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Thermal Analysis for Dry Transport of a Shipping Cask

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수송용기의 건식수송에 대한 열해석

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Abstract

The purpose of this study is to evaluate the thermal safety for dry transport of a shipping cask. Analysis condition was based on an ambient temperature of 38℃ for normal heat condition. The cask was designed to carry 4PWR spent fuel assemblies with a burnup of 38,000 MWD/MTU and 3 years of cooling time.

Thermal analysis was carried out by using the COBRA-SFS code. The fuel cavity was considered to be filled with air, nitrogen or helium gas for dry transport.

The results of analysis showed that the maximum temperatures of fuel rod cladding in air and helium cavity would be 277℃ and 226℃, respectively, for 3 years of cooling time. These values were less than the specified temperature to maintain the thermal integrity of fuel assembly for dry transport.

요 약

본 연구에서는 법규에서 규정하고 있는 주변온도 38℃의 정상수송조건하에서 수송용기의 건식수송조건에 대한 열해석을 평가하였다. 수송용기는 1회에 PWR 핵연료집합체 4개를 운반할 수 있는 용량을 가지며, 설계기준 핵연료는 연소도 38,000 MWD/MTU, 냉각기간 3년을 기준으로 하였다. 건식수송조건에 대한 열해석을 평가하기 위하여 COBRA-SFS 전산코드를 이용하였다.

수송용기 내부 cavity에 공기, 질소 및 헬륨가스를 채우는 세가지 조건에 대한 해석을 수행하였으며, 최대 핵연료봉의 온도는 수송용기 내부 cavity가 공기인 경우에는 277℃, 헬륨인 경우에는 226℃로 계산되었다. 이 값은 건식수송조건에서 수송용기 내부에 장전된 PWR 핵연료집합체가 열적으로 건전성을 유지하기 위한 규정온도보다 낮은 것으로 나타났다.

1. Introduction

In order to transport safely the spent fuel assemblies, a shipping cask should be developed in accordance with technical standards prescribed at IAEA[1] and domestic regulations. Spent fuel to be shipped in a cask is very hazardous due to high radioactivity and decay heat source.

All spent fuel shipping casks should be evaluated to determine their temperature responses under certain condition. The temperatures of fuel rod cladding, cask surface and shield materials should be determined by analytical method or thermal test. Specially the prediction of fuel cladding temperature is very important to the design and the safety analysis of spent fuel shipping cask.

The inner cavity containing fuel rods is filled with gas (dry cavity) or water (wet cavity) as a natural cooling medium. The recent casks tend to be developed in dry condition. Using air or gas instead of water offers several advantages. The main advantage is that the air in the dry cavity is at a slight vacuum and there is no risk of pressure buildup. The second advantage is that the dry shipments result in less contamination during the transport by erosion of activated and contaminated crud. Another advantage is, from a neutron interaction standpoint, that the absence of neutron moderation precludes an accidental criticality of the fissile contents. However, dry shipment results in high temperature of fuel rod due to the poor heat transfer characteristics of gas.

We have performed the thermal analysis when the fuel assembly is considered as a cylinder equivalent of square fuel assembly until quite recently. And this analytical method could not calculate the detailed temperature distribution for fuel rods. Therefore, it was required that detailed thermal analysis should be performed for spent fuel assembly under dry tansport condition. In this study, the temperature of fuel rod cladding is calculated by subchannel analysis.

COBRA-SFS [2] computer code is used to evaluate the temperature of fuel rod in the inner cavity of cask which is filled with three different filling gases such as air, nitrogen or helium.

2. Analysis Modelling

2.1. Heat Source

Decay heat from the irradiated PWR fuel assemblies is considered as a heat source in the thermal analysis. The decay heat is generated from the fuel assembly and is dependent on the burnup and cooling time. The decay heat rate from spent fuel assemblies is calculated by using the ORIGEN-2 [3] computer code.

Table 1 shows the decay heat rate as a function of burnup and cooling time. The heat source for this study is calculated on the basis of 1,2 and 3 years of cooling times with 38,000 MWD/MTU burnup. The decay heat generation from all of the fuel rods is assumed to be uniform and an axial decay heat power is displayed in Fig. 1 [4]. The axial power peaking factor of 1.2 is applied to this decay heat load.

Table 1. Decay Heat Load for 4 PWR Fuel Assemblies dependent on Burnup and Cooling Time

Cooling time (Years)	Decay heat(kw)		
	35,500 (MWD/MTU)	38,000 (MWD/MTU)	40,000 (MWD/MTU)
1	20.2	21.5	22.3
2	10.5	11.3	11.8
3	6.5	7.0	7.4
4	4.6	5.0	5.3
5	3.6	3.9	4.2

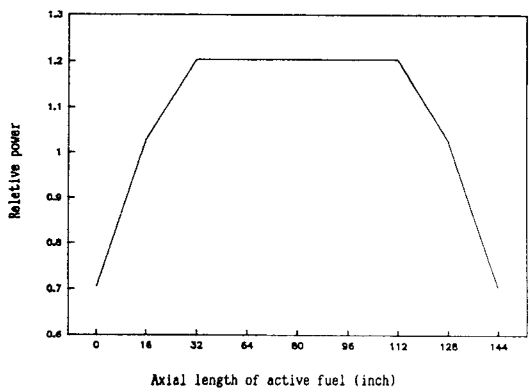


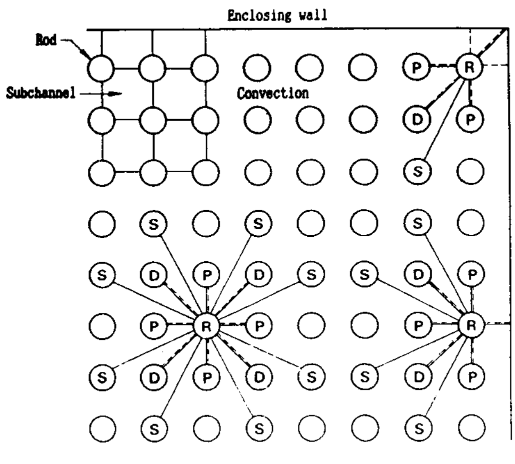
Fig. 1. Axial Decay Heat Profile for PWR Spent Fuel Assembly

2.2. Geometric Model

The COBRA–SFS was designed to predict flow and temperature distributions under a wide range of flow condition, including mixed and natural convection. This code includes a solution mehtod that calculates three-dimensional conduction heat transfer through a solid structure network such as a spent fuel cask basket or cask body, a detailed radiation heat transfer on a detailed rod-to-rod basis and the radiation and natural convection from the cask surface.

The heat transfer in a dry fuel element consists of radiation, conduction and natural convection. Fig. 2 shows the heat transfer links in fuel element consisting of radiation and conduction. The computation of temperature in COBRA-SFS is based on an energy balance of a single fuel pin considering the heat transfer to surrounding pin as far as two rows removed.

Radiation heat transfer occurs between the reference pin and the four closest (primary) pins, four diagonal pins and eight (secondary) pins located two rows from the reference pin. Conduction heat transfer occurs between the reference pin and the adjacent four primary pins as well as four diagonal pins. With the exception of the corner pins, heat transfer at the boundary of the element occurs by means of one conduction link and one combined radiation link between the enclosing wall and each pin of the outside row of the fuel element. One combined radiation link and three conduction links are utilized at each corner of the fuel element.



------ : Conduction links
——— : Radiation links
R : Reference pin
P : Primary pin
D : Diagonal pin
S : Secondary pin

Fig. 2. Heat Transfer Links in Fuel Element

A quarter section model for thermal analysis is shown in Fig. 3. By assuming symmetry of the cask geometry and fuel loading, the cask is simulated with a quarter section model. The cask body is composed of fuel baskets, inner shell and outer shell made of stainless steel. The lead between fuel basket and inner shell is casted for gamma ray shielding. Solid resin between the inner shell and outer shell is also casted for neutron shielding.

Axial length of analytical model is the active fuel length of 144 inches and the regions on the top and bottom are modeled as adiabatic boundaries. A total of 18 uniform nodes are used in the axial direction. The model is considered as a quarter cross section consisting of a fuel assembly, fuel

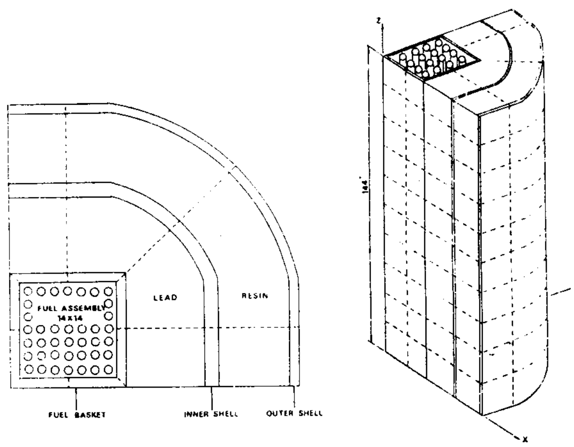


Fig. 3. Quarter Section Subchannel Analysis Model for Shipping Cask

basket, lead shield, inner shell, resin shield and outer shell. A total of 46 wall nodes at each axial level are used to model the heat transfer through the cask body. A 14×14 fuel assembly for Kori 1 unit is employed in the modelling and there are 196 rods and 225 fluid subchannels in a squre section.

Decay heat is removed from the fuel assembly to the inner basket by a combination of conduction, natural convection and radiation heat transfer through the cavity air. Conduction heat transfer through the basket and cask body is modeled by specifying the appropriate thermal resistance between adjacent wall nodes. The thermal resistance values may reflect a composite oı materials and parallel or series heat transfer paths. Decay heat is dissipated by a combination of natural convection and radiation heat transfer from the surface of cask.

2.3. Boundary Condition

The general form of heat transfer from a boundary surface is [5]

$$q_{boundary}=C_1\,[C_2(T_s-T_a)]^{c3}\,(T_s-T_a)+\sigma\,\epsilon\,(T_s^4-T_a^4) \qquad (1)$$

where, C_1, C_2, C_3=constant
σ =Stefan-Boltzmann constant
ϵ =surface emissivity of cask
T_s, T_a=cask surface and ambient temperatures

Natural convection heat transfer is characterized by the Nusselt number, Nu, which generally takes the form

$$Nu=C(Pr\ Gr)^n \qquad (2)$$

where, Pr=Prandtl number Gr=Grashof number

The Grashof number is defined as

$$Gr=\frac{D^3\rho^2\beta g}{\mu^2}\Delta T \qquad (3)$$

Therefore, Grashof-Prandtl number at the cask surface is calculated as

$$Gr.Pr=5.3\times10^9 \qquad (4)$$

The Nusselt number for the surface of cask in a vertical or a horizontal orientation can be calculated using the expression

$$Nu=0.13(Pr\ Gr)^{0.333} \qquad (5)$$

Therefore, the heat flux due to natural convection can be expressed using eq.(1) by specifying the constants

$$C_1=\frac{C\,k}{D},\ C_2=Pr\frac{D^3\ \rho^2\ \beta g}{\mu^2},\ C_3=n \qquad (6)$$

where, ρ =density(kg/m^3)
β =coefficient of thermal expansion(/℃)
g=acceleration due to gravity(m/sec^2)
μ =fluid viscosity(kg/m sec)
D=cask diameter(m)
k=thermal conductivity(W/m℃)

Natural convection coefficient at the cask surface is calculated as

$$C_1=3.35\times10^{-3}\ W/m^2\ ℃,\ C_2=2.64\times10^7/℃,\ C_3=0.333 \qquad (7)$$

Therefore, heat transfer coefficient can be expressed as

$$H_{nc}=1.0(\Delta T)^{0.333}\ W/m^2\ ℃ \qquad (8)$$

Heat transfer from the rods and walls to the coolant is prescribed using the film coefficient of the form Nu=3.66[6]. The formulation is an analytical solution of the energy equation for flow in a circular tube with a coolant surface temperature and fully developed velocity and temperature profiles. The emissivity values for highly oxidized zircaloy clad fuel rods and stainless steel are selected with 0.8[7] and 0.3[8].

3. Subchannel Analysis

Subchannel analysis is performed for three backfills of air, nitrogen or helium gas in the dry cavity of cask. These gases are normally used in the dry type transport cask. The analysis is based on the cooling time of 1 to 3 years for three backfill gases.

Fig. 4 shows the axial temperature profiles of fuel rod with three backfill gases for 1 year cooling time of fuel assembly. As the thermal characteristics of natural air are very similar to nitrogen gas, the temperature profiles are nearly identical. The temperature of fuel rod is higher in the air than the helium gas. This is due to the good conductivity of helium gas in comparison with air. The peak temperature is slightly skewed toward the upper part in the air cavity. It is due to the effects of thermal convection of the backfill gas.

Figs. 5, 6 present the temperature profiles of fuel rod according to the cooling time of fuel assembly in the inner cavity of air and helium gas. As a result, it is found that the temperature increases linearly in proportion to the decay heat rate.

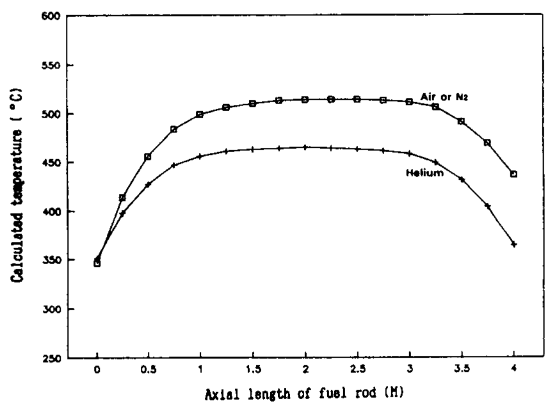


Fig. 4. Axial Temperature Profiles of Fuel Rod according to the Backfills of Air, Nitrogen and Helium Gas (1 year cooling time)

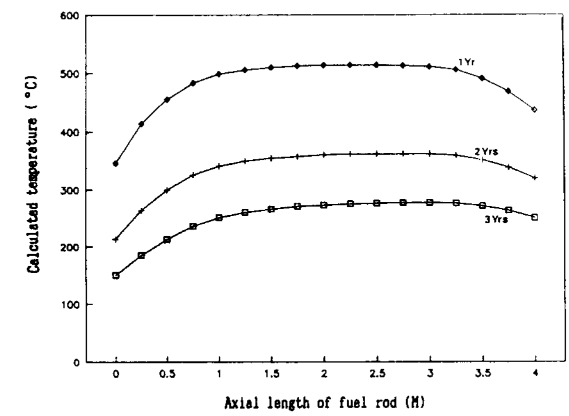


Fig. 5. Axial Temperature Profiles of Fuel Rod according to the Cooling Time 1, 2 and 3 Years (backfill gas : nitrogen)

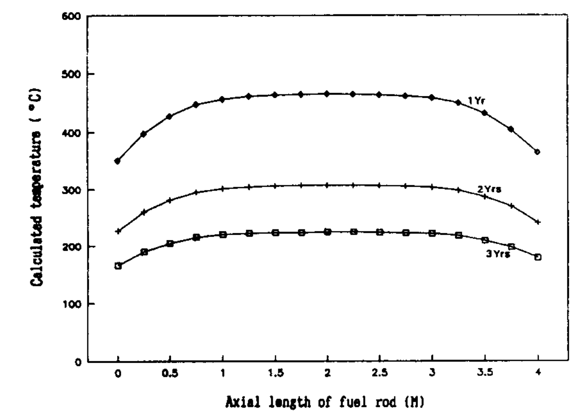


Fig. 6. Axial Temperature Profiles of Fuel Rod according to the Cooling Time 1, 2 and 3 Years (backfill gas : helium)

4. Results and Discussions

The analysis results for dry transport of cask are summarized in Table 2.

Inner cavity of cask is considered to be filled with natural air, nitrogen or helium gas and the decay heat of spent fuel is dependent on the cooling time. The temperatures of cask body are almost identical for three backfills of gas. However, it appears that the temperatures of basket in-

Table 2. Summarized Results of Thermal Analysis for Dry Shipment of the Shipping Cask

Location	Calculated temperatures(℃)				Allowable value
	1 Year		3 Year		
	Air, N_2	Helium	Air, N_2	Helium	
Max. fuel rod	514	465	277	226	532
Fuel basket					
Inner surface	482	440	227	201	
Outer surface	273	274	123	124	
Lead shield	261	262	120	120	327
Inner shell	255	255	118	118	
Resin shield	197	198	99	100	
Cask surface	145	145	83	83	
Ambient temp.	38	38	38	38	38

side and fuel rod are higher when air is used than helium gas. The temperature differences are 26 to 42℃ in the basket and 49 to 51℃ in the fuel rod. This is because the thermal conductivity of air is lower than that of helium gas about one fifth.

The maximum temperature of fuel rod is 514℃ in case of air cavity loaded with fuel assemblies of 1 year cooling time. And when the helium gas is filled in the fuel cavity, the temperature of fuel rod decreases to 465℃. This value is slightly below 532℃ [9] which is the beginning temperature of fuel cladding oxidation in dry cavity.

The maximum temperature of fuel rod is 227℃, however, if the 3 years of cooling time is applied to the design basis spent fuel of cask. Specially, the design basis of fuel cooling time for the shipping cask is 3 years and it is shown that the thermal integrity of fuel assembly is maintained under dry transport condition. The temperature of lead shield is lower than the allowable value.

From the results of the above thermal analysis, it is possible to verify the thermal safety of cask under dry transport condition.

5. Conclusion

The thermal analysis was performed to verify the thermal safety of spent fuel shipping cask under dry transport condition. The maximum temperatures at each part were lower than the allowable values. Specially, the fuel rod temperature was below the specified temperature of 532℃. Therefore, it is shown that the thermal integrity of shipping cask is maintained in the transport under dry condition.

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