Proceeding of the Korean Radioactive Waste Society
Vol. 1, No. 2, November, 2003

# Thermal Analysis of a Spent Fuel Storage Cask under Normal and Off-Normal Conditions

J. C. Lee, K. S. Bang, K. S. Seo, H.D. Kim,
Korea Atomic Energy Research Institute

B. I. Choi, H. Y. Lee
Korea Hydro & Nuclear Power Co., Ltd.

## Abstract

Thermal analyses have been carried out for a spent fuel dry storage cask under normal and off-normal conditions. Environmental temperature is assumed to be 15 ℃ under the normal condition. The off-normal condition has an environmental temperature of 38 ℃. An additional off-normal condition is considered as a partial blockage of the air inlet ducts. Two of the four air inlet ducts are assumed to be completely blocked. The maximum temperatures of the fuel rod and concrete overpack were lower than the allowable values under the normal condition. Temperature distributions for the off-normal conditions were slightly higher than the normal conditions.

## 1. 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 during storage against degradation that leads to a gross fuel rupture. The zircalloy fuel cladding temperature limit at the beginning of the dry storage is typically below 380 ℃[1] for a 5-year cooled fuel assembly for normal operations and a minimum 20 years storage. The fuel cladding temperature should also generally be maintained below 570 ℃[2] for short-term off-normal and accident conditions. The decay heat removal system may be a passive (natural convection and thermal radiation) 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 spent nuclear fuel in a vertical position. Thermal analysis of a storage cask is based on the three heat transfer modes of conduction, convection and radiation. Heat is dissipated from the outer surface of the storage overpack to the environment by a buoyancy induced air flow and thermal radiation. Heat transfer through the cylindrical wall of the storage overpack is by conduction. The analysis considers passive rejection of the decay heat from the stored spent fuel assemblies to the environment under design basis ambient conditions. 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 long-term degradation might occur.

## 2. Description of Dry Storage System

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. 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 for the storage of the spent fuel.

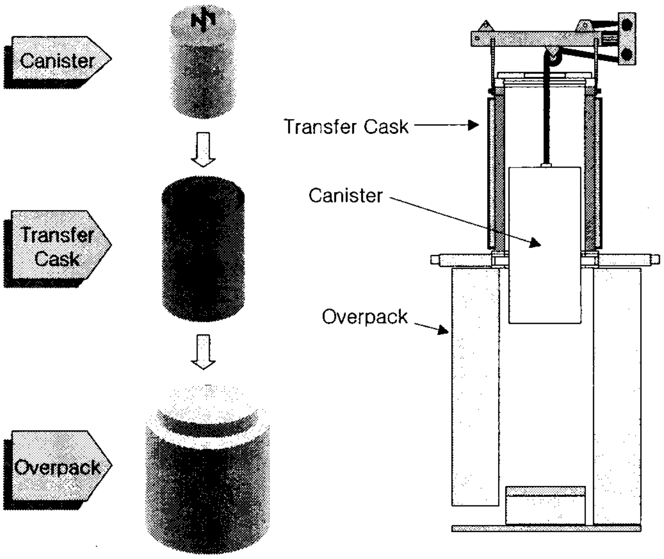


Fig. 1. Spent Fuel Dry Storage System.

Fig. 2 shows the overview of the storage cask. The cask consists of the structural material, concrete shielding, and a natural cooling system. Heat is transferred from the cask to the environment by a passive means only. Four air inlet and outlet ducts are installed at the top and bottom respectively. The main structure 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.

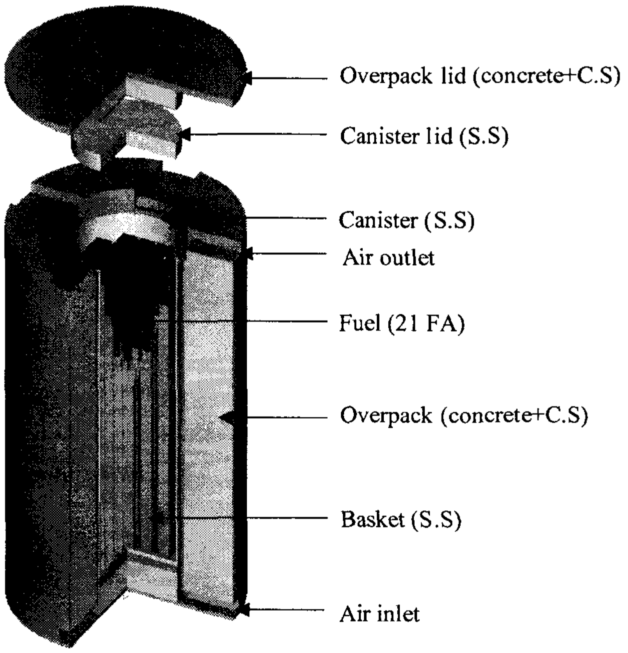


Fig. 2. Overview of Concrete Cask.

Table 1 shows the description of the dry storage system. 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 21 PWR spent fuel assemblies with a burnup of 55,000 MWD/MTU and a cooling time of 7 years. The decay heat load from 21 PWR assemblies is 22.05 kW. Four air inlet and outlet ducts are installed at the top and bottom of the cask for a natural cooling system.

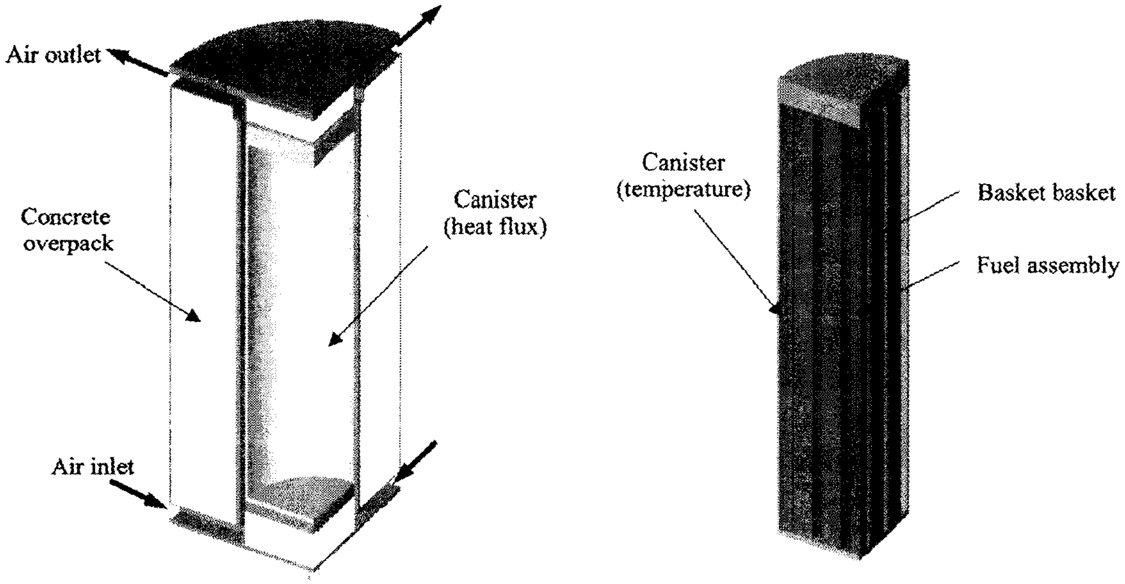
Table 1. Description of the Dry Storage System

| Item | Description |
|---|---|
| Storage capacity | 21 PWR assemblies |
| Component | - Sealed canister<br>- Concrete overpack<br>- Transfer cask |
| Dimension | - Concrete overpack : O.D. 3,550 mm x 5,885 mm L<br>- Canister : OD. 1,680 mm x 4,840 mm L<br>- Transfer cask : OD. 2,284 mm x 5,172 mm L |
| Weight | - Storage cask : 135 tons (loaded canister)<br>- Canister : 41.4 tons (loaded fuels)<br>- Transfer cask : 80 tons (loaded canister) |
| Material | - Overpack : Carbon steel, concrete<br>- Canister : Stainless steel, boral (B4C + aluminum)<br>- Transfer cask : Carbon steel, stainless steel, NS-F-RF |
| Design basis fuel | - Burn-up : 50,000 MWD/MTU<br>- Cooling times : 7 years<br>- Initial enrichment : 5.0 wt.% U235<br>- Decay heat : 22.05 kW / canister |
| Cooling system | - Natural cooling system<br>- Four inlet and outlet ducts |

## 3. Thermal Analysis Modelling

Thermal analyses have been carried out for a dry storage cask under normal and off-normal conditions. Ambient temperatures are assumed to be 15 ℃ and 38 ℃ under the normal and off-normal conditions respectively. The 15 ℃ ambient temperature is utilized to determine the long-term storage temperatures, because the yearly average temperature is about 15 ℃ in Korea. The temperature of 38 ℃ is the maximum observed temperature in Korea. An additional off-normal condition is considered as a partial blockage of the air inlet ducts. Two of the four air inlet ducts are assumed to be completely blocked with an ambient temperature of 15 ℃. Solar insolation and maximum decay heat from the spent fuels are applied to all the analysis conditions. Decay heat from the 21 spent PWR fuel assemblies is 22.05 kW.

The finite volume computational fluid dynamics code Fluent[3] was used for the thermal analysis. Fluent analysis models were performed on the three dimensional cylindrical quarter cask model. The thermal analyses were carried out in two stages. Fig. 3 shows the thermal analysis models for the cask body and canister. In the first stage, the model consists of the cask body, and 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) Cask body

(b) Canister

Fig. 3. Thermal Analysis Model.

Governing equation for the convective and radiation heat transfer at the cask surface to the environment is expressed as follows.

$q = h_{nc}A(T_s - T_a) + \sigma\varepsilon A(T_s^4 - T_a^4)$

Where,

$q$ : heat flow (W)
$h$ : Convective heat transfer coefficient ($W/m^2$-K)
$A$ : Cask surface area ($m^2$)
$T_s$, $T_a$ : Temperature at the cask surface and the ambient (K)
$\sigma$ : Stefan-Boltzmann constant (= $5.669\text{x}10^{8}$ $W/m^2\ K^4$)
$\varepsilon$ : Emissivity of surface material

Natural convection heat transfer coefficient can be derived as follows[5].

$$h_{nc} = Nu_d \frac{k}{L}$$

Where,

$$Nu_d = c(Gr\ Pr)^a, \quad Gr_d = g\ \beta\ (\Delta T) d^3/\nu^2$$

$k$ : Thermal conductivity (W/m-K)
$a$ : Exponent dependent on the flow regime
$c$ : Coefficient dependent on the flow regime and geometry
$g$ : Acceleration of gravity ($m/s^2$)
$L$ : Cask length (m)
$\beta$ : Coefficient of the volumetric expansion (1/K)
$\Delta T$ : Temperature difference between the cask surface and the ambient(K)
$\nu$ : Dynamic viscosity ($m^2/s$)

The storage cask is operated in a vertical position and the convective heat transfer coefficient is derived by the following correlations.

- Laminar range($10^4 < GrPr < 10^9$) : $Nu = 0.59\ (Gr\ Pr)^{1/4}$
- Turbulent range($Gr.Pr > 10^9$) : $Nu = 0.10\ (Gr\ Pr)^{1/3}$

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.

Fuel baskets are constructed with stainless steel and boral plates, and the air gaps remain between the two plates. Thermal conductivity of the composite fuel basket is based on the effective thermal conductivities for the electrical resistance analogy shown in Fig. 4. Serial and parallel conductors are calculated as follows[4].

$$\text{Serial}: \quad \frac{1}{k_{eff}} = \frac{t_1 + t_4}{k_1 t} + \frac{2t_2}{k_2 t} + \frac{t_3}{k_3 t}$$

$$\text{Parallel}: \quad k_{eff} = \frac{k_1(t_1 + t_4) + 2k_2 t_2 + k_3 t_3}{t_1 + 2t_2 + t_3 + t_4}$$

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.

## 4. Results and Discussion

Fig. 5 presents the temperature contour of the cask body and canister under the normal condition. The maximum canister wall temperature was estimated to be 155 ℃. Temperature distribution for the inside of the canister was calculated using the canister wall temperature as a boundary condition.

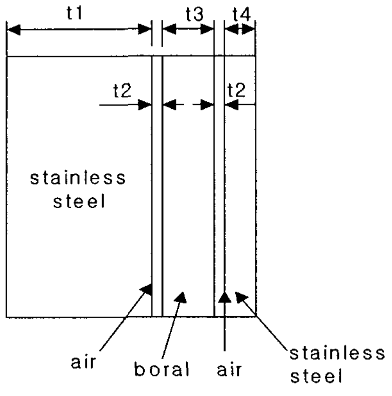
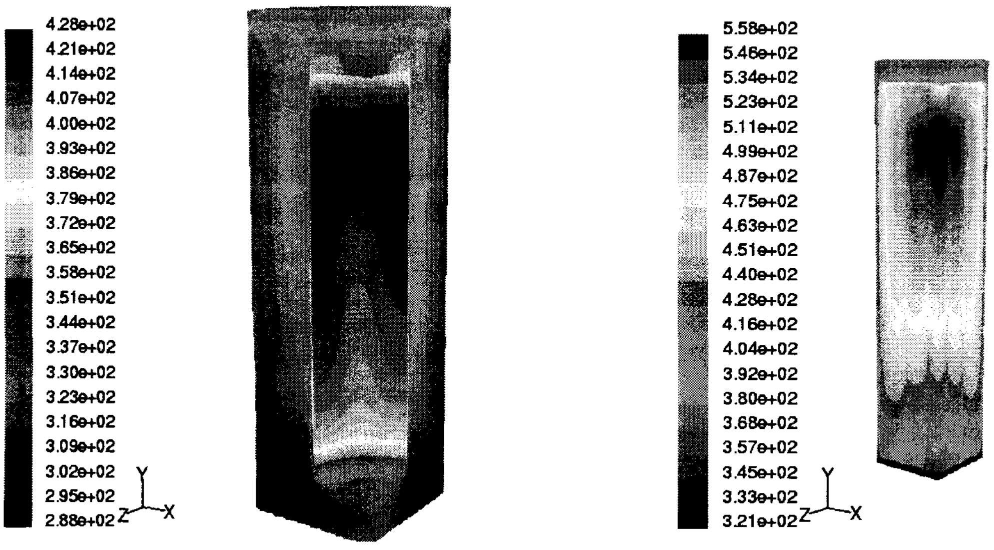


Fig. 4. Fuel Basket Model.



(a) Cask body

(b) Canister

Fig. 5. Temperature Contours under Normal Condition.

Table 2 shows the calculated temperatures under the normal condition. Maximum fuel rod temperature was calculated as 285 ℃. It is lower than the allowable value for the long-term storage of the spent fuel. The fuel cladding temperature limits are typically below 380 ℃ for a 5 years cooled fuel assembly and 340 ℃ for a 10 years cooled fuel assembly. We considered the temperature limit of 345 ℃ for a 7 years cooled fuel assembly. Maximum concrete temperature was calculated as 72 ℃, which is lower than the allowable value.

Table 2. Maximum Calculated Temperatures under Normal Condition

| Location | Calculated temperatures (℃) | Allowable values (℃) |
|---|---|---|
| Fuel rod | 285 | 345 |
| Fuel basket | 277 | |
| Canister surface | 155 | |
| Concrete inside | 72 | 93 |
| Concrete outside | 39 | 93 |
| Air outlet | 57 | |
| Ambient | 15 | |

The off-normal environmental temperature of 38 ℃ is postulated as a constant temperature caused by extreme weather 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 thermal equilibrium. Table 3 shows the cask temperatures under an off-normal environmental condition. The temperatures of the off-normal condition are higher than those of the normal condition by about 23 ℃. The temperature difference of 23 ℃ is the difference of the environmental temperature. The maximum fuel rod temperature is lower than the allowable value of 570 ℃. Table 4 shows the cask temperatures for a partial blockage of the air inlet ducts. The temperatures for a partial blockage condition are slightly higher than the normal condition.

Table 3. Maximum Temperatures under Off-normal Environmental Condition

| Location | Calculated temperatures (℃) | |
|---|---|---|
| | Normal | Off-normal |
| Fuel rod | 285 | 307 |
| Fuel basket | 277 | 289 |
| Canister surface | 155 | 178 |
| Overpack inner surface | 72 | 95 |
| Overpack outer surface | 39 | 62 |
| Air outlet | 57 | 79 |
| Ambient | 15 | 38 |

Table 4. Maximum Temperatures under Partial Blockage of Air Inlets

| Location | Calculated temperatures (℃) | |
|---|---|---|
| | No blockage | Partial blockage |
| Fuel rod | 285 | 294 |
| Fuel basket | 277 | 268 |
| Canister surface | 155 | 165 |
| Overpack inner surface | 72 | 82 |
| Overpack outer surface | 39 | 41 |
| Air outlet | 57 | 65 |
| Ambient | 15 | 15 |

## 5. Conclusion

Thermal analyses of a spent fuel storage cask have been carried out for normal and off-normal conditions. 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. The thermal analysis results will be confirmed by the full scale model thermal tests next year.

## References

[1] PNL-4835, "Technical Basis for Storage of Zircalloy-Clad Spent Fuel Inert Gases," PNL, 1983.

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

[3] “FLUENT Computational Fluid Dynamics Software Version 6", Fluent Inc., 2002.

[4] J. P. Holman, "Heat Transfer," International Student Edition 5th Ed., 1985.

[5] Topical Safety Analysis Report for the NAC Storable Transport Cask for Use at an Independent Spent Fuel Storage Installation", Rev. 3A", NAC International, 1995.