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Structural evaluation and analysis under normal conditions for spent fuel concrete storage cask

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1. Introduction

The purpose of this paper is the verification of stabilities of the structural elements that influence the safety of a concrete storage cask. The structural evaluation of a concrete storage canister must show that it secures the confinement and structural integrities of the dual(transportation and storage) purpose canister (Dual Purpose Canister 21, hereafter canister) under normal conditions. The evaluation results were reviewed with respect to every design criterion, in terms of whether the results satisfy the criteria, provided by 10CFR 72 and NUREG-1536 [1, 2]. The basic information on the design is partially explained in 2. Description of spent fuel storage system and the maintainability and assumptions included in the analysis were confirmed through detailed explanations of the acceptable standards, analysis model, and analysis method. ABAQUS 6.10, a widely used finite element analysis program, was used in the structural analysis [3].

2. Description of spent fuel concrete storage cask

A concrete storage cask used for the dry storage of spent nuclear fuel consists of the concrete cask body, the body of the cask, and canister, which loads 21 spent nuclear fuel bundles. Spent nuclear fuels released from a reactor are stored in wet-storage of the nuclear power plant for a certain period of time. They are then dry-loaded into a canister and sealed for transportation and stored in a storage container for a long period of time.

A concrete cask body is a cylindrical shell structure for the storage of canisters loaded with spent nuclear fuels. Concrete for shielding is filled between the internal and external carbon steel shells of the cask body, and air intake and exhaust vents are installed at the top and bottom of the cask body to eliminate the decay heat from the spent nuclear fuel through air circulation due to natural convection. A canister for the loading of the spent nuclear fuels is a welded cylindrical shell structure that provides the confinement boundary for the concrete storage cask. The canister has a basket assembly with 21 square cells, and helium is charged into the canister to maintain the integrity of the spent nuclear fuel during long-term storage.

The concrete cask body of the concrete cask protects the canister from the external environment to maintain the integrity of the spent nuclear fuel, and the canister maintains the confinement boundary while it is loaded with the spent nuclear fuel. A concrete storage cask is composed of the following parts, and the detailed names of the parts are provided in Fig. 1.

1. Cask body (Cask body and cask lid of a metallic cylindrical shell filled with concrete)
2. Canister (Cylindrical cask body and cask lid maintaining the confinement boundary)
3. Internal elements of the canister (Basket assembly, disc, support rod and neutron absorber)

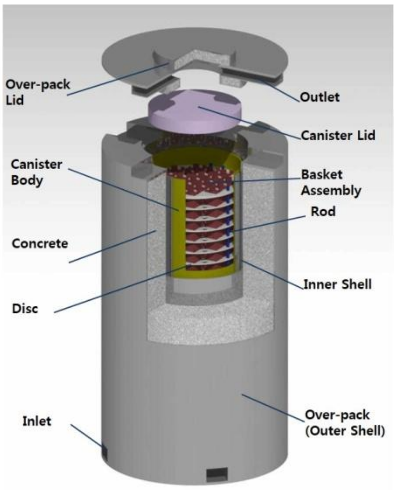


Fig. 1. Cross section of concrete storage cask; general arrangement

The general description of concrete storage cask is included in Table I-II show material components.

Table I: Design dimensions of concrete storage cask

Component	Dimension(mm)	Weight(kg)
Cask body	Ø 3306×6180	108,712
Cask lid	Ø 3206×570	6,302
Basket Assembly	214×241×4550	4,968
Spent fuel	-	13,965
Disc	20(50)THK.× Ø 1630	3,397
Support rod	Ø 50×4565	576
Canister	Ø 1686×4880	10,151
Total		148,071

Table II: Materials and components of concrete storage cask (cask body)

Component	Material	Specification
Cask top plate	Carbon steel	SA-36
Lid bolt block	Carbon steel	SA-36
Lifting lug	Carbon steel	SA-537, Class 2
Outlet duct cover	Carbon steel	SA-36
Cask inner shell	Carbon steel	SA-36
Cask outer shell	Carbon steel	SA-36
Channel	Carbon steel	SS400
Support channel	Carbon steel	SA-36
Support plate	Carbon steel	SA-36
Inlet shell	Carbon steel	SA-36
Inlet duct	Carbon steel	SA-36
Cask bottom plate	Carbon steel	SA-36
Inlet gamma shield	Carbon steel	SA-36
Deformed bar	Carbon steel	SD400
Cask body concrete shield	Concrete	Type I Portland

A manufacturing process, such as welding and concrete placement are performed as per the requirements of ASME Code, Section III, Division 1, Subsection NF and ACI 349 [4, 5].

2.1 Design criteria

A concrete storage cask must maintain its performance without compromising its major safety features regarding every accident condition and natural phenomena in addition to threshold, confinement of the internal canister, and radiation shielding function of the concrete cask body.

The basic design criteria of the concrete storage cask are described in 10CFR 72 and NUREG-1536. These design criteria describes the structural criteria used in the designs and structural analyses of the concrete cask body, canister, and internal elements. The design codes and the functions applied to each part of the canister are listed in Table III. The technical criteria and design requirements were categorized into normal condition and are listed in Table IV.

2.2 Load combination of normal conditions

The load combinations regarding the concrete storage cask were set according to the NUREG-1536, ANSI/ANS 57.9 and ACI 349 criteria based on the structural analyses results on each load to conduct a stress evaluation of the concrete storage cask.

The structural analysis under the normal conditions of the concrete storage cask considered dead load, live load, handling load, pressure load, and thermal load. ASME B&PV Code Section III, Subsection NB (Level A) was applied to the stress evaluation of the canister, the allowable stresses computed from ASME B&PV Code Section III, Subsection NF(Level A) were applied to the cask body, and the allowable stresses computed from ASME B&PV Code Section III, Subsection NG(Level A) were applied to the basket assembly, disc, and rod, respectively.

2.2.1 Dead load

The evaluation of the dead load was conducted through application of the load due to the self-load of the canister of the concrete storage cask, internal elements of the canister, and concrete cask body. Only the self-loads acting in the vertical direction were considered.

Table III: Design codes

Assembly	Component	Function	Codes
Cask	Outer shell	Structural	NF
	Inner shell	Structural	NF
	Bottom plate	Structural	NF
	Body concrete	Structural & shielding	ACI 349
	Lid	Structural	NF
	Lid Bolts	Structural	NF
	Lid concrete	Structural & shielding	ACI 349
	Channel	Structural	NF
Canister	Body	Confinement	NB
	Bottom plate	Confinement	NB
	Lid	Confinement	NB
Canister inner component	Support rod	Criticality safety	NG
	Disc	Criticality safety	NG
	Basket	Criticality safety	NG
	Fuel support	Criticality safety	NG

Table IV: Design criteria under normal condition

Type	Criteria	Basis
Ambient temperature	22℃	ANSI/ANS57.9
Dead load	Self-weight	
Live load	3.63kN/m^2	Korea building code-Structural
Handling load	115% of self-weight, 1/6 of yielding strength	CMAA#70 ANSI 14.6
Pressure	1% Fuel rod rupture	NUREG-1536

2.2.2 Live load

A live load considers loads due to the external conditions possible during the storage condition, and the snow-load due to snow was applied as a live load. Based on Korean Building Code (2009), the basic value (S_g) of ground snow-load in the 100-year return period was conservatively set as 3.0 kN/m^2 with respect to Gangneung. The design snow-load (S_f) was computed with the equation below [6].

$$S_f = C_b \cdot C_e \cdot C_t \cdot I_s \cdot S_g = 0.7 \times 1.2 \times 1.2 \times 1.2 \times 3.0 = 3.629\ kN/m^2$$

Here, S_g : basic value of ground snow-load (3.0 kN/m^2 (with respect to Gangneung))

C_b : Basic roof snow-load coefficient (0.7)
C_e : Exposure coefficient (1.2)
C_t : Temperature coefficient (1.2)
I_s : Importance coefficient (1.2)

The design snow-load of 3.629 kN/m^2 was used as the loading condition.

2.2.3 Handling load

A concrete storage cask under the normal conditions should be able to withstand the handling load from the handling. The handling load in the concrete storage cask considered the conditions in which a transfer cask is attached to the upper part of the concrete cask body and the canister is charged. The load at the upper part of the concrete storage cask body and the load at the upper part of the canister lid during the canister lifting when the transfer cask is attached at the upper part of the concrete storage cask were evaluated.

The load with the transfer cask attached at the upper part of the concrete storage cask considered the summation of the weights of the transfer cask, canister with the spent nuclear fuel, collar for the fastening of the transfer cask, and the lower lid mating device as the handling load and applied it to the upper part of the concrete cask body. The weight of the transfer cask including the canister is 120.5 ton, and the weights of the collar and the mating device are 4.9 ton and 8.4 ton, respectively, and the total weight is 133.8 ton. The load applied at the upper part of the canister lid during the canister lifting is 33.7 ton, which includes the weights of the canister, the internal elements, and the spent nuclear fuel.

2.2.4 Pressure load

The pressure load under normal conditions depends on the volume of inert gas filled to maintain the integrity of the spent nuclear fuel, volume of the gas within the fuel rod, the amount of the fission gas from the fuel, the number of fuel rods assumed to break, and temperature.
As presented by NUREG-1536, the pressure load of normal conditions was applied to the canister based on the assumption of having 1% of the entire spent nuclear fuel damaged, 100% of the injected gas within the damaged spent nuclear fuel rod released into the canister, and 30% of the damaged spent nuclear fuel releasing fission gas. The concrete storage cask body has an open structure and does not generate internal pressure. 0.08MPa, which was computed from thermal analysis results, was set as the canister internal pressure under the normal conditions.

2.2.5 Thermal load

Based on NUREG-1536, the maximum mean annual temperature was set as the temperature of the external environment under the normal conditions. Therefore, through the analysis of the data from the Korea Meteorological Administration, the maximum mean annual temperature of 22℃ was applied as the external environment temperature of the concrete storage cask to evaluate the thermal load. The temperature distribution with respect to the external environment temperature, 22℃, was computed through a thermal analysis with the FLUENT computer program, and the thermal load analysis was conducted with the temperature distribution computed from the results of the thermal analysis.

3. Mechanical properties of the material

This section described the mechanical properties of the major materials used in the structural evaluation of the concrete storage cask. The concrete storage cask body was produced from carbon steel, and the elements other than the body were produced from stainless steel. The canister utilized SA-240 316L material to increase the salt resistance due to the external environment under storage conditions, and the internal elements utilized SA-240(479) 304 material. The mechanical properties of the materials used in the structural analyses of the concrete storage cask are summarized in Table V.

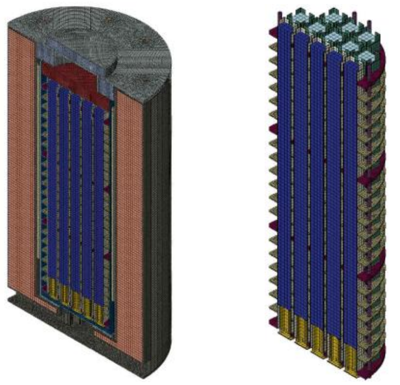
Table V: Design criteria under normal condition

Component	Elastic modulus (MPa)	Density (kg/m^3)	S_y (MPa)	S_u (MPa)	Poisson's ratio
Concrete shield	28,577	2,500	30		0.17
Cask body	202,000	7,750	250	400	0.3
Cask lid	202,000	7,750	250	400	0.3
Side channel	202,000	7,750	250	400	0.3
Bottom channel	202,000	7,750	250	400	0.3
Cask lid bolt	191,000	7,750	965	1,070	0.3
Lifting lug	202,000	7,750	415	550	0.3
Canister body	195,000	8.09E-9	170	485	0.3
Canister lid	195,000	8.09E-9	170	485	0.3
Baske	195,000	8.09E-9	205	515	0.3
Disc	195,000	8.09E-9	205	515	0.3
Support rod	195,000	8.09E-9	205	515	0.3
Fuel support	195,000	8.09E-9	205	515	0.3

4. Structural analysis

For the finite element analysis model used in the structural analyses of the concrete storage cask, one structural model was prepared and the initial conditions and boundary conditions were varied to apply to every analysis. Considering the symmetry of the cask, the analysis model was composed of a 1/2 model (represent 180° of the cask). The analysis model was composed of

809,046 nodes and 556,905 solid elements. The shape of the analysis model is illustrated in Fig. 2.



(a) (b)

Fig. 2. 1/2 analysis model of concrete storage cask; (a) All components, (b) Inner component of canister

A structural analysis on the normal conditions of the concrete storage cask was conducted with a widely used finite element program, ABAQUS. The analysis model included not only the confinement structure but also the concrete cask body. The analysis model for each element was identical to the analysis model used for the off-normal and accident conditions.

Although the normal condition load combination resulted in a slightly large load due to the thermal stress in the normal conditions, the load was within the range of the allowable stress, and the results were below the allowable stress under every condition.

5. Structural analysis results

5.1 Dead load

The dead load considered the load from the self-loads of the spent nuclear fuel assembly, basket assembly, disc, support rod, canister, and cask body of the concrete storage cask. The self-loads with respect to each element were applied as the initial conditions for the structural analysis, and the bottom surface of the cask body was considered as the perfectly-restricted condition for the boundary condition. The stress due to the self-load was not large throughout the cask, and the maximum stress occurred at the internal basket assembly, which has a relatively small thickness. The stress distribution and analysis result are each illustrated in Fig. 3.

5.2 Live load

The snow-load that could occur during the storage condition was conservatively applied at the upper part of the concrete storage cask as the load applied for the live load evaluation. The canister and internal elements were excluded because live load only affects the concrete cask body. The analysis results showed a small stress below 1MPa, and the stress distribution and analysis result are each shown in Fig. 4.

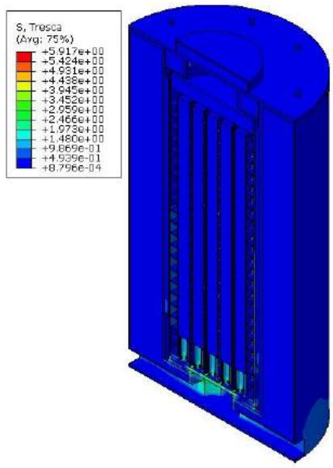


Fig. 3. Stress distribution of dead load for concrete storage cask

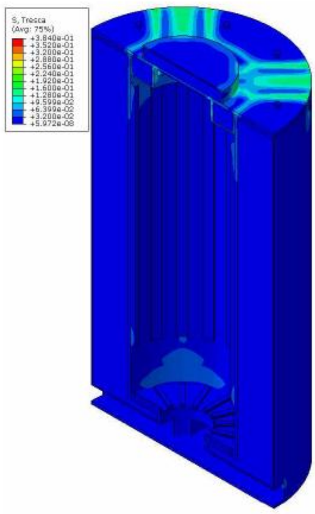


Fig. 4. Stress distribution of live load for concrete storage cask

5.3 Handling load

The load generated when the transfer cask is attached at the top of the concrete storage cask and canister is charged was applied as the handling load. The weights of the transfer cask, canister, and other handling equipment were applied at the upper part of the cask body as the handling load of the concrete cask body. The weight of the canister charged with spent nuclear fuel was set as the handling load generated during the canister lifting because the canister is handled with installation of an auxiliary device adjacent to the lid of the canister.

In the case of the transfer cask, the concrete storage cask lid, the canister, and other internal elements that do not experience the load were excluded from the analysis because the transfer cask is located at the upper part of the concrete storage cask body. In addition, the canister and the internal elements were used in the analysis of the handling load generated from the canister lifter. The analysis results showed localized stress at the upper part of the cask body and it was evaluated to be below the allowable stress. The stress distribution and analysis results are each shown in Fig. 5.

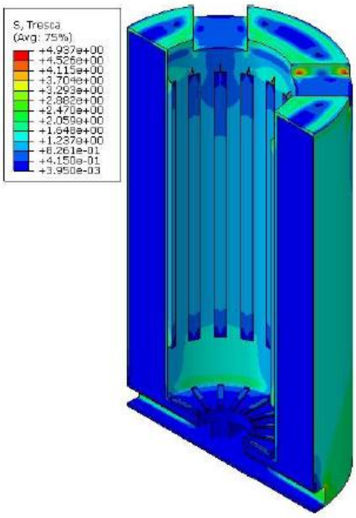


Fig. 5. Stress distribution of cask handling load for concrete storage cask

5.4 Pressure load

The canister internal pressure, with 1% of the internal fuel rods damaged, was applied as the load, and the internal pressure of 0.08064MPa, which was computed from the thermal analysis, was applied inside the canister. The analysis results showed the maximum stress of 12.9MPa on the canister body, and it was evaluated to be below the allowable stress. The stress distribution and analysis results are shown in Fig. 6.

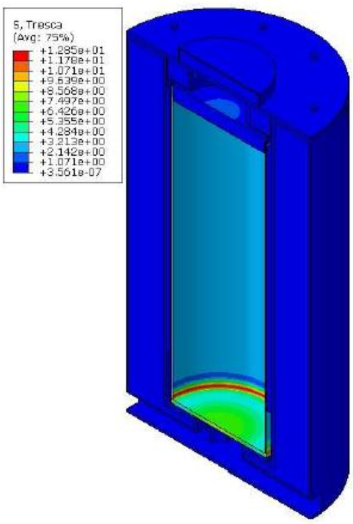
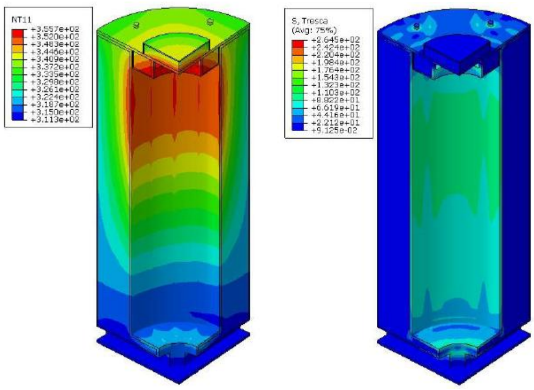


Fig. 6. Stress distribution of Pressure load for concrete storage cask

5.5 Thermal load

The thermal analysis results were applied as the initial condition for the temperature data of the normal conditions, and the temperatures used in the analysis were Kelvin temperatures. In addition, a 1/4 symmetric model was used in the thermal load analysis. The normal condition temperature distributions of the concrete storage cask are illustrated in Fig. 7(a) and the analysis results with respect to the thermal loads are illustrated in Fig. 7(b). In the normal condition, the temperature of the center was the highest for the canister and internal elements, and the temperature of the upper part was the highest in the cask body due to the internal air circulation. The maximum temperature of the external surface of the concrete storage cask body was approximately 50℃ and the internal maximum temperature of the body was approximately 80℃. Since the analysis with consideration of the influence of the temperature considers the secondary stress from the heat in addition to the structural deformation, secondary membrane and bending were compared. The evaluation results showed the maximum stress of approximately 250 MPa but it was evaluated to be below the allowable stress under every condition.



(a) (b)

Fig. 7. Temperature and thermal stress distribution induced from thermal load for concrete storage cask; (a) Temperature distribution of cask, (b) Thermal stress distribution cask

Also, the stress evaluation with respect to the load combination showed large secondary stresses, but they were revealed to be below the allowable stress. Therefore, based on the stress evaluation results, it was evaluated to satisfy the design requirements under the normal conditions.

6. Conclusions

The storage cask shall maintain the sub-criticality, shielding, structural integrity, thermal capability and confinement in accordance with the requirements specified in US 10 CFR 72. The safety of storage cask is analyzed and it has been confirmed to meet the requirements of US 10 CFR 72.

This paper summarizes the structural stability evaluation results of a concrete storage cask with respect to the design criteria.

The evaluation results of this paper show that the maximum stress was below the allowable stress under every condition, and the concrete storage cask satisfied the design criteria.

Acknowledgement

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REFERENCES

[1] 10CFR Part 72, Title 10, Chapter I, of the Code of Federal Regulations, "Licensing Requirement for the Independent Storage of Spent Nuclear Fuel, High-level Radioactive Waste, and Reactor-Related Greater than Class C Waste".
[2] NUREG-1536, "Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility", Revision 1, July, 2010.
[3] Dassault Simulia, ABAQUS 6.10 documentation, 2010.
[4] American Society of Mechanical Engineers, "ASME Boiler and Pressure Vessel Code, Section Ⅲ, Division 1, Subsection NF, Supports" 2010 Edition.
[5] American Concrete Institute, "Code Requirements for Nuclear Safety Related Concrete Structures", ACI 349R-01.
[6] Architectural Institute of KOREA, "Korean Building Code - Structure", 2009.