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Thermal Analysis on the Spent Fuel Shipping Cask for a PWR Fuel Assembly

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PWR 사용후 핵연료 수송용기에 대한 열해석

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Abstract

The thermal analysis on the spent fuel shipping cask for a PWR fuel assembly is performed. Under the normal and fire-accident conditions the temperature distribution through a multilayer cask calculated in compliance with 10 CFR Part 71. A KNU 5&6 spent fuel assembly is assumed to be the decay heat source, which has the maximum discharge burnup of 45,000MWD/MTU and has been stored in the spent fuel storage pool for 300 days. As a result of thermal analysis, the maximum cladding temperature in case of dry cavity under fire-accident conditions is calculated to be 455°C. This value is much less than the limiting value specified in 10 CFR Part 50.46. It indicates that no fuel rod cladding rupture could occur under fire-accident conditions. It was also found that no melting of lead would take place in the major shield region.

요 약

하나의 PWR 핵연료 집합체를 수송할 수 있는 사용후 핵연료 수송용기에 대한 열해석을 수행하였다. 정상 및 화재사고 조건하에서 수송용기에 대한 온도분포는 10CFR Part 71에서 제시한 조건에 맞도록 계산하였다. 붕괴열은 연소도가 45,000 MWD/MTU이고 사용후 핵연료 저장실에서 300일 냉각기간을 가진 KNU 5&6 핵연료 집합체를 고려하였다. 계산결과 화재사고시 dry cavity 조건하에서 핵연료 피복관의 최대온도가 455°C로 계산되었으며, 이 값은 10CFR Part 50.46에 규정된 최대 피복관 제한치 보다 훨씬 낮게 나타났다. 이것은 수송용기의 운반중에 화재사고 조건하에서도 핵연료 피복관의 파손이 일어나지 않는 것으로 설명된다. 그리고 중요 차폐체인 납의 용융도 일어나지 않았다.

I. Introduction

About one third of all the nuclear fuel assemblies installed in a core are discharged from nuclear power plant every year. These assemblies have been also stored in on-site spent fuel storage facility which is continuously cooled by light water. The storage capacity of the on-site storage pool is limited. Therefore, the fuel assemblies should be transported to an away-from-reactor (AFR) storage facility with sufficiently large capacity soon or later, and also some fuels would have to be transferred to a post-irradiation examination facility for the examination of their mechanical integrity, burnup or cause of failure. In order to transport the fuel assemblies, shipping casks are inevitable. Spent fuels to be shipped in a cask are very hazradous due to high radioactivity and high decay heat source. All shipping casks should be evaluated to determine their temperature responses in thermal environments under normal and accident conditions. Specifically, the temperatures that should be determined are the maximum fuel, cask cavity water or air and cask surface temperature under normal conditions. Under fire-accient conditions the temperature profile should be also evaluated.

Analyses are performed for loading a spent fuel assembly of KNU-5&6 (Korea Nuclear Unit 5&6) For calculating the steady-state temperature distributions, the envirature the environ mental temperature under direct solar heat is based on CFR Part 71. Under hypothetical fire-accident conditions the surface of the cask is assumed to be exposed to the 800°C radiant thermal environment for 0.5 hour. The heat transfer problem of the cask was solved by a computer program, HEATING-5[1], based on the finite difference method. In theoretical consideration, the heat transfer equations with possible boundary conditions of the cask are described and considered numerically by using finite difference approximation of a heat balance model. Heat sources are classified as the decay heat load and solar heat load. The geometrical model used for the heat transfer computations is a composite multi-layer that contains conduction and convection layer.

II. Theoretical Consideration

2.1. Heat Transfer Equation

The governing equation for two-dimensional transient condition problem with internal heat generation follows in terms of cylindrical coordinates.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}+\frac{q'''}{k(T)}=\frac{1}{\alpha(T)}\frac{\partial T}{\partial t} \tag{1}$$

where, q'''=internal heat generation rate with constant value,

$k(T)$=thermal conductivity, dependent on temperature and materials,

$\alpha(T)=\frac{k(T)}{\rho(T)C_p(T)}$, thermal diffusivity, dependent on temperature and ma terials,

t=time.

The boundary conditions for multi-layer heat transfer model can be specified as follows;

a) radial convection

$$-k(T)A\frac{\partial T}{\partial r}=hA(T-T_a), \tag{2}$$

b) radial convection and radiation

$$-k(T)A\frac{\partial T}{\partial r}=hA(T-T_a)+\partial FA(T^4-T_a^4), \tag{3}$$

c) radial outer surface solar heat flux, conve ction and radation.

$$-k(T)A\frac{\partial T}{\partial r}=q''_s+hA(T-T_a)+\partial FA(T^4-T_a^4), \tag{4}$$

d) axial insulation

$$-k(T)A\frac{\partial T}{\partial Z}=0, \tag{5}$$

e) axial convection

$$-k(T)A\frac{\partial T}{\partial Z}=hA(T-T_a) \tag{6}$$

where A is the surface area of the boundary, h is the natural convection heat transfer coefficient, T_a is the ambient temperature and the opposing surface of internal boundary, σ is the Stefan-Boltzmann constant, F is the emissivity of surface materials, and q_s'' is the solar heat flux.

2.2. Numerical Analysis

The numerical analysis for the solution of the heat transfer functions, which has no analytical solution, has been carried out in the finite difference and finite element method with the aid of computer. The finite difference method is a possible technique for complexity of the multi-layer. The differential equation and boundary conditions mentioned in the preceding section may be converted into finite difference form.

A specified node, i, is connected with j adjacent nodal points. The heat which is conducted from point i should be equal to the rate of heat generation rate at that nodal point. Thus, the general heat balance equation at node i which has j neighbors could be written as

$$Q_i^n+\sum_{j=1}^{l}{}_iK_j(T_j^n-T_i^n)=C_i\frac{T_i^{n+1}-T_i^n}{\Delta t}, \tag{7}$$

where ${}_iK_j$ is thermal conductance including conductivity, convection and radiation heat transfer between node i and j, Q_i^n is the heat generation rate at time t_n, T_j^n is the temperat ure at node j adjacent to node i at time t_n, and C_i is the heat capacitance of the materials expressing their specific heat and density.

For a steady-state heat conduction, the heat balance equation is reduced to

$$Q_i+\sum_{j=1}^{l}{}_iK_j(T_j-T_i)=0. \tag{8}$$

The values of T_i which satisfy Eq. (8) can be obtained only after many iterations. Since the values of T_j are unknown, the temperature at node i can not be obtained by direct calculation of Eq.(8). An iterative procedure can be, however, used to estimate the steady temperature distribution. The m^{th} iteration in Eq. (8) gives actually

$$Q_i+\sum_{j=1}^{l}{}_iK_j(T_j^m-T_i^m)=R, \tag{9}$$

where R is a residual term, and can be written as

$$R=\sum_{j=1}^{l}{}_iK_j(T^{m+1}-T_i). \tag{10}$$

Combining Eqs. (8) and (9) gives

$$(T_i^{m+1}-T_i^m)\sum_{j=1}^{l}{}_iK_j=\sum_{j=1}^{l}{}_iK_j(T_j^m-T_i^m)+Q_i \tag{11}$$

By using Eq. (10) the temperature unbalance is caused at each node. Then it is desirable to overrelax the unbalance in order to increase the convergence. This can be done by multiplying the relaxation factor β to the right hand terms of Eq. (11).[2] Thus, the temperature at $(m+1)^{th}$ interate becomes

$$T_j^{m+1}=(1-\beta)T_i^m+\beta\left[\frac{\sum_{j=1}^{l}{}_iK_jT_j^m+Q_i}{\sum_{j=1}^{l}{}_iK_j}\right] \tag{12}$$

If the nodes are numbered along the r-axis from left to right and along the z-axis from bottom to top, the rate of convergence in the iterative procedure can be increased by using the above equation.

Successive iterations are carried out until

$$\left|\frac{T_i^m-T_i^{m+1}}{T_i^{m+1}}\right|\leq\epsilon \tag{13}$$

where ϵ is the specified convergence criteria.

The implicit procedure using the Crank-Nicolson heat balance equation[3] is introduced for solving transient thermal problems.

The equation is solved by successive overrelaxation iteration. This technique have been used to apply the optimum acceleration parameter for faster convergence to the approximate of the temperature distribution at the new time level. The procedure that the lefth-and side of Eq. (7) is evaluated at $t_{n+1/2}$ instead of t_n is known as the Crank-Nicolson procedure. A general algorithm of heat balance equation which emploies the Crank-Nicolson procedure becomes

$$Q_i^{n+1/2}+\frac{1}{2}\left[\sum_{j=1}^{l}{}_iK_j^{n+1/2}(T_j^{n+1}-T_i^{n+1})\right]$$

$$+\frac{1}{2}\left[\sum_{j=1}^{l}{}_iK_j^{n+1/2}(T_j^{n}-T_i^{n})\right]$$

$$=C_i^{nn+1/2}\frac{T_i^{n+1}-T_i^{n}}{\Delta t} \tag{14}$$

where the superscript $(n+1/2)$ implies that the parameter is evaluated at time $t_{n+1/2}$. If there are m nodes in the problem and the heat balance equation, Eq. (14), is written for each node, the existance of m equations and m unknowns can be solved by iteration. The brief description of iterate procedure is outlined below. If the temperatures at t_{n+1} in Eq. (14) are arranged on the right-hand side, the resulted equation can be expressed as;

$$-\frac{1}{2}\left(\sum_{j=1}^{l}{}_iK_j^{n+1/2}T_j^{n+1}\right)$$

$$+\left[\frac{C_i^{n+1/2}}{\Delta t}+\frac{1}{2}\left(\sum_{j=1}^{l}{}_iK_j^{n+1/2}\right)\right]T_i^{n+1}=P_i \tag{15}$$

where,

$$P_i=Q_i^{n+1/2}+\frac{C_i^{n+1/2}}{\Delta t}T_i^{n}$$

$$+\frac{1}{2}\left[\sum_{j=1}^{l}{}_iK_j^{n+1/2}(T_j^{n}-T_i^{n})\right] \tag{16}$$

Let

$$D_i=\frac{C_i^{n+1/2}}{\Delta t}+\frac{1}{2}\left(\sum_{j=1}^{l}{}_iK_j^{n+1/2}\right), \tag{17}$$

and delete the superscript $n+1$ on the temperature T, then ***Eq.*** (15) can be written as

$$-\frac{1}{2}\left(\sum_{j=1}^{l}{}_iK_j^{n+1/2}T_j\right)+D_iT_i=P_i, \tag{18}$$

where it is now described that T_i represents the temperature of node i at the new time level. Eq. (18) for T_i term becomes

$$T_i=\frac{\frac{1}{2}\left(\sum_{j=1}^{l}{}_iK_j^{n+1/2}T_j\right)+P_i}{D_i} \tag{19}$$

Since the values of T_j are unknown, the direct solution for the temperature at node i can not be obtained. However, if an estimate of the temperature distribution exists at the new time level, then Eq. (19) can be solved at each node. This process should be continued untill the convergence is reached to its approximation. This algorithm is described by

$$T_i^{(m+1)}=\frac{\frac{1}{2}\left(\sum_{j=1}^{l}{}_iK_j^{n+1/2}T_j^{(m)}\right)+P_i}{D_i}, \tag{20}$$

where the superscript (m) on T_i indicates the m^{th} iteration at node i at the new time level. Eq. (20) is rewritten by introducing an acceleration parameter for faster convergence.

$$T_i^{(m+1)}=(1-w)\,T_i^{(m)}$$

$$+w\left[\frac{\frac{1}{2}\left(\sum_{j=1}^{l}{}_iK_j^{n+1/2}T_j^{(m)}\right)+P_i}{D_i}\right] \tag{21}$$

The iteration for each node in Eq. (21) is continued until the convergence criteria have been met. The convergence criteria are defined as follows, When the m^{th} iteration has been completed, the results obtained by inserting the m^{th} iterated values into Eq. (18) denote the heat residual as

$$R_i^{(m)}=P_i+\frac{1}{2}\left(\sum_{j=1}^{l}{}_iK_j^{n+1/2}T_j^{(m)}\right)-D_iT_i^{(m)} \tag{22}$$

The convergence criteria is defined as the normalized term of heat residual devided by Eq. (16);

$$\left(\frac{R_i^{(m)}}{P_i}\right) \leq \epsilon. \quad (23)$$

In general, a boundary condition is applied along the surface of a region and heat is transferred from a surface node to a boundary node. For the boundary conditions, the leakage term in Eq.(7) is calculated as follows:

$${}_iK_j(T_j^n - T_i^n) = {}_iK_b(T_b^n - T_i^n), \quad (24)$$

where ${}_iK_b$ is the effective conductance from surface node i to the boundary node b or the opposing surface node b considered by internal boundary conditions. T_b^n is either the temperature of boundary node b or the opposing surface node at time t_n. The effective ccnductance is calculated as

$${}_iK_b = h_e A, \quad (25)$$

where h_e is the effective heat transfer coefficient, and A is the surface area, normal to the heat flow path, of node i associated with boundary condition. The effective heat transfer coefficient is defined as

$$h_e = C(T_i^n - T_b^n)^a + h_r[(T_i^n)^4 - (T_b^n)^4], \quad (26)$$

where C and a are the coefficient and exponent for the natural convective heat transfer,[4] and h_r is the coefficient given by gray body shape factor and Stefan-Boltzmann constant for radiative heat transfer[5]. And other thermal properties including conductivity, specific heat and density are dependent on temperature.[6]

III. Definition of Heat Transfer Problems

3-1. Heat Sources

The temperatures of the fuel surface and the cask surface under normal operating conditions are dependent on the heat load.The heat stems from two sources: the decay heat load caused by the radioactive decay of isotopes within the fuel assembly being shipped, and the solar heat load due to solar radiation on the surface of the cask. Although both sources change with time, variations in the decay heat load are generally insignificant during transportation.

Table 1. Decay Heat Rate of KNU-5 & 6 Fuel Assembly

Cooling time (Days)	Decay heat rate (kw)		
	35,000 MWD/MTU	40,000 MWD/MTU	45,000 MWD/MTU
90	11.6	13.5	15.4
150	8.59	10.1	11.6
180	7.62	8.94	10.4
240	6.23	7.36	8.53
270	5.72	6.77	7.87
300	5.30	6.28	7.37
330	4.94	5.86	6.84
365	4.57	5.44	6.41

Decay heat is the major portion of the total heat load that must be dissipated. The amount of decay heat that is generated by the spent fuel assembly is dependent on the irradiation time in the reactor (burnup) and the cooling time in the on-site spent fuel storage. The decay heat rate from one fuel assembly was calculated by using the burnup calculation code, ORIGEN,[7] for Korea Nuclear Unit 5&6(KNU-5 &6). Table 1 represents the decay heat rate of KNU-5&6 fuel assembly versus the cooling time and burnup.

The maximum amount of solar radiation received by a point on the surface of the earth is based on clear summer days. Direct solar radiation at noon on July 21 in 1968 presented by the Pusan Meteorologicae Officl is considered as a maximum solar radiation. At that time, the direct solar heat flux was 894W/m^2. The solar heat load affecting the cask surface must be multiplied by the absorptivity of that surface. The absorptivity on the surface of polished stainless steel is 0.37[9]. Thus, the solar heat load becomes 331 W/m^2.

3-2. Geometrical Model

A triple cylindrical container unit is considered as an inner shell which contains the spent fuel basket, an intermediate shell which

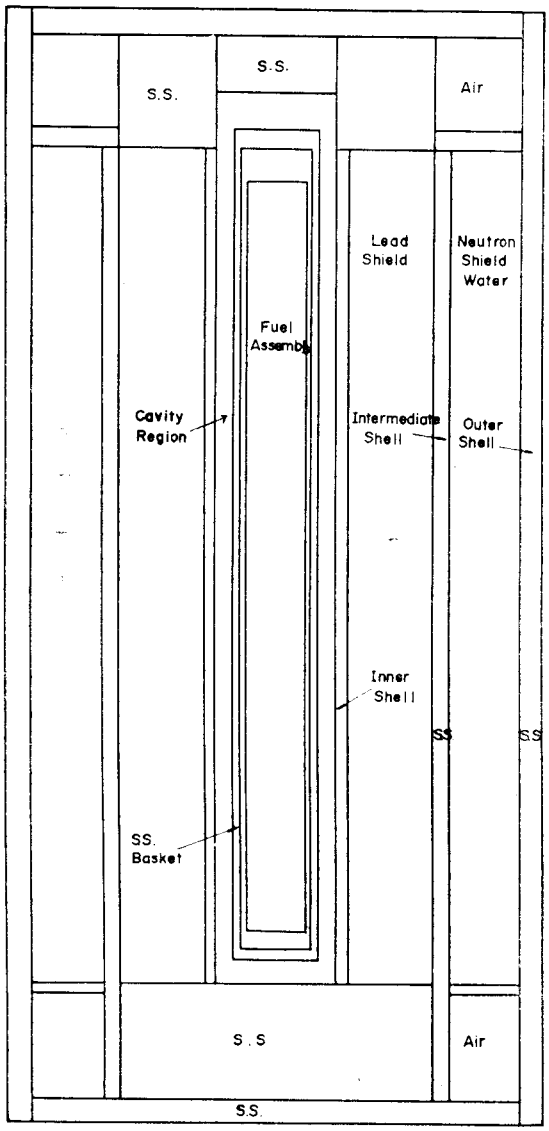

Fig. 1. Geometrical Model of Cask

contains the lead shield and an outer shell which holds neutron shielding water. These shells are made of stainless steel. Upper and lower supports are also made of stainless steel casting. The configuration of the model used for the heat transfer computations is shown in Fig. 1. The fuel assembly is considered to be an cylinder equivalent to a square assembly. The material contents are modelled as a uniform. The cavity between fuel basket and inner shell is either full of water or air.

IV. Results and Discussions

4-1. Normal Conditions

The ambient temperature around the surface of the cask is assumed to be 54.4°C recommended by 10 CFR Part 71. This could be the maximum value of the earth surface temperature during the summer in our country. While air is still, direct solar heating has an effective intensity of 331 W/m^2 on all exposed surface of the cask. The decay heat of a single spent fuel assembly with 300 days cooling time is found to be 7.37Kw from Table 1 in the previous chapter. Decay heat is transfered first from the fuel to the inner basket by the natural convection and then through the cavity region between the basket and inner shell by natural convection and through the lead shield layer by conduction. Natural convection in the water-filled neutron shield is brought about, and finally decay heat is removed by a combination of air natural convection and radiation from the surface of the cask. It is assumed that the potential local boiling on the fuel surface does not occur.

The temperature distribution through each layer of the cask in the radial direction is shown in Fig. 2. The distribution is obtained for normal condition of transport. The temperature gradient is found not to be high in case of the wet condition in which the water is contained in the inner basket and the inner cavity. The fuel surface temperature in the outer zone of fuel assembly reaches 160°C. However, in case of dry condition which the inner basket and the cavity do not contain water, the temperature gradient at inner region is high. This is due to air convection which has a low convection heat transfer rate. In this case, the fuel cladding surface temperature increases to 314°C.

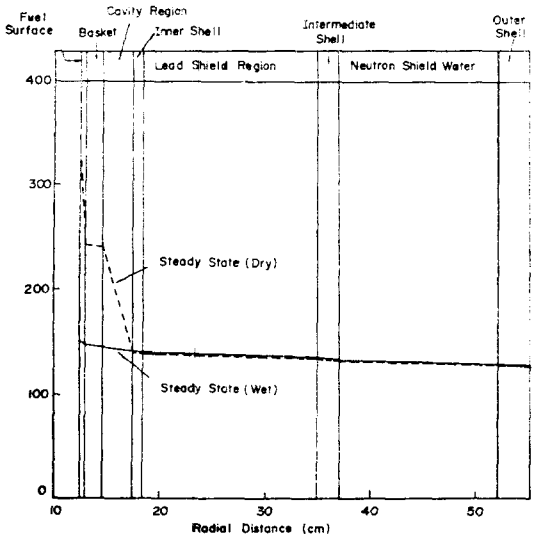

Fig. 2. Steady-state Temperature Distribution from Cask Centerline

4-2. Fire-accident Conditions

The fire-accident conditions are assumed to result in the loss of neutron shield water under 0.5-hour fire as specified in Appendix 3 of 10 CFR 71. When the neutron shield water releases instaneously, the cask is exposed to a the thermal radiation environment of 800°C for 30 minutes. After the fire the shipping cask is cooled by itself untill equilibrium conditions are reached in ambient air at 54.4°C Heat transfer within the cask occurs by a combination of radiation and air natural convection in the neutron shield region. The decay heat load throughout the entire accident is similar to that specified under normal conditions, but solar heat load was neglected during the fire.

Fig. 3 shows the temperature distributions for the wet cavity condition and Fig. 4 shows the temperature distributions for dry cavity condition versus transient time. Under the 0.5-hour fire accident condition, the fuel assembly

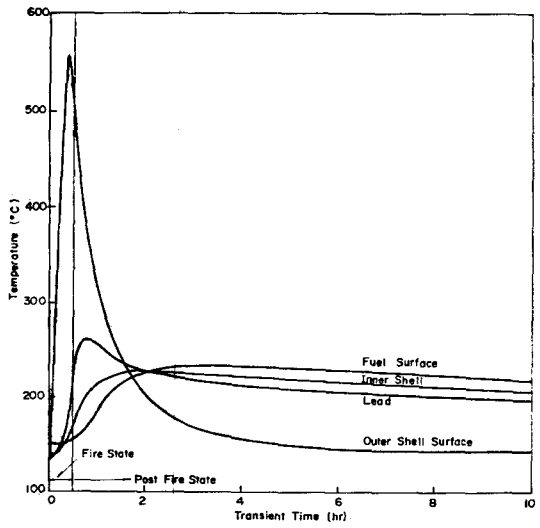

Fig. 3. Transient Temperature Distribution in Wet Cavity Conion

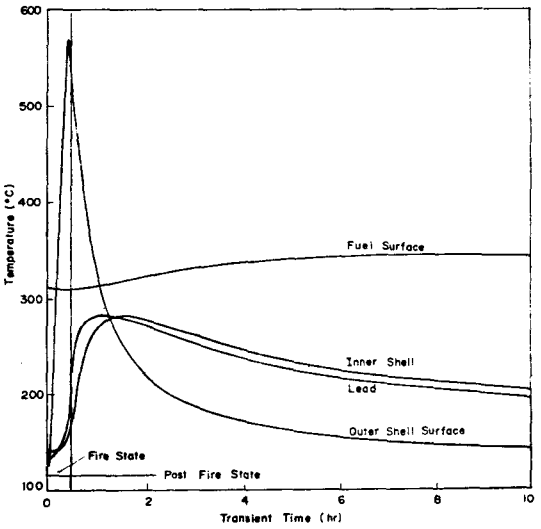

Fig. 4. Transient Temperature Distribution in Dry Cavity Condition

temperatures will increase. During transient state, the temperature on the fuel cladding surface increases from 160°C to a maximum of 243°C in case of wet cavity and from 314°C to a maximum of 350°C in case of dry cavity as shown in Fig. 3 and 4.

The fuel cladding temperatures in the central zone of a fuel assembly are based on a maximum local temperature which includes a radial peaking factor of 1.3. This peaking factor is based on a dry fuel assembly modeled in two dimension.[10] Therefore, the maximum temper-

ature of fuel cladding reaches 455°C in case of dry cavity under fire-accident conditions. Since fuel temperatures affect fuel integrity which may cause the fission gases to leak due to cladding rupture, fuel temperature limitations should be considered in thermal analysis.

The maximum temperature of fuel cladding specified in 10 CFR Part 50.46 is limited to be 1204°C. The calculated cladding temperature of 455°C in the central zone of fuel assembly is lower than the limiting value. It indicates that the fuel rod cladding is not expected to be ruptured during fire-accident state.

No melting of the lead occurs at the lead shielding layer as shown in Fig. 3 and 4, since lead shield temperatures of both cases are below 300°C compared with the melting point of 327.5 °C. Melting of the lead may result in reducing major shielding efficiency of the cask body.

V. Conclusion

The thermal analyses performed indicate that no unusual thermal response characteristics would occur. Under normal operation, the fuel cladding surface in the outer zone of fuel assembly reaches a temperature of 160°C in wet cavity and 314°C in dry cavity. The maximum temperature on the surface of the cask is as high as 134°C under direct solar heat.

As a result of fire-accident analysis, it was concluded that fuel cladding temperatures in the outer zone of fuel assembly would not exceed 243°C in wet cavity and 350°C in dry cavity. The maximum fuel cladding temperature of 455°C in the central zone of fuel assembly is lower than the limiting value of 1204°C. This shows that no fuel cladding rupture would occurs. And the melting of lead is not expected to occur for post-fire state.

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