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Structural Analysis for the Determination of Design Variables of Spent Nuclear Fuel Disposal Canister

Youngjoo Kwon*†, Shinuk Kang
Department of Mechano-Informatics & Design Engineering, Hongik University
Jongwon Choi, Chulhyung Kang
Korea Atomic Energy Research Institute

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 high swelling pressure from the bentonite buffer. Hence, the canister must be designed to withstand these high 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 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.

Key Words : Spent Nuclear Fuel Disposal Canister, Design Variables, Inner Basket Array Type, Deep Repository, Hydrostatic Pressure, Bentonite Buffer, Swelling Pressure

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. Usually this repository is expected to be located deep underground. 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 high loads. Hence, much work 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). But few domestic works concerning this matter have been conducted except for other topics (Jo et al., 1991 ; Kim et al., 1994 ; Kwak et al., 2000).

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 groundwater 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.

† First Author
* Corresponding Author,
E-mail : yjkwon@wow.hongik.ac.kr
TEL : +82-41-860-2484 ; **FAX** : +82-41-866-6598
Department of Mechano-Informatics & Design Engineering, Hongik University Jochiwon-eup, Yeonki-gun, Chungnam, 339-701, Korea. (Manuscript **Recevied** July 26, 2000; **Revised** November 30, 2000)

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 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 castiron 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.

Actually, there exists small gap between the cast iron insert and the outer shell (or the lid and bottom), but in this computation it is assumed that there is no gap between the cast iron insert and the outer shell (or the lid and bottom), i. e, they stick to each other. The validity of this assumption is that the gap decreases the magnitude of a portion of the external load transmitted to the cast iron insert and so higher load is exerted to the cast iron insert than in the case of nonzero gap.

For more accurate data for the design of canister, other analysis techniques are required: namely, fracture mechanics which treats the case where there exist flaws or voids inside the cast iron insert, a structural analysis for the sudden rock shear load (Borgessen, 1992), a thermal analysis for the high temperature of inner fuel baskets, a vibration structural analysis for sudden earthquake, and a creep analysis for long term deposition. However, these analyses are not conducted in this computation. Hence, only the linear static structural analysis for the canister structure is conducted in this work to determine the design variables mentioned above.

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

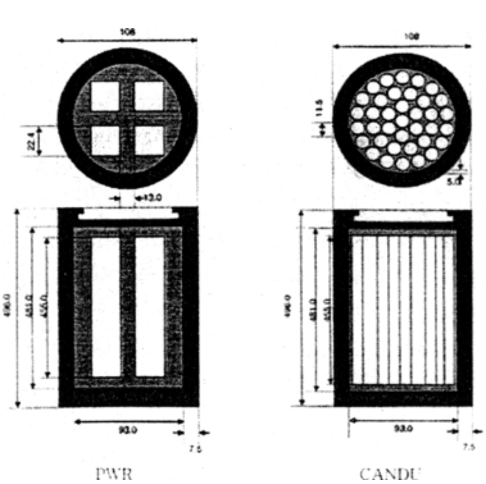

Fig. 1 Canister geometry in concept design

Table 1 Material properties

Properties \ Material	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

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 baket 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.

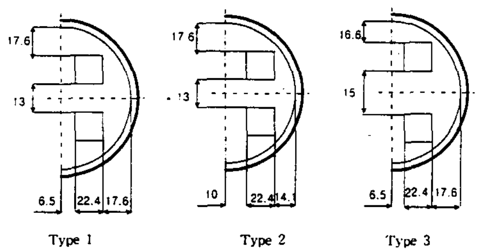

Fig. 2 Array variation of inner basket positions in the canister structure for PWR fuel

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.. In this linear static analysis, two types of boundary conditions below are considered.

- Fixed end boundary condition
- Simply supported end boundary condition

The canister can be settled in various ways in the crystalline bedrock. According to these settle-

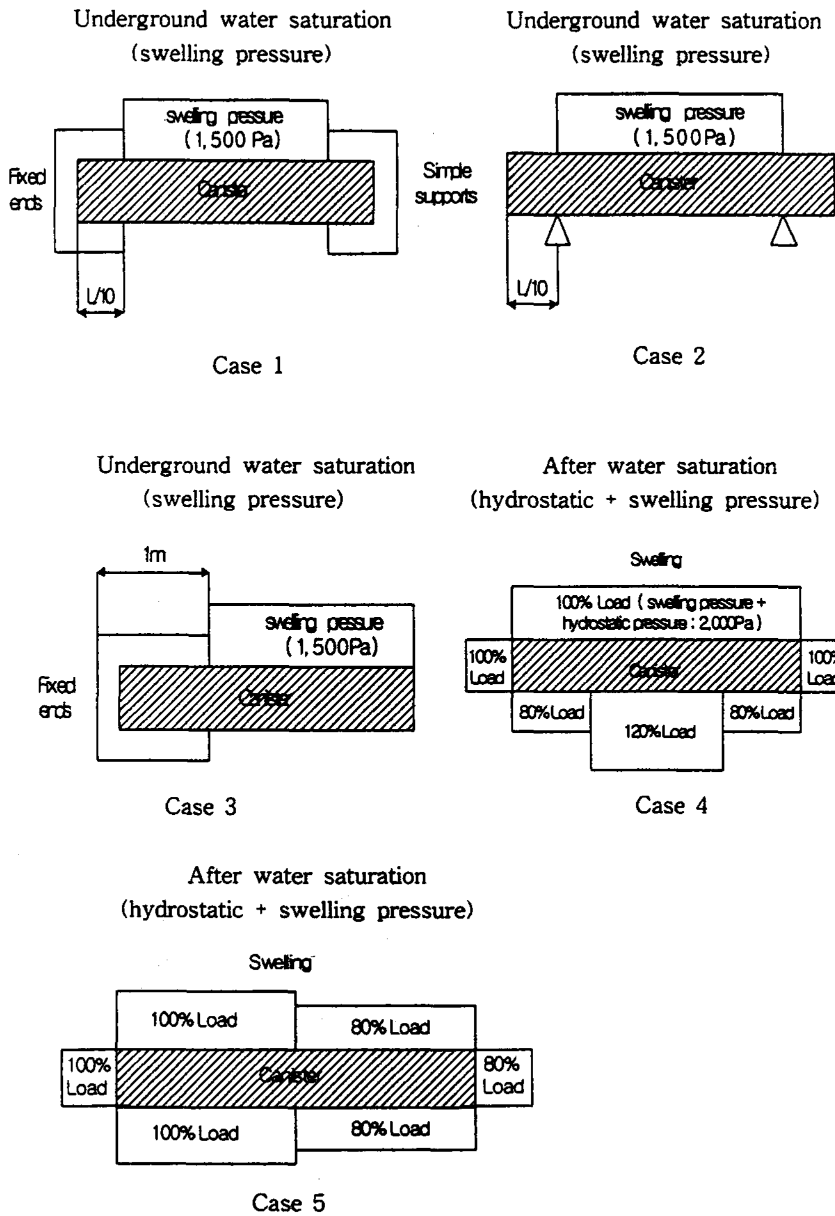

Fig. 3 Constraint conditions for boundary and external force

ment methods, the boundary conditions at the support ends are determined. Three possible settlement methods (Case 1-Case 3) are shown in Fig. 3. The purpose of this work is to determine the best one among those settlement methods through the structural analysis.

There are six load cases according to the loading conditions mentioned in the previous section. These load cases are typically used for the structural analysis of spent fuel canister (H. Raiko et al., 1996; H. Raiko et al., 1999). 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.

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 an 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

Following displacement boundary conditions and load conditions are used for the finite element analysis for the load case 1, where the canister structure is under the swelling pressure with fixed ends.

- Displacements u_x, u_y, u_z are constrained at both fixed ends.
- Displacement u_x is constrained on the symmetry plane $(x=0)$.
- Uniform pressure is applied normally on the upper half outer surface.

Following displacement boundary conditions and load conditions are used for the finite element analysis for the load case 2, where the canister structure is under the swelling pressure with simply supported ends.

- Displacements u_x, u_y, are constrained on the lower half positions at locations L/10 from both ends.
- u_z is constrained on the symmetry plane $(z=L/2)$. This constraint is required to prevent the rigid body translation in the z-direction.
- Displacement u_x is constrained on the symmetry plane $(x=0)$.
- Uniform pressure is applied normally on the upper half outer surface.

Following displacement boundary conditions and load conditions are used for the finite element analysis for the load case 3, where the canister structure is under the swelling pressure with one fixed end.

- Displacements u_x, u_y, u_z are constrained at one end.
- Displacement u_x is constrained on the symmetry plane $(x=0)$.
- Uniform pressure is applied normally on the upper half outer surface.

Following displacement boundary conditions and load conditions are used for the finite element analysis for the load case 4, where the canister structure is under the hydrostatic and swelling pressures.

- Displacement u_x is constrained at the center points of both end surfaces.
- Displacement u_z is constrained at the center point of the symmetry plane. This constraint is required to prevent the rigid body translation in the z-direction.
- Displacement u_x is constrained on the symmetry plane $(x=0)$.
- Pressure is applied normally on the whole outer surface unevenly.

Following displacement boundary conditions and load conditions are used for the finite element analysis for the load case 5, where canister structure is under the hydrostatic and swelling pres-

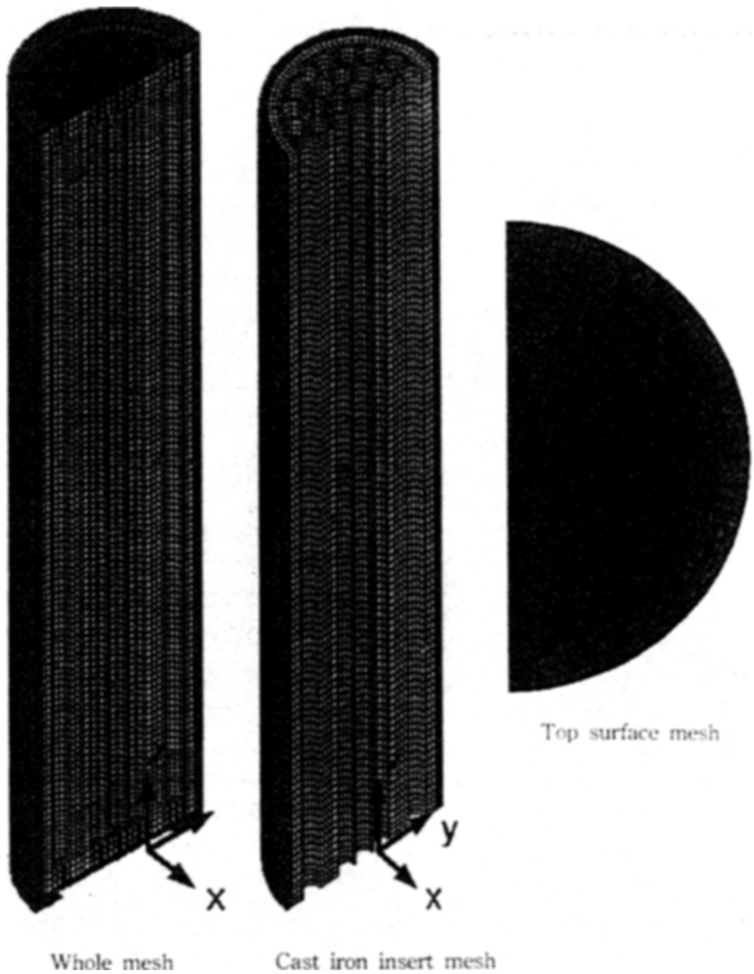

Fig. 4 Finite element mesh of the canister structure for CANDU fuel

sures.

- Displacement u_y is constrained at the center points of both end surfaces.
- Displacement u_z is constrained at the center point of the symmetry plane. This constraint is required to prevent the rigid body translation in the z-direction.
- Displacement u_x is constrained on the symmetry plane $(x=0)$.
- Pressure is applied normally on the whole outer surface unevenly.

3.4 Analysis

In this study, the linear static analysis is conducted to determine the design variables such as the array type of inner basket positions, thickness of the outer shell, thicknesses of the lid and bottom, and material type of the outer shell, under the assumption that only small structural deformations occur for the applied loads mentioned in the previous section.

The bentonite swelling external pressure of 1, 500 Pa mentioned in the previous section is assumed to be exerted to the concept structure of canister in Fig. 1 for this linear structural analysis. This external load may give accurate small deformation results which can be used to determine the design variables listed above. Throughout the analysis, the gap between the cast iron insert and the outer shell/ the lid and bottom is neglected, That is, it is assumed that they stick to each other. In this analysis the dimension such as the diameter and length of the cast iron insert are fixed as in Fig. 1.

4. Analysis Results and Discussions

Using NISA, a linear 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.

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 and 4. 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

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

Stress, Deflection	Array Type	Type 1	Type 2	Type 3
Maximum von-Mises stress (MPa)	Shell (Cu)	9.475851	9.994530	11.230030
	Cast iron	7.460018	7.497296	7.720148
	Lid (Cu)	0.681958	1.005967	1.618002
	Bottom (Cu)	1.028118	1.069605	1.719983
Maximum deflection (cm)		0.000936	0.001000	0.001080

Table 3 Structural analysis results for the outer shell thickness variation (Case 1, PWR canister)

Stress, Deflection	Shell thickness	5 cm	7.5 cm	10 cm
Maximum von-Mises stress (MPa)	Shell (Cu)	9.595978	9.475851	10.493190
	Cast iron	7.178212	7.497296	7.665123
	Lid (Cu)	1.426798	0.681958	1.326875
	Bottom (Cu)	1.055310	1.028118	1.198713
Maximum deflection (cm)		0.000871	0.000936	0.000969

Table 4 Structural analysis results for the outer shell thickness variation (Case 1, CANDU canister)

Stress, Deflection	Shell thickness	5 cm	7.5 cm	10 cm
Maximum von-Mises stress (MPa)	Shell (Cu)	11.712480	12.461950	12.785930
	Cast iron	8.774426	9.323941	9.965812
	Lid (Cu)	0.741009	0.785846	0.795125
	Bottom (Cu)	0.724522	0.764919	0.815122
Maximum deflection (cm)		0.000884	0.000955	0.000986

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).

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 5 and 6. 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.

The stress distribution contours and deformation shape for canister structure from this static analysis are shown in Fig. 5.

4.4 Structural analysis results for outer shell material variation

The structural analysis for the outer shell material variation is done for the canister struc-

Table 5 Structural analysis results for lid and bottom thickness variations (Case 1, PWR canister)

Stress, Deflection \ Lid and bottom thickness		1.7 cm	2.0 cm	2.5 cm	3.0 cm	3.3 cm
Maximum von-Mises stress (MPa)	Shell (Cu)	8.079372	9.596070	9.595978	9.597229	8.080856
	Cast iron	7.865002	7.181355	7.178212	7.181279	7.866314
	Lid (Cu)	0.885768	1.427531	1.426798	1.424962	0.903521
	Bottom (Cu)	0.699263	1.022303	1.055310	1.017725	0.726409
Maximum deflection (cm)		0.000889	0.000887	0.000871	0.000887	0.000889

Table 6 Structural analysis results for lid and bottom thickness variation (Case 1, CANDU canister)

Stress, Deflection \ Lid and bottom thickness		1.7 cm	2.5 cm	3.3 cm
Maximum von-Mises stress (MPa)	Shell (Cu)	13.433710	11.712480	13.652180
	Cast iron	12.352690	8.774426	12.375630
	Lid (Cu)	0.787181	0.741009	0.795684
	Bottom (Cu)	0.766914	0.724522	0.768547
Maximum deflection (cm)		0.000914	0.000884	0.000916

Table 7 Structural analysis results for the outer shell material variation (Case 1, PWR canister)

Stress, Deflection \ Shell material		Hig Ni Alloy	Copper (Cu)	Stainless Steel
Maximum von-Mises stress (MPa)	Shell	11.771960	9.595978	12.334030
	Cast iron	6.176806	7.178212	6.266034
	Lid (Cu)	0.742751	1.426798	0.717065
	Bottom (Cu)	0.682138	1.055310	0.683548
Maximum deflection (cm)		0.000719	0.000871	0.000726

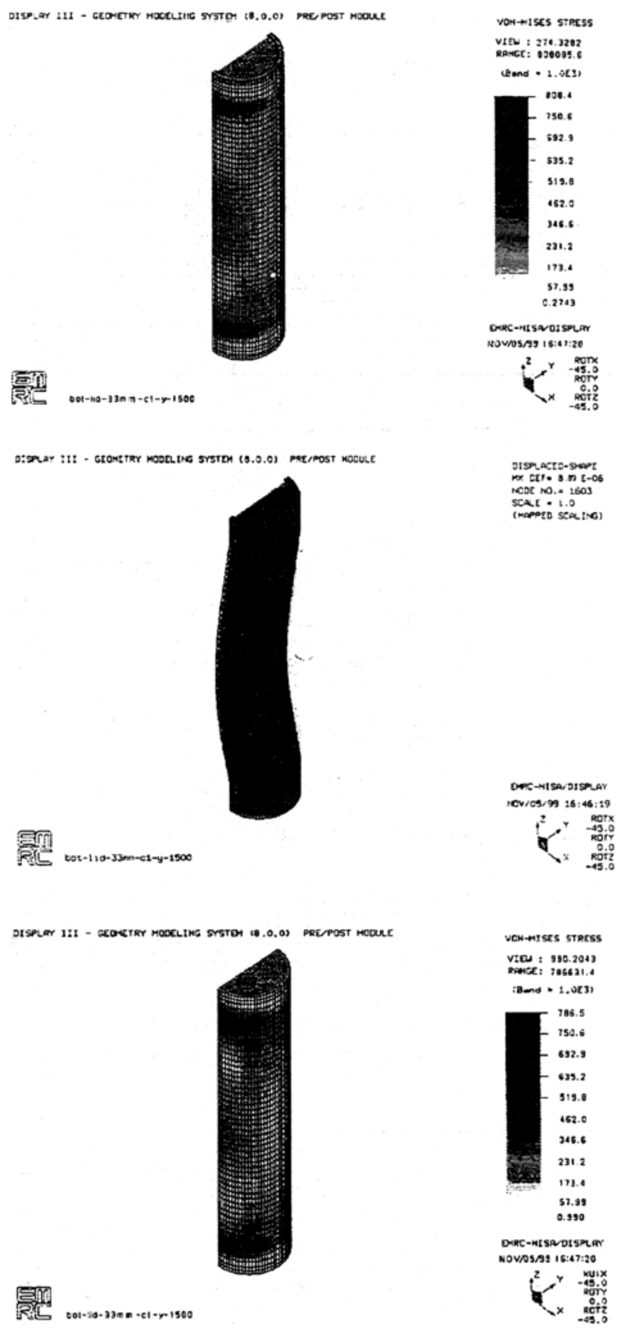

Fig. 5 Stress contour and deflection shape for the canister structure (Case 1, lid and bottom thickness: 3.3 cm, PWR canister)

ture 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 7 and 8. As expected, results show that the canister structure with the outer shell of high Ni alloy is structurally stronger than other cases.

Table 8 Structural analysis results for the outer shell material variation (Case 1, CANDU canister)

Stress, Deflection	Shell material	High Ni Alloy	Copper (Cu)	Stainless Steel
Maximum von-Mises stress (MPa)	Shell	13.722160	11.712480	14.449260
	Cast iron	7.421953	8.774426	7.574693
	Lid (Cu)	0.589254	0.741009	0.593679
	Bottom (Cu)	0.451960	0.724522	0.456480
Maximum deflection (cm)		0.000745	0.000884	0.000769

Table 9 Synthesis of the structural analysis results for each case (Case 1 ~ Case 6, PWR canister)

Stress, Deflection	Cases	Case 1		Case 2		Case 3		Case 4	Case 5
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical		
Maximum von-Mises stress (MPa)	Shell (Cu)	11.771960	11.465890	35.739600	34.856200	76.592530	76.461890	2.534830	2.535101
	Lid (Cu)	0.742750	0.732560	0.825989	0.958433	0.532298	0.779167	0.109817	0.115668
	Bottom (Cu)	0.682137	0.858510	0.598100	0.658943	0.294286	0.894975	0.082557	0.083643
	Cast iron	6.176806	4.256125	10.686890	10.236590	7.646189	4.503885	1.940490	1.942837
Maximum deflection (cm)		0.000719	0.000711	0.002060	0.00202	0.021300	0.007790	0.000129	0.000129

Table 10 Synthesis of the structural analysis results for each case (Case 1 ~ Case 6, CANDU canister)

Stress, Deflection	Cases	Case 1		Case 2		Case 3		Case 4	Case 5
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical		
Maximum von-Mises stress (MPa)	Shell (Cu)	13.722160	14.124550	55.325680	43.253680	91.646380	91.342590	3.256189	3.356254
	Lid (Cu)	0.594011	0.544991	1.021575	0.973593	0.657013	0.776167	0.789564	0.865231
	Bottom (Cu)	0.457264	0.568977	0.956840	0.935680	0.435263	0.751631	0.623252	0.642356
	Cast iron	7.421953	6.892543	13.124580	6.452894	36.807550	24.265970	2.456235	2.564325
Maximum deflection (cm)		0.000745	0.000714	0.014800	0.003960	0.206000	0.125000	0.000281	0.000298

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 Tables 9 and 10. However, some stress concentration phenomenon occurs around the basket for swelling cases as shown in Fig. 6. And these results also show that the verticaly positioned canister in the repository is structurally stronger than the horizontally positioned 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 con-

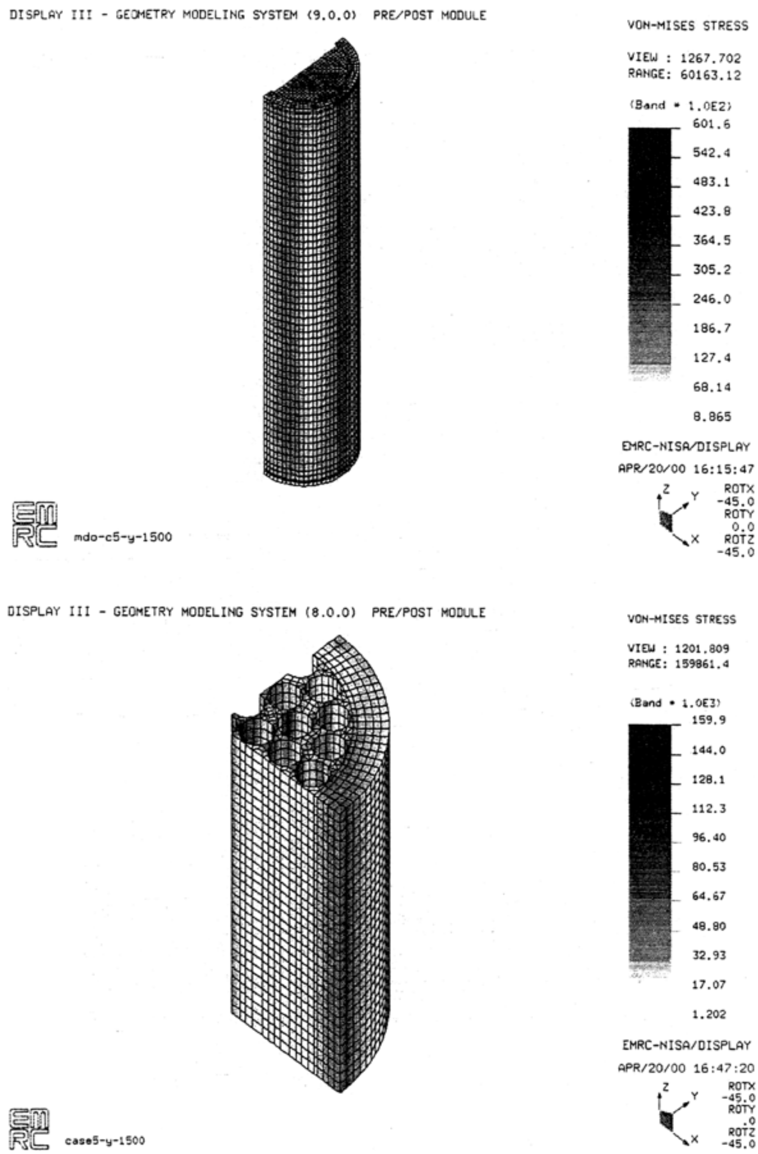

Fig. 6 Stress contour for the canister structure (Case 5, CANDU canister)

cept 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. But the exact value of thickness cannot be deter-

mined. Other analyses such as a nonlinear elsto-plastic analysis and chemical analysis for corrosion may be required in order to determine the exact value of thickness. These analyses are beyond this work, and are not treated here.

- 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 orientation in the repository is structurally stronger than the horizontally positioned structure.

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