

A Reference Container Concept for Spent Fuel Disposal : Structural safety for dimensioning of the reference container

Jongwon Choi · Sang-ki Kwon and Chul-Hyung Kang

Korea Atomic Energy Research Institute

Youngjoo Kwon

Hong Ik Univ.

(AOCRP-1 ORAL 발표, 2004년 3월 5일 채택)

Abstract - This paper presents the mechanical and thermal stress analysis of a disposal canister to provide basic information for dimensioning the canister and configuration of the canister components. The structural stress analysis is carried out using a finite element analysis code, NISA, and focused on the structural strength of the canister against the expected external pressures due to the swelling of the bentonite buffer and the hydrostatic head, and the thermal load build up in the container.

Key words : spent fuel disposal, disposal canister, repository system, spent fuel

INTRODUCTION

Since the Kori Nuclear Unit 1 commissioned in 1978, today Korea's nuclear power program has sixteen operating plants, four Canadian deuterium-uranium (CANDU) and twelve pressurized-water reactor (PWR). And four units will be added from 2003. With respect to such a promotion plan of nuclear energy, spent nuclear fuel (SNF) inventories storing at reactor sites naturally increase. By the end of 2000, total amount of spent PWR fuels is 5,710 assemblies (about 2,510 tHM). The corresponding amount of CANDU fuel is about 2,310tHM. According to the "Fifth Long-term Plan for Electric Power Demand and Supply" announced by MOCIE (Ministry of Commerce, Industry and Energy) in January 2000, eight units will be added to by the year 2015. Such a dramatic growth in nuclear power needs us to secure a systematic and long-term national plan or strategy for safe spent fuel management.

Korea launched a long-term R&D program for high-level waste (HLW) disposal technology development in 1997. The main purpose of this program is to establish a reference HLW repository system by 2006. The disposal concept being conceived in the program is to encapsulate the intact spent fuel in corrosion resistant containers and the packaged spent fuels are then to be disposed in a mined underground facility located at about 500m below surface in a crystalline rock mass. No site for the underground repository has been specified in Korea, but a generic site with granitic rock is considered for the study.

The study to establish a reference repository system development starts with waste package design work, because most disposal tunnel shapes, spacing and dimensions are determined by the engineering and design parameters of the waste package. For the first step to develop a reference disposal container for geological disposal of SNF, this study focuses on the

structural stress analyses of the proposed container concept to provide basic information for dimensioning the container, selection of the container component materials, and proper spent fuel configurations within the container. This information will be used and revised during the conceptual design study of the geological repository system that is being developed.

DESIGN BASES

These design bases provide the information that identifies the specific functions to be performed by the repository system, as well as the specific values or ranges of values chosen as controlling parameters to bound the container design. These key design constraints include:

- Total spent fuel inventory to be packaged for disposal: 36,000 tHM[3],
 - Spent PWR fuel: 20,000 tHM (45,500 assemblies, based at 0.44 tHM/assembly)
 - Spent CANDU fuel: 16,000 tHM (842,100 bundles, based at 0.019 tHM/bundle)
- Decay heat (40yr cooling): 385 watt/assembly for PWR, 2.28 watt/bundle for CANDU
- The container filling material for void space within the container: carbon steel
- Spent fuel packaging criteria :
 - Temperature of spent fuel cladding in the container $< 200^{\circ}\text{C}$ (in air), which is to protect long-term integrity of spent fuel by preventing UO_2 oxidation, oxidation film on fuel clad, and etc. under the underground repository conditions.
 - Surface temperature of the disposal container $< 100^{\circ}\text{C}$, which is to keep the desired functions of the bentonite buffer as physical and chemical barrier.
 - The maximum dose rate on the surface of the container $< 500\text{mSv/hr}$, which is to prevent significant radiolysis of surroundings of near-field.
 - The container should be subcritical ($K_{\text{eff}} \leq 0.95$) even if the expected void space of the container would be filled with water.
 - The container has to withstand the

mechanical loads caused by disposal at a depth of 500 m, which entails the external load on the container of 5MPa of hydrostatic pressure from groundwater and 10 MPa of swelling pressure of bentonite buffer. The container strength will be demonstrated under the abnormal cases that uneven pressure build-up in the bentonite buffer could occur during the waster saturation of the buffer.

CONTAINER DESCRIPTION

As listed in the previous section, spent PWR and CANDU fuels have significantly different properties. Because of that point of both fuels and the retrieval potential of PWR fuel for reuse, the both fuels are recommended to be separately packaged for disposal. The design basis container consists of the fuel storage basket, the filler and the outer shell as illustrated in Fig.1. As shown in the figure, the overall sizes and component materials for both PWR and CANDU fuels are designed to be exactly identical to make the encapsulation and handling processes in the repository simple. The outer shell contains fuel storage baskets (4 square tubes for spent PWR fuel and 33 circular tubes for spent CANDU fuel). The filler that fill with cast iron in the void space between the outer shell and the storage basket provides mechanical strength and radiation shielding, and it keeps the fuel assemblies in a fixed configuration. For the filler material, carbon steel to be placed in the contained as the type of cast iron is considered as the design basis material. For the complete isolation of waste for a long time, high nickel alloy (Alloy22), stainless steel or carbon steel are considered as the candidate corrosion resistant materials for the outer shell.

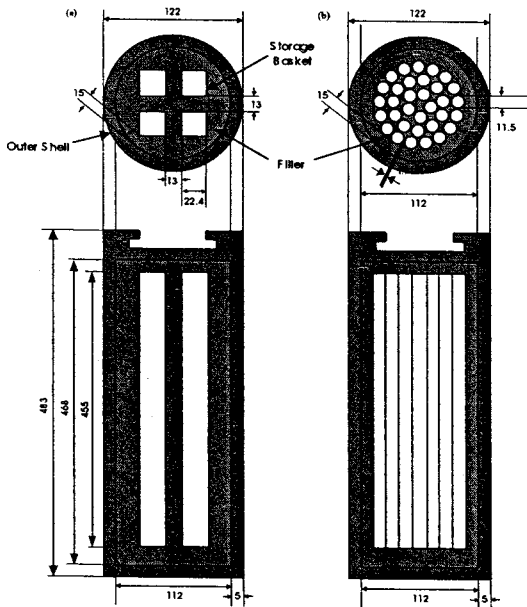
FORMULATION OF THE STRUCTURAL ANALYSIS

The structural strength of the disposal container depends on the structural shape and

dimensions of the container and the material. The design variables in this study to perform the mechanical structural analysis of the proposed container and the dimensioning work are the thicknesses of the outer shell and the lid/bottom, the minimum thickness of the thinner section between the storage basket and the surface of the cast insert. Other issues studied here include structural safety due to the temperature build-up within the container and the unexpected rock movement.

Values of material properties used as the input parameters for the structural stress analysis are listed in Table 1. Mean values are adopted for some indefinite property values in this computation.

As mentioned previously, the mechanical design load for the container is assumed to be 15MPa of external pressure consisting of 5MPa of hydrostatic pressure and 10MPa of swelling pressure of the compacted bentonite buffer. In the case of a normal load, a total of 15MPa of external load is assumed to be evenly distributed and acting on the whole surfaces of the container as shown in Fig. 2 (Load Case 1). In the abnormal cases during the groundwater saturation of the bentonite buffer, the swelling pressure could unevenly develop due to the different direction of ground water intrusion as illustrated as Load case 2 of Fig. 2. The abnormal case may caused a mal-positioned container in the hole, heterogeneous rock properties, or a banana-like curved disposal hole.



	Ni-Alloy (or Copper or SUS)	Ni-Alloy (or Copper or SUS)
Container Outer shell	Carbon steel	Carbon steel
Filter (rod space in the container)	4 PWR 5 part Fuel Assemblies	297 CANDU 5 part Fuel Bundles
Capacity	11,375	2,926
Total No. of the Required Containers	1,340 Wtft	760 Wtft
Required steel in Container	5.64 m ³	5.64 m ³
Total Volume of the container	19.67 m ³	19.67 m ³
Total Surface Area	39,112 kg	39,099 kg
Total Weight	2,660 kg	7,425 kg
• Fuel wt.	27,345 kg	22,567 kg
• Cast Insert	9,107 kg	9,107 kg
• Outer shell (Case for Ni-alloy) (Case for Copper)	9,211 kg	9,211 kg

Fig. 1. Schematic diagram of the reference disposal container for spent PWR (a) and CANDU (b) fuels.

Table 1. Material properties for the structural stress analysis.

Properties	Materials		
	Cast iron	High Ni alloy	Stainless steel
Young's Modulus, E (GPa)	83-170	210	190-200
Poisson's ratio, ν	0.2-0.3	0.31	0.3
Thermal Exp. Coeff., α ($10^{-6}/^{\circ}\text{C}$)	9.9-12	13	17
Mass Density, ρ (kg/m^3)	7,400	8,800	7,857
Yield Stress, σ_y (MPa)	200-290	114-624	128-700
Ultimate Stress, σ_u (MPa)	340-1,400	310-760	400-1,000
Thermal Conductivity, k ($\text{W}/\text{m} \cdot \text{K}$)	52	26	31
Specific Heat, C ($\text{kcal}/\text{kg} \cdot ^{\circ}\text{C}$)	420	460	460

In this case, uniform pressure of 8 MPa is applied perpendicularly on the upper half outer surface of the container with fixed ends.

For the mechanical structural analysis, the length of the container is fixed as 483cm to accommodate spent fuels with 453cm-height and the outer shell thickness and the lid/bottom are fixed as 5cm because it would be determined from the corrosion analysis. Because of the nuclear criticality safety, the basket positions inside the container are fixed at 13cm-basket spacing as shown in Fig. 1. For the structural safety of the proposed container, the equivalent von Mises defined as the yield stress of carbon steel divided by the maximum von Mises stress occurred inside the filler is calculated. The safety factor (S) allowable for the safe design of the container is considered as 2.0 in this study.

The structural strength of the disposal

container is analyzed by the finite element analysis method, using the commercial finite element code (NISA), with respect to the normal and abnormal load conditions as specified in Fig. 2. In the numerical analysis for load case 1, some symmetric boundary conditions are used for displacements due to the symmetric loading condition and to prevent a rigid body motion.

RESULTS AND DISCUSSION

Figure 3 shows that the container with 4-basket configurations at 13-cm spacing is structurally stronger than the container with the greater configuration of the baskets.

Figure 4 shows the maximum von Mises stress occurred in the filler as the diameter of the filler diameter increases. When the safety factor for the stress due to the external loads (hydrostatic and swelling pressure) is taken as 2.0, the safe diameter of the container is found to be more than 112 cm to secure the structural safety. This result was applied for the structural analysis of the CANDU container to find the possible numbers of inner baskets to accommodate CANDU fuels. The results for the abnormal load case (Load case 2) are summarized in Table 2. The table shows that the CANDU container with 3-circular baskets may give the safety factor of 2.0 when the diameter of the container is 122 cm. From this result, the

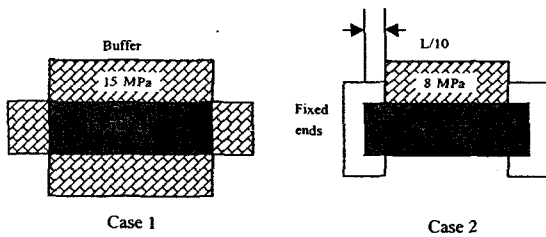
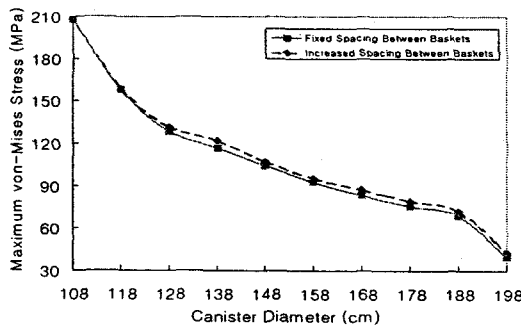
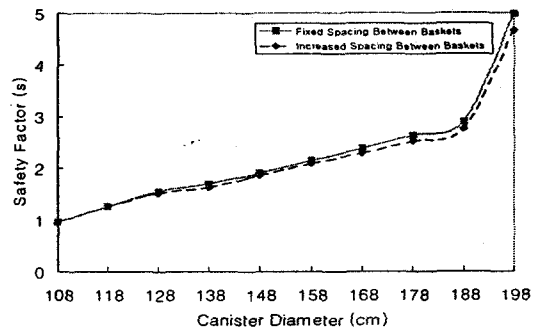


Fig. 2. External load conditions due to the hydrostatic pressure and the swelling pressure of bentonite buffer : (a) load case 1 (normal case for the design basis pressure load after saturation), (b) load case 2 (abnormal case during the groundwater saturation phase).



(a) Maximum von Mises stress occurred in the cast insert of the canister for the PWR fuel versus the canister diameter



(b) Safety factor versus the canister diameter

Fig. 3. Maximum von Mises stress occurred in the Filler of the canister for PWR fuel and safety factor versus the canister diameter (Load case 2).

Table 2. Structural stress analysis results of CANDU fuel container (Load case 2).

Number of baskets Inside cast insert of container	17	19	25	33	37
Maximum von Mises Stress occurred inside Cast insert (MPa)	93.06	93.11	99.75	108.2	112.7
Maximum deflection Occurred inside container (cm)	0.097	0.099	0.106	0.11	0.112

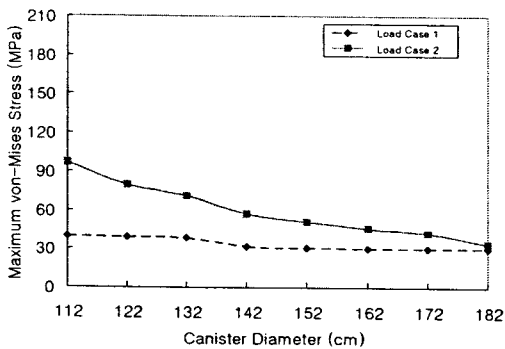


Fig. 4. Maximum von Mises stress occurred in the cast insert of the canister for PWR fuel versus the canister diameter (Load case 1&2).

thickness of the thinner section of the filler between the fuel basket and the surface of the filler (or inner surface of the outer shell) is determined to be 15cm, which is evaluated to provide enough container strength under the assumed external loads, for both PWR and CANDU fuel containers. Regarding the dimensions of the filler and the fuel, the PWR fuel container could accommodate 4 assemblies

and the CANDU fuel container could accommodate 297 bundles (33 circle tubes x 9 stacks). Of course thus configurations satisfy the thermal constraints mentioned in the previous section.

Figure 5 shows the stress distributions inside container. The stress is concentrated at the outer corner of the square basket in PWR fuel container with Load case 1, but not in other cases. But this stress concentration may not be serious in the actual case.

Thermal stresses of the container due to thermal loads of the heat generation of spent nuclear fuels inside baskets may be another reason affecting the structural safety of the container emplaced in the underground repository. Fig. 6 shows the thermal stress analysis result of the container. Even though some high thermal stresses occur in the container, the container appears to be still structurally safe less than about 170°C. Because the maximum stress occurred in the canister is smaller than the yield strength of the cast iron.

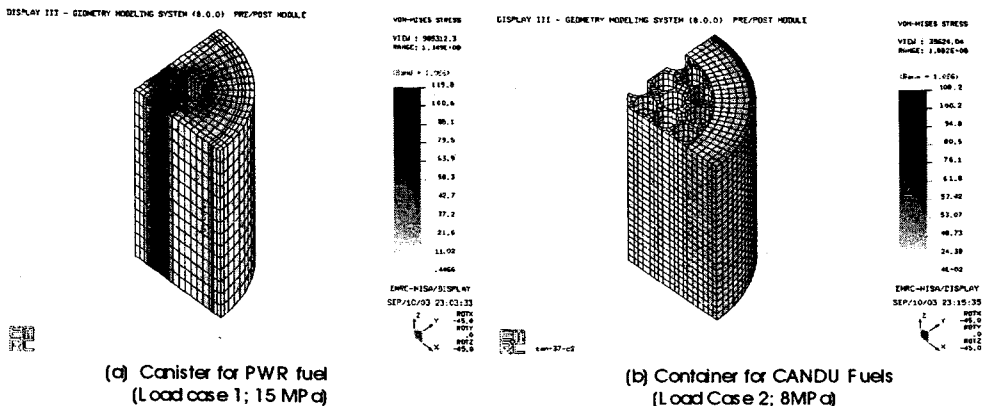


Fig. 5. Stress distributions inside the cast insert of canister.

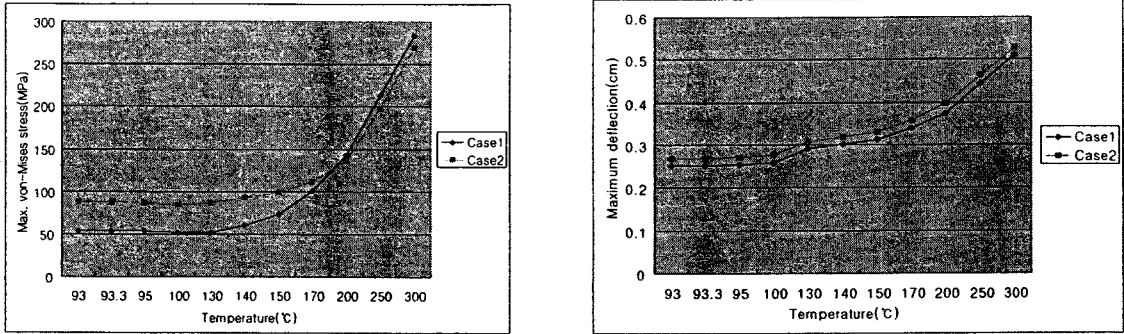


Fig. 6. The maximum von Mises stress (a) and the Maximum deflection in the filler (cast iron) as a function of Temperature (PWR container, D=122 cm).

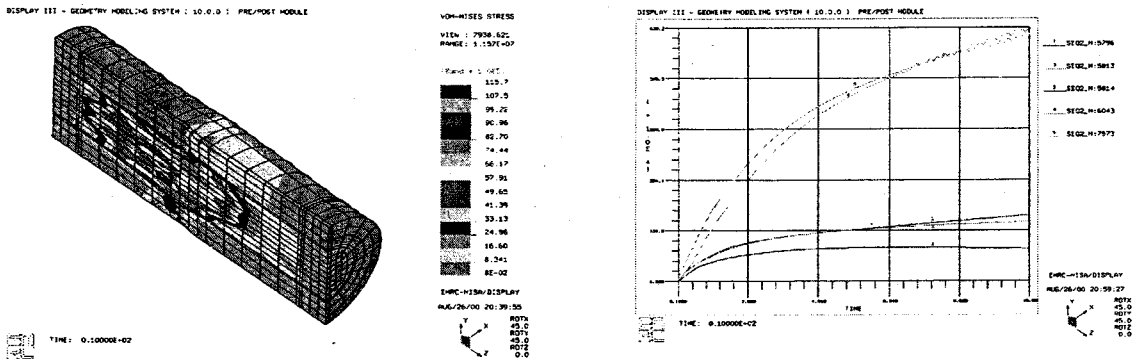


Fig. 7. The maximum von Mises stress of the Container (PWR container, D=122 cm).

Fig. 7 shows the nonlinear structural analysis of the container with 50cm-bentonite buffer that is to predict the structural safety of the container while the host rock is unexpectedly moved up by 10cm. This case may be caused by the earthquake etc. at a deep underground. For the analysis, horizontal symmetric rock movement is assumed to simulate this case and the elastoplastic material model is adopted. Drucker-Prager yield criterion is used for the material yield prediction of the bentonite buffer and von-Mises yield criterion is used for the material yield prediction of the canister (cast iron insert, copper outer shell and lid and bottom). The analysis result shows that even though very large deformations occur beyond the yield point in the bentonite buffer, the canister structure still endures elastic small strains and stresses below the yield strength. Hence, the 50cm thick

bentonite buffer can protect the canister safely against the 10cm sudden rock movement by earthquake etc.. Analysis results also show that bending deformations occur in the canister structure due to the shear deformation of the bentonite buffer.

CONCLUSIONS

After emplacing the disposal container in the repository, the containers may get structural deformations by hydrostatic and bentonite swelling pressure and high thermal load built-up in the container, rock movement, etc.. For the first step to develop a reference disposal container for geological disposal, this paper presents the structural stress analyses of the container to provide basic information for

dimensioning the container and configuration of the container components, and safe disposal condition.

When the safety factor for stress due to the external loads (hydrostatic and swelling pressure) is taken as 2.0, the safe diameter of the filler material to provide enough container strength under the assumed external loads is found to be 112cm and the spacing between inner baskets in the cast insert of PWR fuel container is found to be 13cm. Based on this result, the thickness of the thinner section between the fuel baskets and the surface of the cast insert is determined to be 150mm for both PWR and CANDU fuel containers. Regarding these dimensions of the cast insert and the shape and size of the fuel, the PWR fuel container is sketched to accommodate 4 square assemblies and the CANDU fuel container 297 bundles (33 circle tubes x 9 stacks). It appears that thus dimensions and configuration of the container do not affect the structural safety under the given load conditions.

Acknowledgement

This study has been carried out under the Nuclear R&D Program of the Ministry of Science and Technology of Korea.

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