2D Thermal Analysis of a Cask using an Advanced Neutron Absorbing Material under Normal Condition

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1. Introduction

Current issues on treatment and management of domestic radioactive wastes are emerging. And development of the nuclear spent fuel storage and transportation cask of which is one of the plans for treatment of the radioactive waste becomes more and more important. Accordingly, development of materials which can be applied for the storage and transportation cask and of manufacturing techniques thereof is demanded.

The objectives of thermal analysis includes confirmation that the temperatures of the fuel cladding will be maintained below the specified temperature that could lead to gross rupture of the cladding throughout the whole storage period in order to protect the fuel against degradation[1]. In this paper, when the cask uses an advanced neutron absorbing material, this study aims to confirm that the fuel temperature will remain within the allowable values. The advanced neutron absorbing material was developed through the criticality analysis. The thermal analysis of the cask has been performed for the case for hot and cold conditions by the CFD simulation using ANSYS FLUENT code.

2. Description of Dry Storage System

Dry casks typically have a sealed metal cylinder to contain the spent fuel enclosed within a metal or a concrete outer shell to provide radiation shielding.

2.1 Model

A metal cask usually transports spent fuel assemblies and has a cask body, a canister with basket structures and impact limiters at top and bottom of the cask body to absorb the impact during transportation and handling. We took the KSC-1 model [2], which can transports one fuel assembly or 12 fuel rods. The KSC-1 cask has the lead intermediate shell in cask body to shield the gamma-ray and the outer shell which is filled with ethylene glycol solution mixed fifty-fifty with water to shield neutron. A computational fluid dynamics (CFD) model is based on KSC-1. The model transports one fuel assembly and has inner cavity helium-filled as shown in Fig 1 and Table 1.

The CFD model is designed for a 2D model and the axis-symmetry condition is applied along a dotted line in Fig 1. In the fuel region, the volume of the fuel assembly is designed to be the same as the interior cavity of the basket.

2.2 Material Properties

The thermal properties were taken from the FLUENT database and from a reference [3] and input as linear functions of the temperature in FLUENT calculation.

The thermal properties of the advanced neutron absorbing material, which contains gadolinium, are calculated considering the effect of Gd addition. The effective thermal conductivity is calculated with the Bruggeman model. The gadolinium content is decided from the criticality analysis [4]. The effective thermal conductivity of the advanced neutron absorber follows the similar trend with the thermal conductivity of stainless steel. The effective density and specific heat were calculated in consideration of the volume fraction.

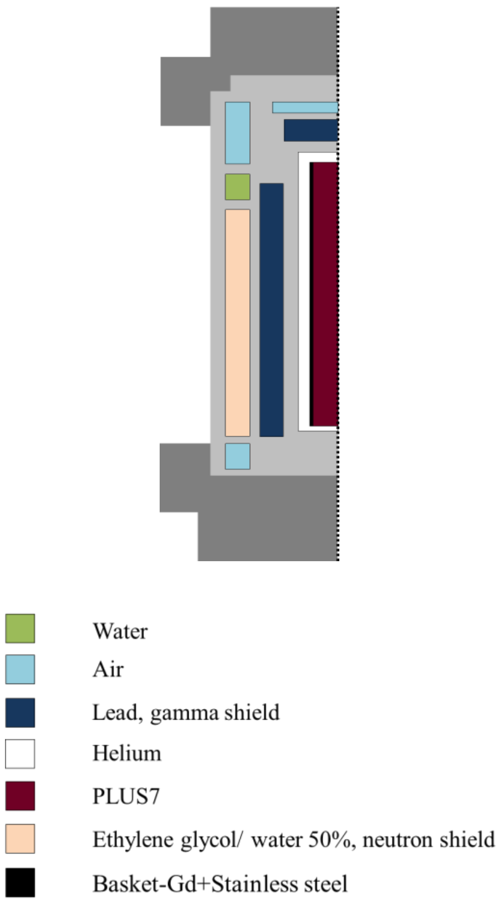

Fig 1. 2D thermal analysis model and description

Table 1. Description of the Dry Storage System

Items	Description
Capacity	1 PWR SF
Component	- Canister - Inner, Intermediate and Outer shell - Canister - Basket - Gamma shield - Neutron shield - Air cavity
Material	- Canister: SS304L - Shell: SS304L - Basket: Gadolinium+SS304L - Gamma shield: lead - Neutron shield: 50% Ethylene glycol/water mix
Design basis fuel	- Dimension: 207mm x 4.54.66mm - Initial enrichment: ~4.5wt% U235 - Burnup: 50,000 MWD/MTU - Cooling times: 7 years - Decay heat: ~1kW/Assembly

3. Thermal Analysis Modeling

For the container transporting the spent fuel, Thermal analysis was performed in normal condition and accident condition stated in 'Nuclear Safety and Security Commission Notification No. 2014-50' and 'IAEA Safety Standard Series No. TS-R-1'. Normal condition is composed of hot condition, cold condition and cold condition. Hot condition is that the decay heat and solar radiation load are applied to the maximum in ambient temperature 38℃. Cold condition is that the decay heat and solar radiation load are not applied in ambient temperature -40℃. In this study, the cask is analyzed under hot and cold condition.

3.1 Fuel Assembly Model

In the CFD model, the fuel assembly, basket and inner cavity are simply modeled to form one analytical model. The interior space of the basket is homogeneously modeled to simplify the analysis. In order to obtain the effective thermal conductivity in transverse direction of the region, the basket temperature as the boundary condition and the maximum temperature of the fuel assembly are applied to the Wooton-Epstein model. The effective thermal conductivity in longitudinal direction is calculated by the area weighted average of the components in the region[5].

Inside the canister, inert helium gas is circulated the inside and outside of the basket structures. Inside the basket, a porous media model is considered in order to depict the fluid flow of the inert gas.

3.2 Numeric, Heat Transfer models for the Simulation

ANSYS-FLUENT solves the mass, momentum conservation equation. Additionally, it solves the energy conservation equation for fluid flow which involves heat transfer.

The pressure-based, steady-state solver of ANSYS-FLUENT was used in simulating the flow field and Coupled algorithm and PRESTO are used. Gradients were calculated with a Least Squares Cell Based.

Heat transfer in cask is composed of conduction, convection and radiation. Therefore, the selection of the convective and radiative heat transfer coefficient is important. The convective heat transfer coefficient in outer wall of cask is calculated for turbulence region[2]. Inside cask, the fluid-flow is the laminar natural convection. Natural convection from a heated cylinder depends upon the product of the Grashof(Gr) and Prandtl(Pr) numbers[6].

$$Ra = \frac{g\beta\Delta T L^3}{\nu\alpha}$$

where,
Ra: *Rayleight number*
g: *the gravity acceleration*
β: *the thermal expansion coefficient*
ν: *the kinemetic viscosity*
α: *the thermal diffusivity*
ΔT: *themperature difference*

4. Results and Discussion

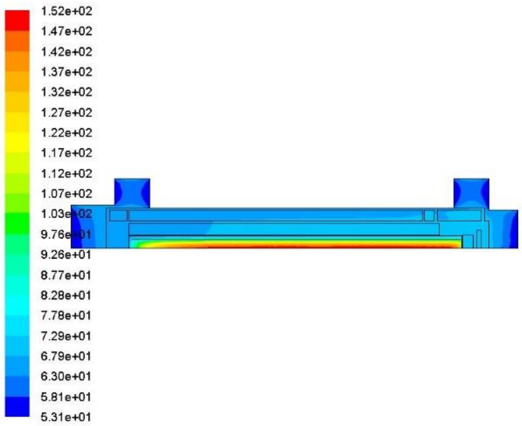

Fig 2. Contour of temperature in the cask.

Table 2 presents the temperature of the cask components under hot condition. The calculated temperatures are much lower than the allowable values under hot condition. The temperature distribution of the cask is shown Fig 2.

Under cold condition, after time is sufficiently elapsed, the cask is thermally in equilibrium at -40℃ because the decay heat and solar load are not applied. In this case, although the water is frozen, it does not affect structural integrity of the cask because it has 15% extra volume to accommodate the volume increase from the freeze of the water.

Table 2: Maximum temperature of cask components

Cask Components	Calculated Temperature (℃)	Allowable Temperature (℃)
Fuel region	152	400(normal) 570(accident)
Basket	122	
Lead shield	69	Max. 327
Neutron shield	69	Min. -40
Cask outer shell surface	67	
Ambient	65	

3. Conclusions

CFD simulation on the 2D cask model is conducted using ANSYS FLUENT code under normal condition. For fuel region, the maximum rod surface temperature is 152℃ and it does not exceed the allowable temperature limit of 400℃.

Also other components of cask, such as the lead shield and the neutron shield, etc., satisfy the allowable temperature limits.

In cold condition, the calculated temperature results do not violate the allowable temperature limits.

Therefore, the thermal integrity of the KSC-1 type cask which adopts advanced neutron absorbing material is shown to be maintained under normal operation. Additional thermal analysis for the cask under accident condition will be conducted.

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