Thermal Analysis of a Storage Cask for 24 Spent PWR Fuel Assemblies

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Abstract

The purpose of this paper is to perform a thermal analysis of a spent fuel storage cask in order to predict the maximum concrete and fuel cladding temperatures. Thermal analyses have been carried out for a storage cask under normal and off-normal conditions. The environmental temperature is assumed to be 27 ℃ under the normal condition. The off-normal condition has an environmental temperature of 40 ℃. An additional off-normal condition is considered as a partial blockage of the air inlet ducts. Four of the eight inlet ducts are assumed to be completely blocked. The storage cask is designed to store 24 PWR spent fuel assemblies with a burn-up of 55,000 MWD/MTU and a cooling time of 7 years. The decay heat load from the 24 PWR assemblies is 25.2 kW. Thermal analyses of ventilation system have been carried out for the determination of the optimum duct size and shape. The finite volume computational fluid dynamics code FLUENT was used for the thermal analysis. In the results of the analysis, the maximum temperatures of the fuel rod and concrete overpack were lower than the allowable values under the normal condition and off-normal conditions.

Introduction

The objective of a thermal evaluation is to ensure that the decay heat removal system is capable of a reliable operation so that the temperatures of the fuel assembly cladding material and storage system components remain within the allowable limits under normal, off-normal, and accident conditions. The spent fuel cladding must be protected from degradation during storage that leads to a gross fuel rupture. The zircalloy fuel cladding temperature limit at the beginning of the dry storage is typically below 380 ℃ for a 5-year cooled fuel assembly for normal operations and minimum 20 years storage. The fuel temperature should also generally be maintained below 570 ℃ for the short-term off-normal and accident conditions. The decay heat removal system may be a passive or an active cooling system for the dry storage of the spent fuel.

A spent fuel dry storage system is designed for the long-term storage of the spent nuclear fuel in a vertical position. Thermal analysis considers the passive rejection of the decay heat from the stored spent fuel assemblies to the environment under the design basis ambient conditions. Thermal analysis is based on the three heat transfer modes of conduction, convection and radiation. Heat is dissipated from the outer surface of the storage cask to the environment by a buoyancy induced air flow and thermal radiation. Heat transfer through the cylindrical wall of the storage overpack is done by conduction. Natural circulation of the air inside the storage cask allows the concrete temperature to be maintained below the allowable value and maintains the fuel cladding temperature below the limit where a long-term degradation might occur.

Description of Dry Storage Cask

A spent fuel dry storage system consists of an overpack, sealed canister including the fuel baskets and a transfer cask as shown in Fig. 1. In order to protect the environment from a radiation exposure, spent fuel is first placed in the canister. The overpack cannot be placed in the cask pit for the loading of the spent fuel. Therefore, the canister must be carried out using the transfer cask. The canister is used in combination with the transfer cask and the storage cask components of the dry storage system. Fig. 2 is the overview of the storage cask. The cask consists of the structural material, a concrete shielding, and a natural cooling system. Heat is transferred from the cask to the environment by a passive means only. Eight air inlet and outlet ducts are installed at the top and bottom for a natural cooling system. The main structural function of the overpack is provided by carbon steel, and the main shielding function is provided by concrete. The overpack is enclosed by cylindrical steel shells. Table 1 shows the description of the dry storage cask. The outer diameter of the storage cask is 3,550 mm and the overall height is 5,885 mm. The gross weight of the cask is approximately 135 tons. The storage cask is designed to store 24 PWR spent fuel assemblies with a burn-up of 55,000 MWD/MTU and a cooling time of 7 years. The decay heat load from the 24 PWR assemblies is 25.2 kW.

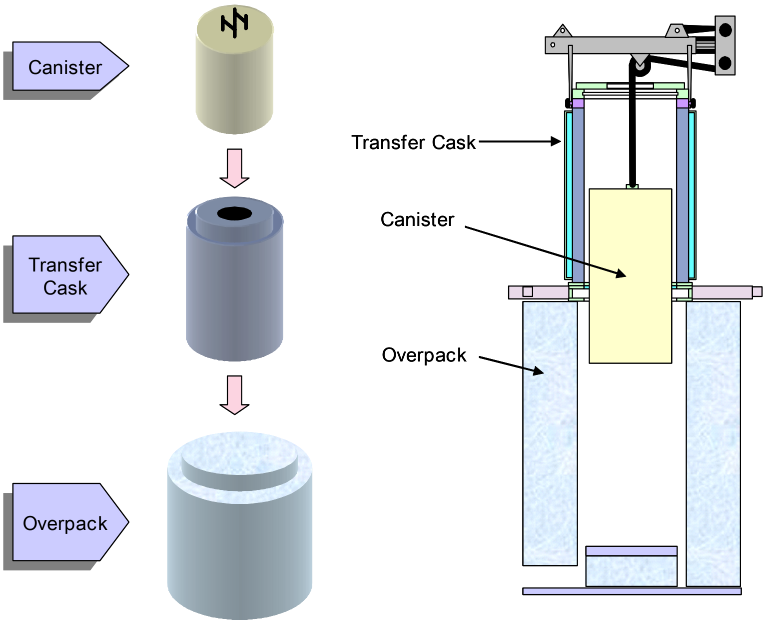


Fig. 1. Spent Fuel Dry Storage System.

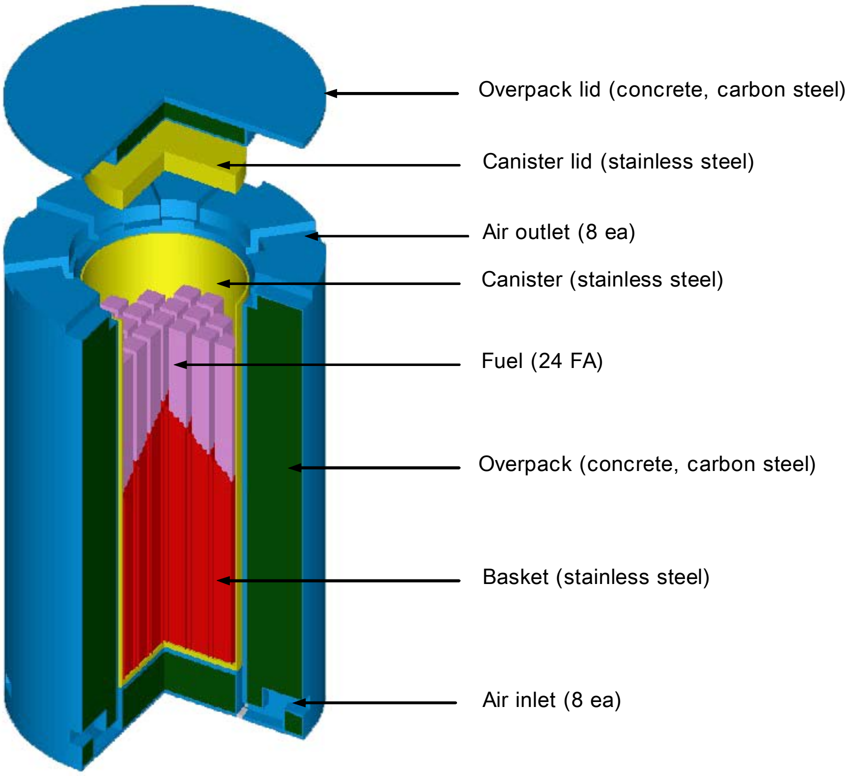


Fig. 2. Overview of Concrete Cask.

Table 1. Description of the Dry Storage Cask

Item	Description
Storage capacity	24 PWR assemblies
Component	- Sealed canister - Concrete overpack
Dimension	- Concrete overpack : O.D. 3,520 mm x 5,885 mm L - Canister : OD. 1,840 mm x 4,845 mm L
Weight	- Storage cask : 154.5 tons (loaded canister) - Canister : 38.2 tons (loaded fuels)
Material	- Overpack : Carbon steel, concrete - Canister : Stainless steel, boral (B_4C + aluminum)
Design basis fuel	- Burn-up : 50,000 MWD/MTU - Cooling times : 7 years - Initial enrichment : 5.0 wt.% U235 - Decay heat : 25.2 kW / canister
Cooling system	- Natural cooling system : 8 air inlet and outlet ducts - Cavity : inert gas (helium)

Thermal Analysis for Determination of Ventilation Ducts

The overpack is ventilated to allow the heat transfer from the spent fuel within the canister to be removed to the atmosphere. The ventilation system of the concrete cask has air entrance ducts at the bottom of the overpack and hot air exhaust ducts at the top, and a vertical space between the overpack and the canister. The air flow rate into the lower ducts, up along the space between the overpack and the canister, and out of the upper ducts is a function of the flow resistance in the air travel path and the temperature of the canister external surface. The ventilation system is designed to prevent an escape to the environment of a significant radiation from the spent fuel but not to interface with the flow of the air. Thermal analyses of the ventilation system have been carried out for the determination of the duct size and shape using the FLUENT code[1].

Fig. 3 shows the thermal analysis model for the ventilation system. The analysis model is only included in the air part except for the solid part of the canister and the overpack. Because most heat from the spent fuel is removed by a natural circulation of the cooling air. Heat flux from the spent nuclear fuel was applied to the inner surface of the air. Table 2 shows the thermal analysis conditions and results as a variation of the ventilation duct sizes. The air temperatures decrease with an increasing of the duct sizes. Therefore, it is found that the thermal efficiency is enhanced in the large duct size. But the large duct size has a disadvantage from the aspect of structural and radiation shielding safeties. Therefore, the duct sizes of the air inlet and outlet were selected as 290 mm x 275 mm, 425 mm x 120 mm, respectively.

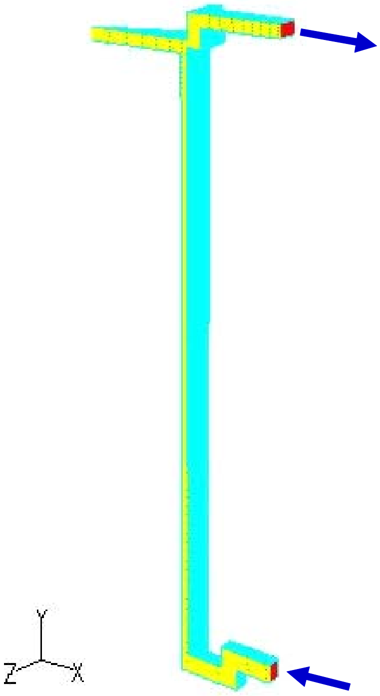
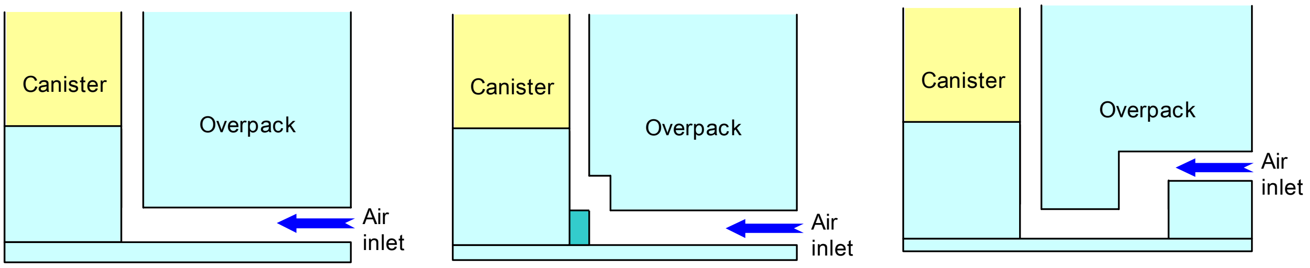


Fig. 3. Thermal Analysis Model for Ventilation Duct.

Table 2. Thermal Analysis Results as a Variation of Duct sizes

Duct size (mm)		Calculated temperatures (□)	
Inlet	Outlet	Maximum air	Air outlet
290 x 175	425 x 120	97	54
347 x 208	520 x 139	85	67
400 x 240	600 x 160	77	81

Thermal analyses have been carried out for an evaluation of the thermal efficiency as a variation of the ventilation duct shapes. In this model, the applied duct sizes of the air inlet and outlet are 290 mm x 275 mm, 425 mm 120 mm. The air inlet ducts are considered as straight and curvilinear passageways as shown in Fig. 4. Table 3 shows the thermal analysis results as a variation of the air inlet duct shapes. Thermal efficiency of the ventilation duct for a straight shape is better than that of a curvilinear shape. Ventilation duct must be designed to prevent an escape to the surrounding area of a significant radiation emitting from the spent fuel. Therefore, even if it has a disadvantage in thermal efficiency, the curvilinear passageway is selected as the shape of the air inlet duct to protect the environment from a radiation exposure through the duct opening. Fig. 4(c) was selected as the shape of air inlet duct for a storage cask.



(a) Straight (b) Curvilinear - A (c) Curvilinear - B

Fig. 4. Ventilation Duct Shapes for Air Inlet.

Table 3. Thermal analysis results as a Variation of the Duct Shapes of Air Inlet

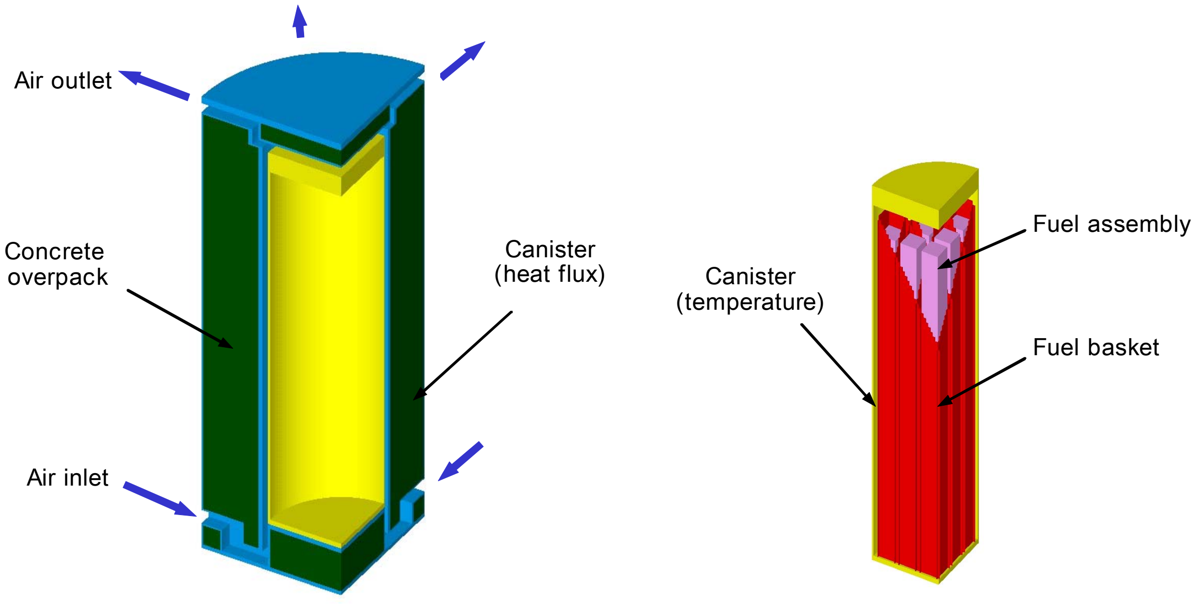
Duct shape	Calculated temperatures (℃)	
	Maximum air	Air outlet
Straight	86	69
Curvilinear - A	98	81
Curvilinear – B	95	79

Thermal Analysis Modelling for a Storage Cask

Thermal analyses have been carried out for a dry storage cask under normal and off-normal conditions. Generally, the annual average environmental temperature is applied to the thermal analysis for a normal condition[2]. The annual average environmental temperature is about 15 ℃ in Korea, but the ambient temperature was considered as 27 ℃ in the normal condition. This temperature is the maximum monthly average temperature in the summer season in Korea. Therefore, the ambient temperature for a normal condition was assumed very conservatively. The ambient temperature of 27 ℃ was used to evaluate the long-term fuel degradation and concrete properties and to serve as the base temperature for the thermal cycle evaluations under a normal condition.

Off-normal severe environmental condition was selected as 40 ℃. The temperature of 40 ℃ is the maximum observed temperature in Korea. An additional off-normal condition is considered as a partial blockage of the air inlet ducts. Four of the eight air inlet ducts are assumed to be completely blocked with an ambient temperature of 27 ℃. Solar heat flux and maximum decay heat from the spent fuels are applied to all the analysis conditions. Decay heat from the 24 spent PWR fuel assemblies is 25.2 kW.

FLUENT analysis models were performed for the three dimensional cylindrical quarter cask model. The thermal analyses were carried out in two stages to increase the computational speed substantially, as well as to reduce the requirements for the computer memory and space. Fig. 5 shows the thermal analysis models for the overpack and canister. In the first stage, the model consists of the overpack, and q storage canister with a heat flux from the spent fuel. This model calculates the steady state temperature distributions of the overpack, ventilated air and canister wall. In the second stage, the canister with the fuel baskets and fuel assemblies is modeled. The canister wall temperature is applied as a boundary condition calculated from the first stage.



(a) Overpack (b) Canister

Fig. 5. Thermal Analysis Model for Storage Cask.

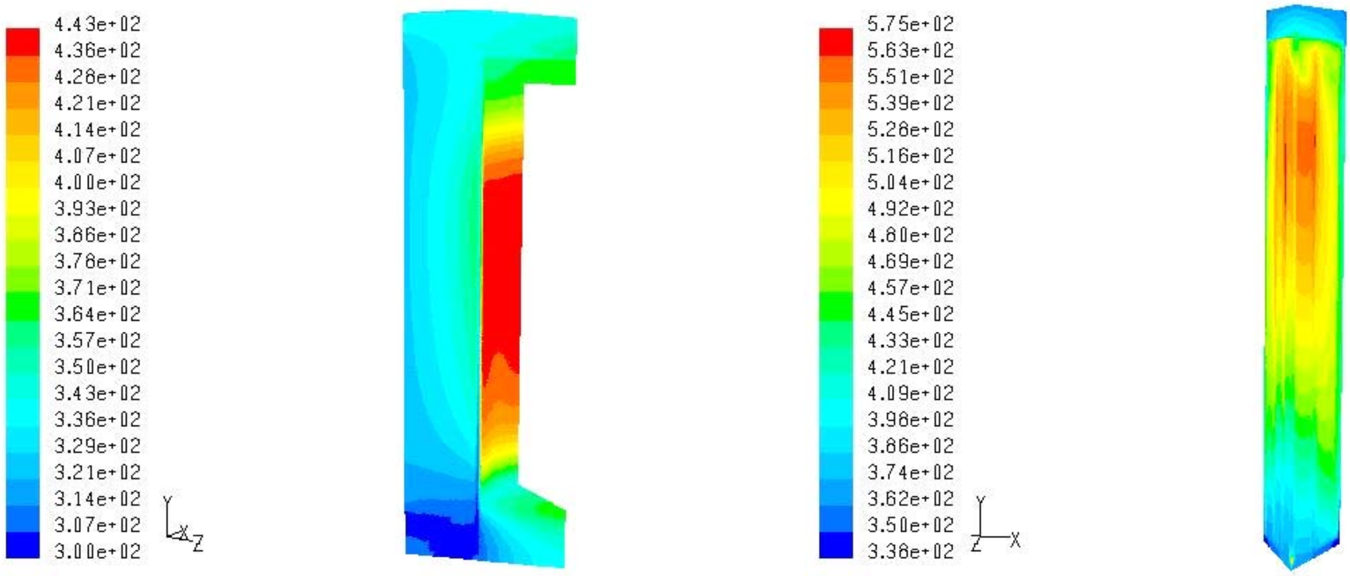
The cask's outer shell material is carbon steel and the surface is painted. In the thermal analysis, an emissivity of 0.85 is applied to the painted surface. The emissivities of the stainless steel and carbon steel are applied at 0.36 and 0.66. Pressure outlet boundary conditions are used for the air inlet and outlet ducts. The gauge pressure and backflow total temperature are considered as the atmospheric pressure and environmental temperatures in the pressure outlet boundary conditions. The porous model, which can simplify the complex configuration of a fuel assembly, has been used in the thermal analysis. Thermal conductivity, and flow resistance are modeled to approximate the fuel assembly as a porous media. Flow resistance characteristics of the fuel assemblies are used with the porous medium parameters of the permeability and the inertial resistance factor.

Results and Discussion

Fig. 6 presents the temperature contours of the overpack and the canister under a normal condition. The air temperature of the upper part is considerably affected by the hot air going along the canister surface by a buoyancy force. The maximum canister wall temperature was estimated to be 170 □. Temperature distribution for the inside of the canister was calculated using the canister wall temperature as a boundary condition.

Table 4 summarizes the calculated temperatures under a normal condition. As can be seen in this table, the maximum fuel rod temperature is lower than the allowable value for a long-term storage of the spent fuel. The fuel cladding temperature limits are typically below 380 □ for a 5 year cooled fuel assembly and 340 □ for a 10 year cooled fuel assembly. The temperature limit is about 345 □ for a 7 year cooled fuel assembly[4]. Maximum concrete temperature was calculated as 91 □, which is lower than the allowable value of 93 □. ACI-349[5] specifies a normal operating concrete temperature limit of 66 □, except for local areas which may not exceed 93 □, and a short-term or accident temperature limit of no more than 177 □. The heat discharged from the concrete cask to the environment is attained by the cooling air and heat conduction on the cask body. In the thermal analysis result, about 80 % of the heat was removed by the cooling air. It is shown that a natural convection through the air circulation is very dominant in the heat transfer of a storage cask.

Thermal analyses have been carried out for an off-normal environmental condition and a partial blockage of an air inlet duct. The off-normal environmental temperature of 40 □ is postulated as a constant temperature caused by an extreme weather condition. Four of the eight inlet ducts are assumed to be completely blocked a for partial blockage condition. To determine the effects of the off-normal temperature, it is conservatively assumed that this temperature persists for a long time to allow the cask to achieve a thermal equilibrium. Table 5 shows the cask temperatures under the off-normal conditions. The temperatures for the off-normal conditions are slightly higher than those of the normal condition. The fuel rod temperature is lower than the allowable value of 570 □[6]. Also, the concrete overpack temperature is lower than the allowable limit of 177 □ under an off-normal condition.



(a) Overpack (b) Canister

Fig. 6. Temperature Contours under Normal Condition.

Table 4. Maximum Calculated Temperatures under Normal Condition

Item	Maximum temperature (℃)	Allowable value (℃)
Fuel rod	302	345
Canister outer surface	170	-
Overpack inner surface	91	93
Overpack outer surface	64	93
Air outlet	67	-

Table 5. Maximum Temperatures under Off-Normal Conditions

Item	Maximum temperature (℃)		Allowable value (℃)
	Off normal environment	Partial blockage	
Fuel rod	304	312	570
Canister outer surface	172	183	-
Overpack inner surface	97	102	177
Overpack outer surface	73	67	177
Air outlet	76	74	-

Conclusions

In the results of the thermal analysis for the ventilation ducts, it was found that the large size and straight shape of the ventilation ducts had an advantage from the aspect of the thermal efficiency. Optimum ventilation ducts were selected for consideration of radiation shielding and structural safety as well as the thermal safety. The maximum calculated temperatures of the fuel rod and concrete overpack were lower than the allowable values under the normal condition. Temperature distributions of the off-normal conditions were slightly higher than the normal condition. Therefore, the thermal integrity of the dry storage cask will be maintained under the normal and off-normal conditions.

References

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[6] NUREG-1567, "Standard Review Plan for Spent Fuel Dry Storage Facilities," U.S. Nuclear Regulatory Commission, 2000.