A Study on the Temperature Distribution in the Shipping Cask of Spent Nuclear Fuels at LOCA

AUTHOR(S):

NAKAI, Hiroshi; SHIBATA, Toshinobu

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By

Hiroshi NAKAI* and Toshinobu SHIBATA*

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Abstract

In this paper, the authors studied the temperature distribution in a shipping cask of spent nuclear fuels at LOCA (loss-of-coolant accident) after a failure of the cask. The calculation was made on a model of a uni-axial (in radial direction) thermal transfer.

The result shows that the decay heat which cannot be cooled down will cause the temperature to go over 1000°C at the central part of the cask. A very dangerous accident will occur at such a high temperature; i.e., the vapor of cesium, a radioactive isotope, will flow out from the cask into air, and the water-metal reaction will produce a great deal of heat and hydrogen. Because of this, the nuclear fuels at the central part will collapse and melt down.

1. Introduction

The increasing number of atomic power generating stations and the developement of self-made nuclear fuel cycles are accompanied by the need to increase the transportation of various radioactive matters. In particular, the transportation of spent nuclear fuels is said to be one of the most dangerous and difficult of operations. Since 1961, in Japan, spent nuclear fuels have been transported many times[1)], but nowadays experiments have been continuously made to test the safety of such transportation.[2)]

The spent nuclear fuels, in a special vessel which is called "cask", are transported by sea or by land from the atomic power generating stations to reprocessing plants. Therefore, the cask should be perfectly safe so as to prevent the danger of any radioactive rays leaking, and also to prevent the radiation shield ability and cooling ability from failling off.

Discussion has been done on the core-melting accident, one of the major accidents of atomic power generating plants, caused by the loss of cooling water. What would happen by the loss of the cooling water in the cask? The conclusion for this problem has not yet been finalized.

* Department of Mechanical Engineering.

In this paper, the authors calculated the temperature distribution in a cask at a loss-of-coolant accident by the cask failure. Then, they discussed whether such an accident could develop into a major accident, meaning the melting of the spent nuclear fuels.

2. The Cask Forms and the Behavior at the Accident

The spent nuclear fuels are usually transported from an atomic power plant after a cooling period of 90 to 180 days. Even after this cooling period, the fuels include a great deal of nuclear fission products which continue to produce many kinds of radioactive rays and decay heat. Table 1 shows the radioactive rays

Table 1. Specific radioactivity (Ci/ton) and specific decay heat (W/ton) of spent nuclear fuels[3)]

Cooling period (day)		90	150	365	3650
Specific radio-activity (Ci/t)	Total fission products	6.19×10^6	4.39×10^6	2.22×10^6	3.17×10^5
	^{85}Kr	1.13×10^4	1.12×10^4	1.08×10^4	6.05×10^3
	^{131}I	3.81×10^2	2.17×10^0	—	—
	^{137}Cs	1.10×10^5	1.06×10^5		
	Actinides (Pu, etc.)	1.42×10^5	1.36×10^5	1.24×10^5	
Decay heat (watt/ton)		2.71×10^4	2.01×10^4	1.04×10^4	1.06×10^3

Degree of burn-up of spent nuclear fuel is 33000MWD/ton

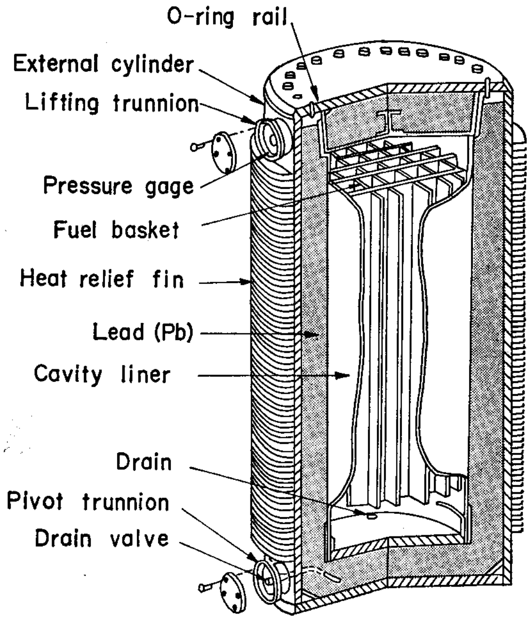

Fig. 1.

and decay heat per 1 ton of the spent nuclear fuels. A large scale cask can hold about 10 tons of such spent nuclear fuels.

A skeleton of the standard type cask is shown in Fig. 1. At present, the type of cask used in Japan is the HZ75T type, corresponding to the B (or M) type transporting vessel prescribed by IAEA. The major dimensions of the HZ75T cask are as follows:

dimensions	total length (including the buffer)	5.9 m
	external diameter	2.1 m
weight	total weights	77~78 tons
number of fuel assemblies received	7 for PWR	
	17 for BWR	

Fig. 2 shows a cross-sectional figure of the HZ75T cask, in which the arrangement of the fuel assemblies are for the BWR types.

After 90 days cooling, when the spent nuclear fuels (the weight of which is 3.2~3.4 tons) are placed into the cask, the cask will hold a total radioactivity of 2×10^7 *Ci* and a decay heat of about 90 kw (about 78000 kcal/h). Of course, these values are changed by the degree of burn-up as well as the cooling days of

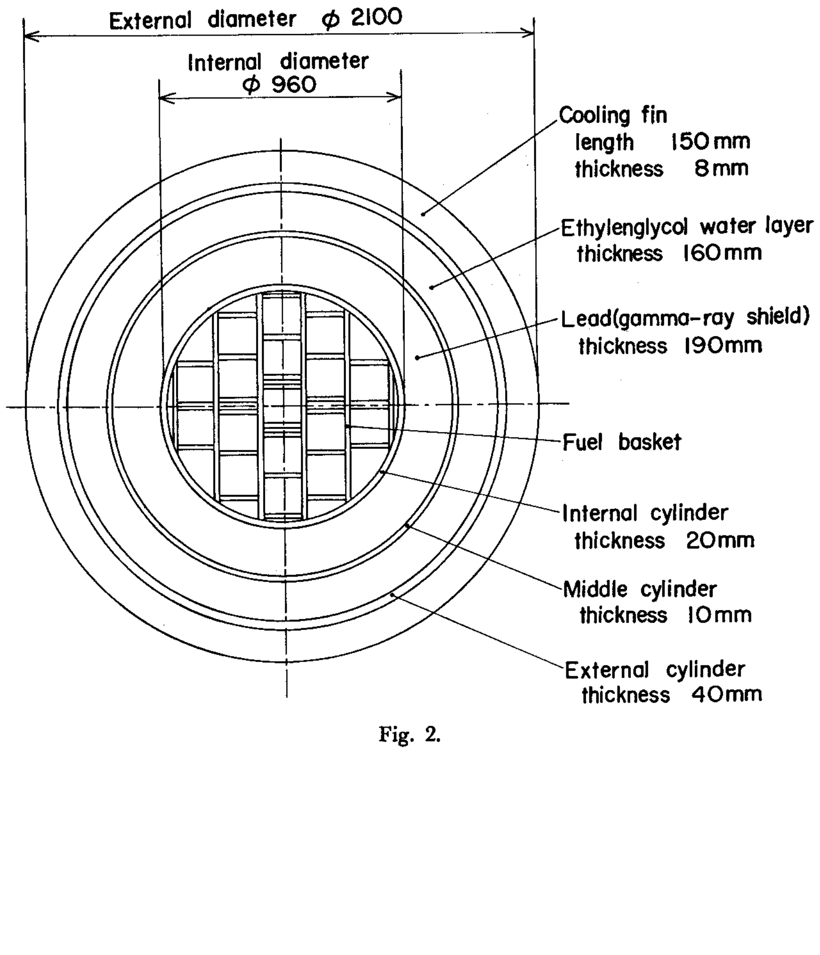

Fig. 2.

the fuels.

The HZ75T type cask consists of three concentric cylinders made of stainless steel. The internal cylinder receives the fuel baskets, and is filled with cooling water to remove the decay heat. Lead, with a thickness of 19 cm, is placed between the internal and the middle cylinders to shield the γ-ray. The space between the middle and the external cylinders is filled with 50 % ethylenglycol water to shield the neutron, and is arranged with forced-circulating cooling water pipes which are used when the cask is transported by sea. The external surface of the external cylinder is covered by 80 cooling fins with a rectangular cross section. The lid of the cask is fixed by use of bolts. The enclosing of the cooling water and the regulation of the pressure are made by the valves set at the cask. The decay heat is removed by the natural convection of the coolant in the cylinder and the conduction of the cylinder metal in order to hold the fuel within a safe temperature.

However, when the cooling water is lost by some accident during the transportation, the heat removal mentioned above will be obstructed, and the temperature of the fuel will be increased by the decay heat.

In the following, we obtain the temperature distribution analytically at a loss-of-coolant accident, and discuss the results.

3. The Model to Calculate the Temperature Distribution and the Analytic Method

It is impossible to obtain the temperature distribution in the cask for the real arrangement of the nuclear fuels. Therefore, we try to make a calculation by assuming an adequate model of the nuclear fuel arrangement. That is, we assume that the fuels are arranged concentrically in the cask, as shown in Fig. 3, and that the dimension of the cask is simplified as shown in Fig. 4. In this model, 833 fuel rods (17 fuel assemblies for BWR) are assumed to be arranged into 15 concentrically cylindrical fuel layers as shown in Fig. 3. The first layer at the center contains one fuel rod and the *k-th* layer contains $8(k-1)$ fuel rods. Let the thickness of each layer be equal to the diameter of the fuel rod 14.4 mm, and let the space between each layer be the same. Then the internal diameter of the *k-th* layer is $64(k-1)$mm. Let the temperature at the *k-th* layer by $T(k)$, the temperature at the internal wall of the cask be T_6, the temperature at the external surface of the cask (at the bottom of the cooling fin) be T_1, and the temperature of the surrounding air be T_0.

The analytical method to determine the temperature distribution is as follows: (1) First, we assume adequately the temperature at the first fuel layer $T(1)$. (2) Then, we calculate the temperature at each part by using equations which will be

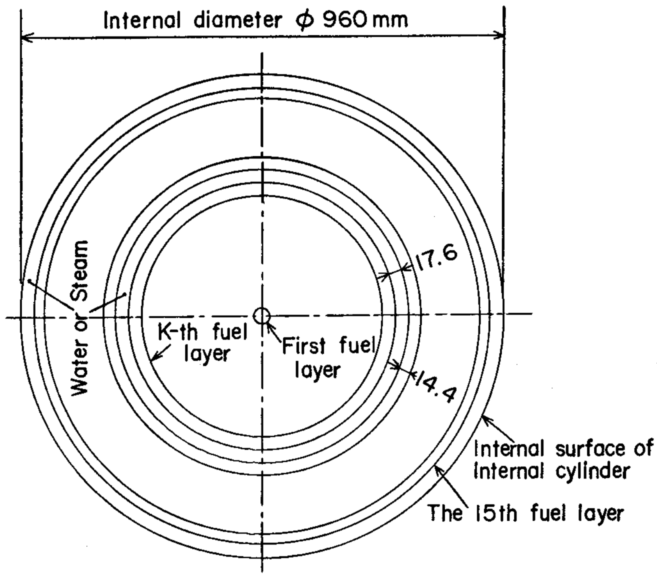
Internal diameter ϕ 960 mm
17.6
Water or Steam
K-th fuel layer
First fuel layer
14.4
Internal surface of Internal cylinder
The 15th fuel layer

Fig. 3.

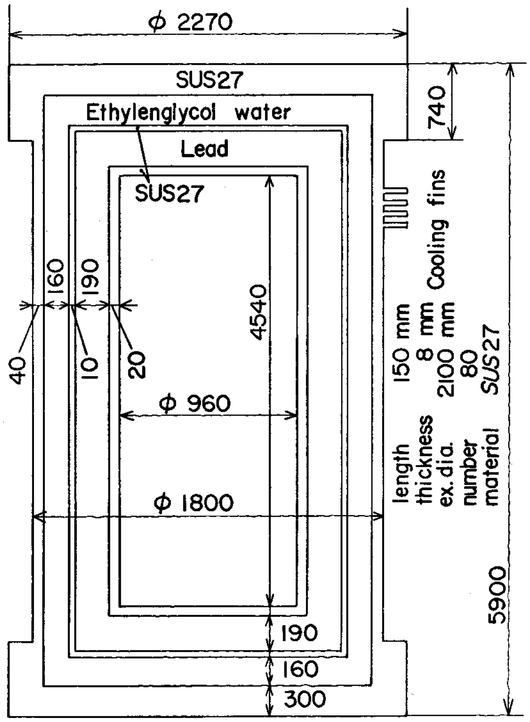
ϕ 2270
SUS27
Ethylenglycol water
Lead
SUS27
740
Cooling fins
length 150 mm
thickness 8 mm
ex.dia. 2100 mm
number 80
material SUS27
160
190
40
10
20
4540
ϕ 960
ϕ 1800
5900
190
160
300

Fig. 4.

described later in section 3–1. (3) We check to know if the temperature of the surrounding air T_0, obtained by the above mentioned method, is a rational value. (4) If T_0 is an irrational value, then we give a different temperature $T(1)$ and repeat the process from (1) to (3). Of course, it is easy to calculate from T_0 to $T(1)$, but when the surface temperature of the fuel rod exceeds 900°C, the water-zirconium reaction becomes very remarkable, and we should correct the calculation by considering its chemical reaction heat. In the method to calculate from the internal part to the external part there is no need for correction, though it is a complicated process to repeat the calculation.

There may be a great difference in temperature distributions by the cask locations, vertical or horizontal, because of the natural heat convection. In this paper, we consider the case of a cask located horizontally, in which the natural heat convection is difficult to occur, and which is a dangerous state in thermal condition.

3.1 The Calculation of the Internal Surface Temperature of the Cask T_6

If the water (or steam) layer between two fuel layers is assumed as a fluid layer tightly sealed, the heat transferred from one fuel layer to another is the sum of the heat by the convection of the fluid and the radiation (which does not exist when the fluid is liquid)[5].

Let the density of the decay heat be 5.25 kw per fuel assembly. (The total decay heat for 17 assemblies is 76800 kcal/h, as mentioned already.) Then the heat transferred from the *k-th* layer to the $(k+1)$*-th* layer equals the total decay heat in the internal layers from the *k-th* at the steady state, i.e.,

$$Q(k) = 76800(2k-1)^2/841 \text{ kcal/h} .$$

The heat transferred in the steam layer by the radiation Q_{HC} for the steady state is given by

$$Q_{HC}=q_{HC}+q_{HG}=q_{HC}+q_{GC} \qquad (1)$$

where the suffix H stands for the higher temperature surface, C the lower one, and G the fluid. q_{ij} stands for the heat transferred by the radiation from i to j, and each q_{ij} in Eq. (1) is

$$\begin{aligned} q_{HC} &= A_H\phi_{HC}(E_H-E_C) \\ q_{HG} &= A_H\phi_{HG}(E_H-E_G) \\ q_{GC} &= A_C\phi_{CG}(E_G-E_C) \end{aligned} \qquad (2)$$

where A_i stands for the area of the surface i, ϕ_{ij} the total absorbing rate (the effective blackness), E_i the total radiation of the black body, and $E_i = 4.88 (T_i/100)^4$ kcal/m²h. ϕ_{ij}'s are given by

$$\begin{aligned} \phi_{HC} &= \varepsilon_H \varepsilon_C (1-\varepsilon_G)/M \\ \phi_{HG} &= \varepsilon_H \varepsilon_G [1+(1-\varepsilon_C)(1-\varepsilon_G)]/M \\ \phi_{CG} &= \varepsilon_C \varepsilon_G [1+(1-\varepsilon_H)(1-\varepsilon_G)]/M \end{aligned} \quad (3)$$

where

$$M = 1-(1-\varepsilon_C)(1-\varepsilon_G)[1-(\varepsilon_H+\varepsilon_G-\varepsilon_H\varepsilon_G)] \quad (4)$$

ε_H, ε_C: for the radiation rate of the fuel cladding pipe, we use $\varepsilon_H = \varepsilon_C = 0.5$,

ε_G: the radiation rate of steam.

ε_G is given by Schack's approximate equation[6] as

$$\varepsilon_{H_2O} = 7.0(P_{H_2O} \cdot L)^{0.8} (T_G/100)^{-1} \quad (5)$$

$$\varepsilon_G = \frac{1}{2}[(\varepsilon_{H_2O})_{T=T_G} + (\varepsilon_{H_2O})_{T=T_H}], \quad (6)$$

where

L : the distance between pipes (0.0176 m)

T_G : the steam temperature,

P_{H_2O}: the steam pressure.

We consider 1, 10, and 25 atm as P_{H_2O}. Letting $q_{HG} = q_{GC}$, then T_G is given by

$$T_G = [(d_H T_H^4 + d_C T_C^4)/(d_H + d_C)]^{1/4}, \quad (7)$$

where

$$d_H = 64(k-1)+28.8 \text{ mm}, \quad \text{and} \quad d_C = 64\,k \text{ mm}.$$

The heat transferred per unit time at the surface of the cylinder by the natural heat convection in the fluid layer tightly sealed q'(kcal/h·m) is given by

$$q' = 2\pi \Delta t \, Nu \, \lambda l / ln(d_C/d_H), \quad (8)$$

where

λ : the thermal conduction rate (kcal/mh°C)

l : the length of cylinder (m)

Nu: the Nusselt number.

The Nusselt number Nu is defined by Kraushold's experimental equations[7] as

$$\begin{aligned} Nu &= 1 && \text{for } \log(Gr \cdot Pr) < 3 \\ Nu &= 0.11(Gr \cdot Pr)^{0.29} && \text{for } 3.8 < \log(Gr \cdot Pr) < 6 \\ Nu &= 0.4(Gr \cdot Pr)^{0.20} && \text{for } 6 < \log(Gr \cdot Pr) < 8 \end{aligned} \quad (9)$$

where

Gr : the Grashof number

$Gr = g\beta(d_C - d_H)^3 \Delta t / 8\upsilon^2$

Pr : the Prandtl number

g : the acceleration of the gravity

β : the expansion coefficient of the fluid

and υ: the dynamic coefficient of viscosity.

We use the values[5] of λ, Pr, β, and υ of the saturated water at the temperature $T_G = (T_H + T_C)/2$ for the state where the cask has not failed. We use those of the over heated steam at 1, 10 and 25 atm and the temperature T_G in Eq. (7) for the state at the loss-of-coolant accident.

We then determine the temperature $T(k)$ which satisfies the condition

$$Q(k) = Q_{HC} + q' \quad (11)$$

from $T(1)$. The temperature $T(16)$ coincides with the temperature at the internal surface of the cask T_6.

3.2 The Calculation of the Temperature at the Middle Cask Cylinder Surface T_3

The process to obtain T_3 from T_6 concerns the problem of solving the uniaxial steady state thermal conduction of the three concentric cylinders made of metals, i.e., the internal cask cylinder made of stainless steel, the cylinder of shield meterial made of lead, and the middle cask cylinder made of stainless steel. The total heat generated in the cask Q kcal/h satisfies the following equation;

$$Q = k^*(T_6 - T_3) 2\pi l, \quad (12)$$

in Eq. (12), k^* corresponding to the heat transfer rate for the cylinder is given by

$$\frac{1}{k^*} = ln(d_5/d_6)/\lambda_{sus} + ln(d_4/d_5)/\lambda_{pb} + ln(d_3/d_4)/\lambda_{sus} \quad (13)$$

3.3 The Calculation of the Temperature at the Internal Surface of the External Cylinder T_2.

In this process, the problem is the heat transfer in the ethylenglycol water layer. Therefore, the temperature T_2 can be obtained by the same way as mentioned in section 3.1, and by using the same values of λ, Pr, β, and υ for the saturated water (or over heated steam). The length of the cylinder l equals 4.98 m.

3.4 The Calculation of the Temperature at the External Surface of the External Cylinder T_1

This process can be solved as the uniaxial steady state thermal transfer problem of the stainless steel cylinder, as mentioned in section 3.2. The heat transferred Q satisfies the following equation;

$$Q = k^*(T_2 - T_1)2\pi l, \tag{14}$$

where

$$k^* = \lambda_{sus}/ln\ (d_1/d_2)\ .$$

The cylinder length l is 5.3 m.

3.5 The Caluculation of the Surrounding Air Temperatures T_0

The total heat generated in the cask is all transferred to the surrounding air by natural convection[5], whereby the temperature T_0 satisfies the following heat equation;

$$Q = Q_h + Q_v + Q_{fin} \tag{15}$$

where Q_h stands for the heat transferred from the lateral surface of the external cask cylinder, Q_v that from the base surface of the cask cylinder, and Q_{fin} that from the cooling fins. If the mean heat transfer rate αm and $\alpha m'$ can be determined, then Q_h and Q_v are given by

$$Q_h = A_h(T_1 - T_0)\alpha m \tag{16}$$

$$Q_v = A_v(T_1 - T_0)\alpha m' \tag{17}$$

where A_h and A_v are the area. αm and $\alpha m'$ are determined by the Grashof number and the Nusselt number. We should take care that for $Gr > 2\times10^9$ the case is natural convection in turbulent flow. In our analysis, as the Grashof number becomes greater than 10^{10}, we obtain the value αm and $\alpha m'$ by using the experimental equation for the turbulent flow[8]; i.e.,

for the horizontal lateral surface of the cylinder

$$\alpha m = \lambda_{air} Nu/d_0 \tag{18}$$

$$Nu = 0.1(Gr\cdot Pr)^{1/3} \tag{19}$$

$$Gr = g\beta d_1^3(T_1 - T_0)/\upsilon_{air}^2, \text{ and} \tag{20}$$

for the vertical plane plate

$$\alpha m' = \lambda_{air}\cdot Nu\Big/\left(\frac{\pi}{4}\ d_0^2\right)^{1/2} \tag{21}$$

$$Nu = 0.0199\, Gr^{2/5} \tag{22}$$

$$Gr = g\beta\left(\sqrt{\frac{\pi}{4}d_0^2}\right)^3 (T_1 - T_0)/\upsilon_{air}^2 \,. \tag{23}$$

In these equations d_0 is the external diameter of the cask, and we use the values λ_{air}, υ_{air}, and Pr for the air at temperature $(T_0+T_1)/2$.

The heat transferred from the fins to the air is given by

$$Q_{fin} = \alpha_f \cdot A_f \cdot \phi \cdot \theta_b \cdot Z \tag{24}$$

where

α_f : the heat transfer rate of the fin

A_f : the surface area of the fin, 1.89 m^2

ϕ : the fin efficiency

θ_b : the temperature difference in the fin, nearly 30°C[9]

Z : the number of fins, 80.

The value ϕ of a ring fin with a rectangular cross section is determined for the given material, form, and dimension.[5] When the temperature T_0, obtained by the analysis mentioned above, becomes 20°C, the temperature $T(1)$ is assumed at first and each $T(k)$ and T_i give the temperature distribution in the cask.

4. Calculation Results

In this investigation, the calculations were made on the conditions shown in Table 2. The calculation results for each condition are shown in Fig. 5. The results show the steady-state temperature distributions of the cask, i.e., the state which the cask holds in each condition after a long time. If the cask is in a normal state (i.e., in the state of no failure), the temperatures are about 300°C at the

Table 2. Conditions of numerical analysis

No.	State of cask	Cooling water	Ethylenglycol water
1	Normal	Saturated water	Liquid
2	LOCA by small failure of cask	Steam (25 atm)	Liquid
3		Steam (10 atm)	Liquid
4		Steam (1 atm)	Liquid
5	LOCA by large scale failure of cask	Steam (25 atm)	Steam (25 atm)
6		Steam (10 atm)	Steam (10 atm)
7		Steam (1 atm)	Steam (1 atm)
8	Water-metal reaction	Steam (25 atm)	Liquid

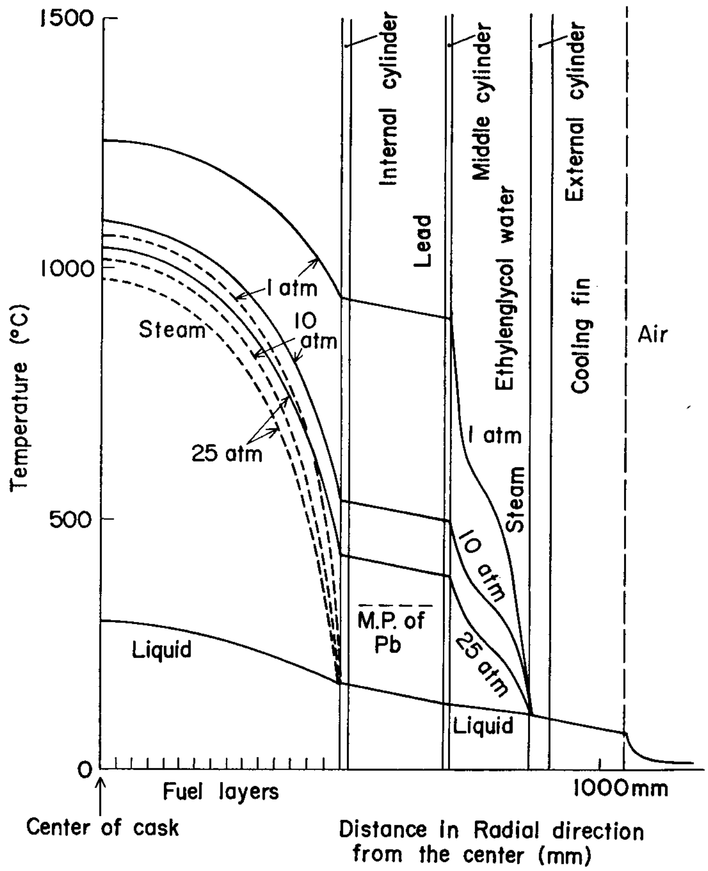

Fig. 5.

center of the cask, and 60°C at the tip of the cooling fins. However, when the cooling water is lost, and the interior of the cask is full of over heated steam, the decay heat can not be transferred to the surrounding air, and the temperature begins to increase. At the center of the cask the temperature exceeds 1000°C. The dependency of the steady-state temperature distribution on the pressure can be considered to be small.

Fig. 5 shows the steady-state temperature distribution, assuming that the water-zirconium reaction does not occur. However, really, this reaction will occur before the temperature distribution reaches a steady state. By the calculation considering the water-zirconium reaction heat[10], the temperature distribution does not reach a steady state at 1850°C, the melting point of fuel cladding pipe made of zirconium, and the temperature continues to increase. This reaction will stop after all the water or zirconium is used in the reaction. However, at that state the spent nuclear fuels at the cask center will be in collapse and melting. (This state corresponds to condition 8 in Table 2. As the steady state can not be obtained, the distribution is not drawn in Fig. 5).

If the ethylenglycol water leaks away by the cask failure, the heat transfer in this part drops down, and the lead shield will have a temperature 400~1000°C. As the melting point of lead is 327.4°C, the lead shield will melt and flow. Though Fig. 5 shows that the flow of lead is considered not to effect the temperature distribution, since it is known that the phase change of lead decreases the ability of the gamma ray shield, the state is very dangerous.

5. Discussion

Some papers have been reported on the thermal characteristics of the cask. Especially, in 1962 JSME (Japan Society of Mechanical Engineers) published a report titled "The Experimental Research on the Heat Removal from the Transferring Vessel of Spent Nuclear Fuels" (in Japanese)[11]. In this paper they reported an experiment on LOCA, using a cask model with an internal diameter 500 mm, a length 1200 mm, and a shield thickness of lead 190 mm, which included four electrical heaters (0.2~1.5 kw per heater) instead of the PWR fuels. The maximum temperatures were obtained when half and all the coolant water were lost. Fig. 6 shows the results. From the figure, even the center where all the water is lost

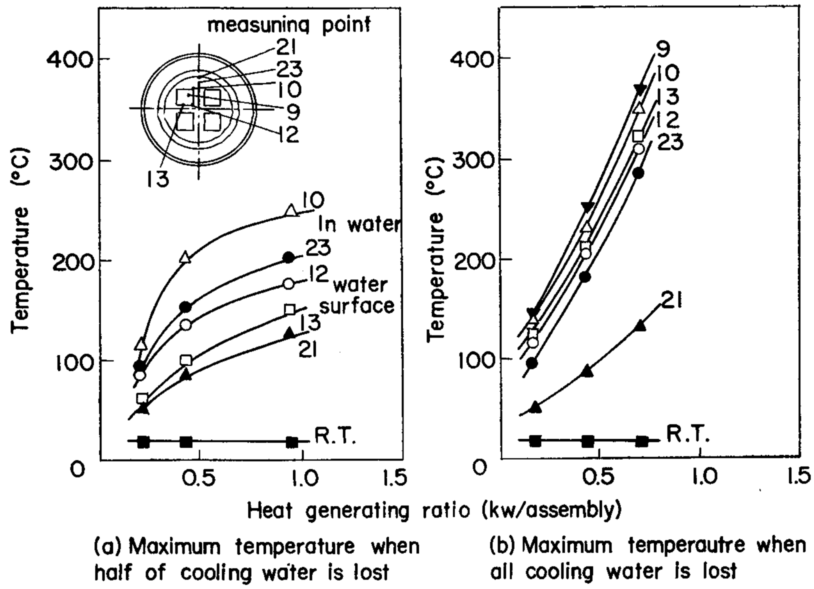

Fig. 6.

does not yet reach the dangerous temperature.

What we must take care of in this paper is the heat generating density of the heater. In Fig. 6 (b), the experimental data were not reported over the 0.7 kw per heater, though the experiments are thought to have been done at 1.5 kw per heater. If we suppose the maximum temperature at high heat generating density from Fig. 6 (b), it may not differ from our results.

After this paper was reported, many experiments have been made on the cask reliability, for example, fall-shock test, heat transfer test, anti-fire test, anti-water pressure test, shield test, etc. However, they do not include the loss-of-coolant test.[2)]

As the cask is generally made very strong and does not fail by the fall-shock test, the loss-of-coolant is considered to be a latent danger. However, the cask has a high temperature and high pressure water, whereby small failures at the bolts of caps, seals, or valves are considered to occur by accidents during tranportation or mis-operations. Therefore, the interior water will leak away from such small failure parts. Even if a small amount of water or steam leaks, the cooling ability decreases. It increases the temperature in the cask and also the pressure, and the increased pressure helps the water leak. This phenomenon leads to the entire loss of the coolant. If a major failure of the cask does not occur, we should consider that a loss-of-cooling accident may happen.

Mark-Loss pointed out that vaporized cesium flows out with the steam leak if the spent nucler fuels are at a temperature over 680°C. He reported[12)] that, if a major accident occurs with the big type cask, people who live leeward within about 800 m, will be showered with a radioactive dose 160 rem, and the generating rate of cancei will increase 2 % for 25 years.

6. Conclusion

The temperature distributions of the transporting vessel of the spent nuclear fuels at LOCA were obtained by the method of numerical analysis using a uniaxial model. The results show that the temperature at the center of the cask exceeds 1000°C by only the decay heat, if all the cooling water is lost. Also, if the cask has failed, and not only the cooling water but also the ethylenglycol water leak away, the interior temperature increases. Also, the lead, the gamma ray shield material, begins to melt and the shielding ability decreases.

Really, the zirconium, the fuel cladding material, begins to generate the metal reaction with the steam, whereby the temperature in the cask continues to increase and the fuel rods at the center begin to melt.

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