysis to determine design variables such as the inner basket array type, and thicknesses of the outer shell and the lid and bottom of a spent nuclear fuel disposal canister. The canister construction type introduced here is a solid structure with a cast iron insert and a corrosion resistant overpack, which is designed for the spent nuclear fuel disposal in a deep repository in the crystalline bedrock, entailing an evenly distributed load of hydrostatic pressure from the groundwater and large swelling pressure from the bentonite buffer. Hence, the canister must be designed to withstand these large pressure loads. Many design variables may affect the structural strength of the canister. In this study, among those variables, the array type of inner baskets and thicknesses of outer shell and lid and bottom are attempted to be determined through a linear static structural analysis. Canister types studied here are one for the pressurized water reactor (PWR) fuel and another for the Canadian deuterium and uranium reactor (CANDU) fuel.

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1. Introduction

This report constitutes a summary of research and development for the design and dimensioning of a canister for spent nuclear fuel disposal. Since the spent nuclear fuel disposal emits heat and much radiation, its careful treatment is required. For this purpose, a long term (usually 10,000 years) safe repository for the spent fuel disposal should be secured. Once the canister is disposed and surrounded by the bentonite buffer in a mined underground facility located deep underground, below the surface of a crystalline bedrock, during the water saturation phase after closure it will experience large loads. Hence, much work(2) (9) concerning this matter has been done so far (Anttila, 1996 ; Anttila, 1999 ; Auerkar et al., 1997 ; Raiko et al., 1992 ; Raiko et al., 1996 ; Salo et al., 1990 ; Werme et al., 1995). The canister construction type introduced here is a solid structure with a cast iron insert and a corrosion resistant overpack, which is designed for spent nuclear fuel disposal in an underground repository in the crystalline bedrock, causing an evenly distributed load of hydrostatic pressure from groundwaer and swelling pressure from the bentonite buffer. The canister strength will be demonstrated also in non-symmetric cases of the bentonite swelling without groundwater pressure.

In this work, two canister types are studied: one for the PWR fuel and another for the CANDU fuel. The canister consists of two major components: massive cast iron insert and the corrosion resistant outer shell of copper or high Ni alloy, etc.. The insert provides mechanical strength and radiation shielding, and keeps the fuel assemblies in a fixed configuration. Actually, this cast iron insert withstands the external loads mentioned above. Unless the canister structure is mechanically strong enough for the external loads, structural collapse of the canister may occur. This is not desirable for the

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long term repository of spent fuel disposal. Hence, the mechanical structural strength of the canister is very critical to the design of the canister. To secure this structural strength, a proper structural analysis is required for the external loads mentioned above. The dimensions of the cast iron insert mainly affect the structural strength, and the outer shell, lid and bottom may affect the strength additionally. Hence, to determine the structural strength of the canister, proper dimensions of the canister such as the diameter and length of the cast iron insert, thicknesses of the outer shell and the lid and bottom must be decided. Also the number and position array of inner fuel baskets must be decided, because all of these design variables affect the structural strength of the canister. Hence, an appropriate mechanical structural analysis should be done to determine these design variables.

In this work, the array type of inner spent nuclear fuel baskets is determined. Thicknesses of the outer shell, and the lid and bottom are also attempted to be determined using the linear static structural analysis. In this computation, the external bentonite swelling load is assumed to be 1,500 Pa which gives accurate small deformations for the determination of desired design variables.

2. Formulation of Structural Analysis Problem

2.1 Canister geometry in concept design

For the structural analysis, the geometry of the canister should be defined. The dimensions of the canister are given as depicted in Fig. 1 in this work. Throughout the analysis, the length of the canister and the diameter of the cast insert are kept as 498 cm and 108 cm respectively in Fig.1, but thicknesses of the outer shell, the lid and bottom will vary until the structural strength is satisfied for the applied loads. Also the positions of inner fuel baskets will vary until the structural strength is satisfied, but the number of inner fuel baskets of the canister for the PWR fuel will be fixed as four and that for the CANDU fuel will be fixed as thirty seven.

2.2 Material properties

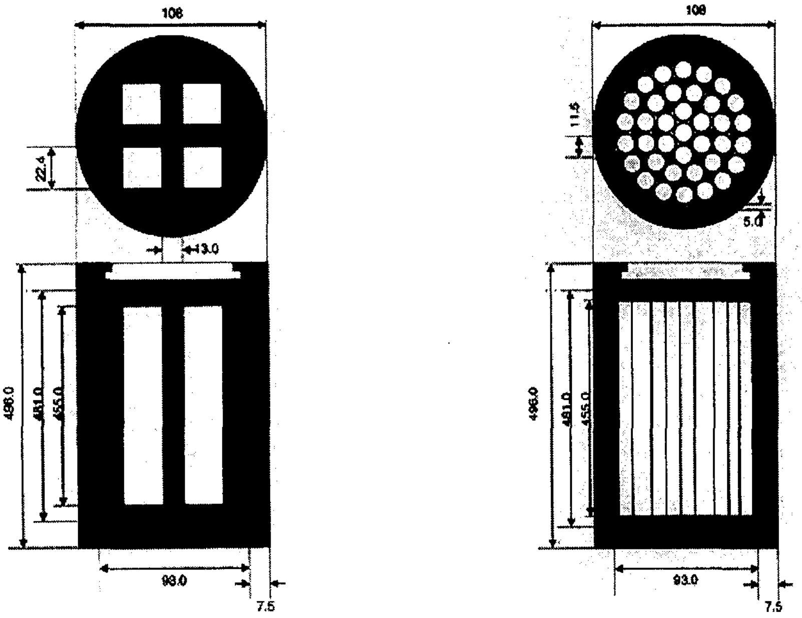
The materials of the outer shell and lid and bottom may be copper (Cu), high Ni alloy, or stainless steel, and the material of the canister insert is the cast iron. Properties and their values at the room temperature (20℃) of these materials are listed in Table 1.

2.3 Array variations of basket positions

For the canister with a fixed diameter of 108 cm, the following variation of the inner basket positions will be considered in this work. For the canister for PWR fuel, three types of inner basket positions are considered as depicted in Fig. 2. The number of inner baskets is fixed as four. Due to the symmetry position of inner baskets, the variation does not change for a fixed number of inner baskets for the canister for the CANDU fuel. And the number of inner baskets is assumed to be thirty seven here.

2.4 Constraint conditions

Constraint conditions are two types. One is the displacement boundary condition for the support ends of the canister. Another is the external load condition for the various loading cases mentioned in the previous section. The boundary condition is for displacements at support ends. The support end may be fixed or simply supported, etc.. The hydrostatic pressure loads are always evenly distributed, but the swelling pressure of bentonite may have some disturbances, especially in the early years after the sealing of the repository when the bentonite starts to wet. These types of special loads are depicted in Fig. 3, cases 1 to 3. The bentonite swelling pressure is assumed to be unevenly distributed also in the saturated condition, cases 4 to 5 in Fig. 3. These kinds of swelling pressure conditions may be due to a tilted canister in the disposal hole or heterogeneous rock properties, or a banana-like curved disposal hole. The structural analysis result may be different according to the vertical and horizontal position changes of canister.

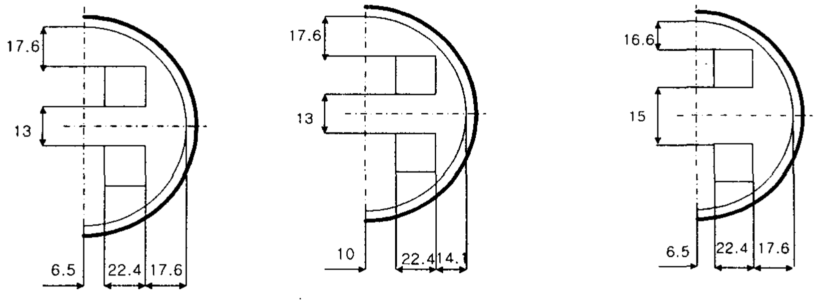


PWR CANDU

Fig. 1 Canister geometry in concept design (unit: cm)

Table 1 Material properties

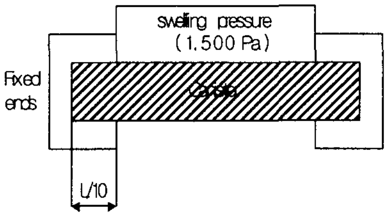
Material / Properties	Cast iron	Copper	High Ni alloy	Stainless steel
Young's modulus E (GPa)	126.5	117	210	195
Poisson's ratio ν	0.25	0.3	0.31	0.3
Thermal expansion coefficient α (10E-6/℃)	10.8	16.5	13	17
Mass density ρ (kg/m^3)	7,400	8,900	8,800	7,857
Yield stress σ_y (MPa)	200	64	624	700
Ultimate stress σ_u(MPa)	1,400	200	760	1,000
Thermal conductivity k(W/mK)	52	386	26	31
Specific heat C (kcal/kg ℃)	420	410	460	460



Type 1 Type 2 Type 3

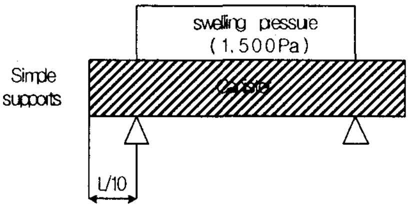
Fig. 2 Array variation of inner basket positions for PWR and CANDU type canister structures

Underground water saturation
(swelling pressure)



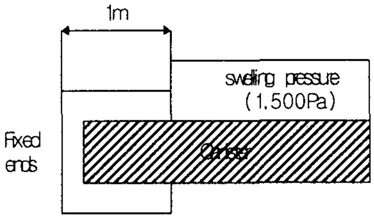
Case 1

Underground water saturation
(swelling pressure)



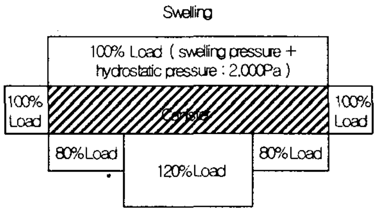
Case 2

Underground water saturation
(swelling pressure)



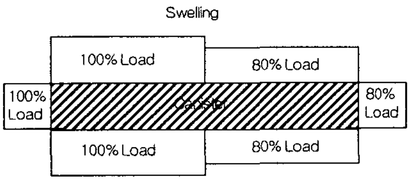
Case 3

After water saturation
(hydrostatic + swelling pressure)



Case 4

After water saturation
(hydrostatic + swelling pressure)



Case 5

Fig. 3 Constraint conditions for boundary and external force

3. Finite Element Analysis

The finite element analysis method is used for the linear static structural analysis. For the analysis, a finite element analysis code, "NISA", is used.

3.1 Solid modeling

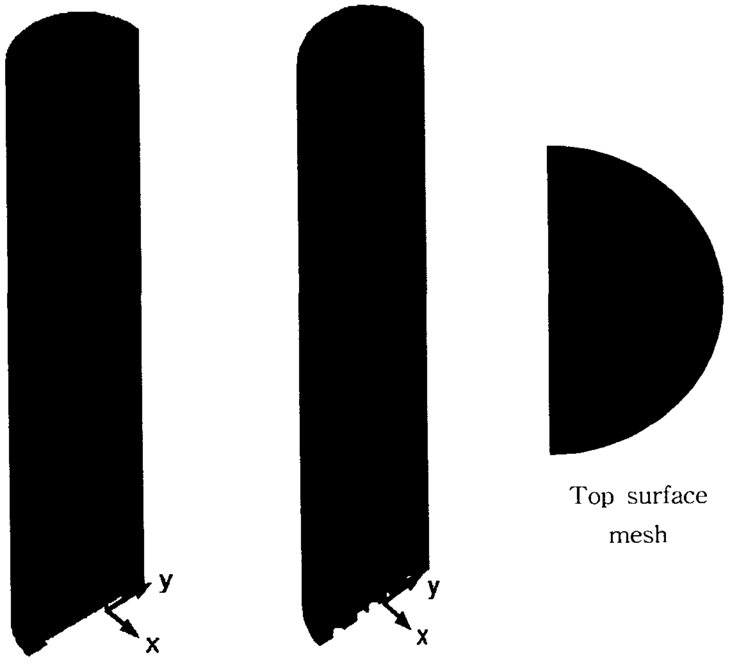
The spent nuclear fuel is a ash-like material, and so its rigidity is negligible compared with that of cast iron insert. Hence, the bundle of spent fuel inside inner baskets is neglected in the structural analysis of canister even for the more safe design variable values.

3.2 Finite element modeling

In the finite element mesh generation, hexagonal eight node cubic solid elements are usually used for both canisters of the PWR fuel and the CANDU fuel. The finite element mesh of canister for the CANDU fuel is shown in Fig. 4. The total number of elements is 119,344 and total number of nodes is 137,372 for the CANDU type structure.

3.3 Boundary and load conditions

Proper displacement boundary conditions and load conditions are used for the finite element analysis for the load case 1 to 5, where the canister structure is under various swelling pressure conditions with proper end conditions. That is, u_x, u_y, u_z are constrained at ends in various ways according to various load conditions(load cases 1 to 5). Also u_x, u_y, u_z are constrained on some symmetry planes.



Top surface mesh

Whole mesh

Cast iron insert mesh

Fig. 4 Finite element mesh of the canister structure for CANDU fuel

4. Analysis Results and Discussions

Using NISA, a linear static structural analysis is conducted for the concept design structure of canister in Fig. 1. The analysis results and discussions are as follows.

4.1 Structural analysis results for array variation of inner basket positions

The structural analysis results are shown in Table 2 for three array types of the inner spent fuel baskets. The canister structure with the array type 1 is structurally stronger than others in Table 2.

Table 2 Structural analysis results for the array type variation (case 1, PWR canister)

Array Type Stress, Deflection	Type 1	Type 2	Type 3
Maximum von-Mises stress (MPa) inside cast insert	7.460018	7.497296	7.720148
Maximum deflection (cm)	0.000936	0.001000	0.001080

4.2 Structural analysis results for outer shell thickness variation

The structural analysis results for variations of outer shell thickness are shown in Tables 3. The outer shell thickness varies as 5 cm, 7.5 cm, 10 cm. The analysis results show that the thinner shell structure *compared with the diameter of the cast iron insert becomes structurally stronger.*

Hence, the magnitude of thickness of the outer shell may not be determined explicitly. Other analysis such as a nonlinear structural analysis may be required to determine the outer shell thickness. Also the chemical analysis for corrosion may be required to determine the outer shell thickness (Ahonen, 1995).

Table 3 Structural analysis results for the outer shell thickness variation (case 1)

Shell thickness Stress, Deflection		5 cm	7.5 cm	10 cm
Maximum von-Mises stress (MPa) inside cast insert	PWR canister	7.178212	7.497296	7.665123
	CANDU canister	8.774426	9.323941	9.965812
Maximum deflection (cm)	PWR canister	0.000871	0.000936	0.000969
	CANDU canister	0.000884	0.000955	0.000986

4.3 Structural analysis results for lid and bottom thickness variation

The structural analysis for the variation of lid and bottom thickness is done for type 1 array canister structure. The structural analysis results are shown in Tables 4. The results show that the canister structure with lid and bottom of 2.5 cm thickness is structurally stronger than other cases when the canister diameter is 108 cm and the canister length is 496 cm.

Table 4 Structural analysis results for lid and bottom thickness variations (case 1)

Lid and bottom thickness Stress, Deflection		1.7 cm	2.5 cm	3.3 cm
Maximum von-Mises stress (MPa) inside cast insert	PWR canister	7.865002	7.178212	7.866314
	CANDU canister	12.352690	8.774426	12.375630
Maximum deflection (cm)	PWR canister	0.000889	0.000871	0.000889
	CANDU canister	0.000914	0.000884	0.000916

4.4 Structural analysis results for outer shell material variation

The structural analysis for the outer shell material variation is done for the canister structure with type 1 array basket position, the outer shell thickness of 5 cm and the lid and bottom thickness of 2.5 cm. The structural analysis results are shown in Tables 5. As expected, results show that the canister structure with the outer shell of high Ni alloy is structurally stronger than other cases.

Table 5 Structural analysis results for the outer shell material variation (case 1)

Stress, Deflection \ Shell material		High Ni Alloy	Copper (Cu)	Stainless Steel
Maximum von-Mises stress(MPa) inside cast insert	PWR canister	7.421953	8.774426	7.574693
	CANDU canister	6.176806	7.178212	6.266034
Maximum deflection (cm)	PWR canister	0.000745	0.000884	0.000769
	CANDU canister	0.000719	0.000871	0.000726

4.5 Structural analysis results for swelling cases (Cases 4 and 5)

The stresses and deformations for swelling cases (cases 4 and 5) are smaller than the unswelling cases (cases 1-3) as shown in Table 6. However, some stress concentration phenomenon occurs around the basket for swelling cases as shown in Fig. 5. And these results also show that the vertically positioned canister in the repository is structurally stronger than the horizontally positioned canister.

Table 6 Synthesis of the structural analysis results for each case (case 1~ case 5)

Stress, Deflection \ Cases		Case 1		Case 2		Case 3		Case 4	Case 5
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical		
Maximum von Mises stress(MPa) inside cast insert	PWR canister	6.176806	4.256125	10.686890	10.236590	7.646189	4.503885	1.940490	1.942837
	CANDU canister	7.421953	6.892543	13.124580	6.452894	36.80755	24.26597	2.456235	2.564325
Maximum deflection (cm)	PWR canister	0.000719	0.000711	0.002060	0.00202	0.021300	0.007790	0.000129	0.000129
	CANDU canister	0.000745	0.000714	0.014800	0.003960	0.206000	0.125000	0.000281	0.000298

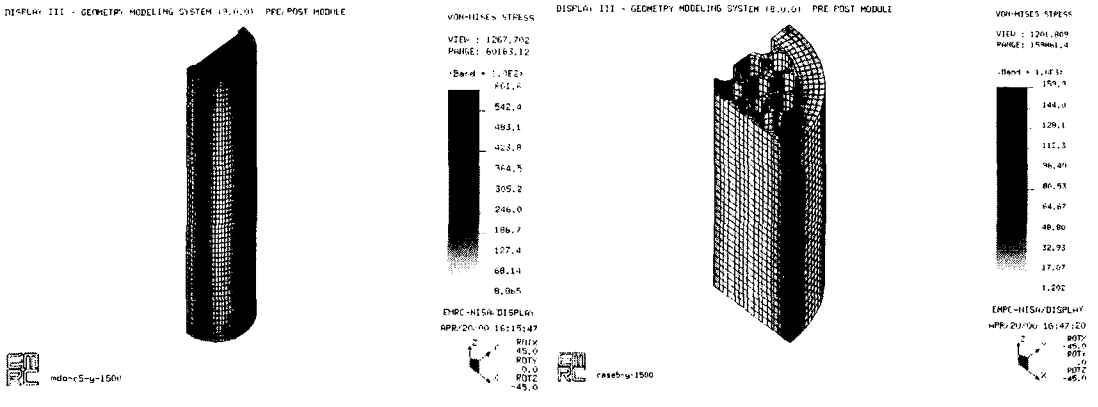


Fig. 5 Stress contour for the canister structure (case 5, CANDU canister)

5. Conclusions

In this work, a linear static structural analysis for the canister structure is done using the finite element analysis code, "NISA", in order to determine the proper design variables such as the array type of inner baskets, thicknesses of the outer shell and the lid and bottom versus the diameter of canister, and the material type of the outer shell. The analysis is a linear static one for the concept design structure of canister in Fig. 1. In this analysis, dimensions of the canister structure are fixed as in Fig. 1 and the bentonite swelling pressure load is assumed to be 1,500 Pa. The number of inner baskets is fixed as four in the canister for the PWR fuel and the number of inner baskets in the canister for the CANDU fuel is assumed to be thirty seven. Reviewing the analysis results, we may draw the following conclusions.

The symmetrical array type of inner baskets provides good structural strength. Especially, type 1 array in Fig. 2 is good for the structural strength of the canister for the PWR fuel.

Canister structures for both the PWR and CANDU fuels are structurally stronger as the outer shell becomes thinner compared with the diameter and the length of the cast iron insert.

Canister structures for both the PWR and CANDU fuels are structurally stronger than others when the thickness of the lid and bottom is 2.5 cm for the canister diameter of 108 cm and the canister length of 496 cm.

Canister structures for both the PWR and CANDU fuels with the high Ni alloy outer shell are structurally stronger than other cases.

Canister structures fixed at both ends (clamped ends) in the repository (see the load case 1 in Fig. 3) are structurally stronger compared with the other cases (cases 2, 3)

The canister structure in vertical direction in the repository is structurally stronger than the horizontally positioned structure.

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