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EFFECTS OF SEASON (WINTER AND SUMMER) ON FLAME TEMPERATURE IN OPEN POOL FIRE

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ABSTRACT

Fire tests were conducted using a one-sixth slice model of a real cask in winter and summer to evaluate the effect of the season on the flame temperature and the thermal integrity of the metal cask. Comparing the maximum and average temperatures of the test model measured in the fire tests conducted in winter and summer, both the maximum and average temperatures were higher in the fire test conducted in summer. That is because in the fire test conducted in summer, the test model received more heat input from the flame. In the fire test conducted in summer, it took longer for the high-temperature flame to transfer inside than the fire test conducted in winter. This is because the temperature of the test model itself was higher due to the higher ambient temperature in summer than in winter, and the thermal resistance was a little greater. In addition, in the fire test conducted in summer, it is estimated that the test model received more heat from the flame and took a little longer to transfer heat to the inside. Accordingly, a more conservative test result can be obtained if the fire test is carried out in the summer than in winter. Therefore, it is desirable to conduct fire tests in summer to evaluate the thermal integrity of the transport cask, if possible. As a result of fire tests conducted in winter and summer, it was evaluated that the metal cask can maintain its thermal integrity under a fire accident condition (800 °C for a period of 30 min).

1. INTRODUCTION

To safely transport spent fuel assemblies arising from nuclear power plants, a shipping package is required. A metal cask that contains 21 spent fuel assemblies is under development by the Korea Radioactive Waste Agency (KORAD). Because the metal cask is used for both transport and storage of spent fuel assemblies, it should satisfy the requirements prescribed in the related regulations (Korea Nuclear Safety Security Commission Act 2021-2, 2021[1]; IAEA Specific Safety Requirements No. SSR-6, 2018[2]; US 10 CFR Part 71, 2005[3]). These regulatory guidelines classify the metal cask as a Type B package and state that a Type B package must be able to withstand a temperature of 800 °C for a period of 30 min.

The metal cask was designed as a shipping cask to accommodate 21 pressurized water reactor (PWR) spent fuel assemblies with a burn-up of 45,000 MWD/MTU and a cooling time of 10 years. The decay heat from the 21 PWR spent fuel assemblies is 16.8 kW. A description of the metal cask is listed in Table 1. Its outer diameter is 2,126 mm and its overall height is 5,285 mm. It weighs approximately 125 t. It consists of a thick-walled cylindrical cask body, a neutron shielding, a dry shielded canister (DSC), a lid, baskets to hold the spent nuclear fuel, and impact limiters (Fig. 1). The cask body is made of carbon steel. The lid is made of stainless steel and is fixed to the cask body using stud bolts and cap nuts. The outer-shell is made of stainless steel.

Table 1. Description of the metal cask

Item	Description
Storage capacity	21 PWR Assemblies
Components	Cask Body DSC (Dry Shielded Canister) Impact Limiters
Dimension	Cask Body : 2126 mm(⌀) × 5285 mm(l) × 215 mm(t) Neutron Shielding : 2369 mm(⌀) × 4305 mm(l) × 104 mm(t) Outer-shell : 2384 mm(⌀) × 4355 mm(l) × 10 mm(t) DSC : 1686 mm(⌀) × 4880 mm(l) × 25 mm(t) Impact Limiters : 3600 mm(⌀) × 1090 mm(l) × 665 mm(t)
Weight	Cask Body : 103 tons (Loaded Canister) Neutron Shielding : 5.1 tons DSC : 24.1 tons (Loaded Fuels) Impact Limiters : 16.5 tons (Upper + Bottom)
Material	Cask Body : Carbon Steel & Stainless Steel (Cladding) Neutron Shielding : Stainless Steel Housing & NS-4-FR DSC : Stainless Steel & Boral (B_4C + Al) Impact Limiters : Stainless Steel Housing & Balsa Wood
Design basis fuel	Burn-up : 45,000 MWD/MTU Cooling Time : 10 years Enrichment : 4.5 wt% ^{235}U Decay Heat : 16.8 kW

The baskets containing the spent fuel assemblies are made of stainless steel. The inner cavity between the outer-shell and the cask body is filled with NS-4-FR, which acts as a neutron shielding. NS-4-FR has a low thermal conductivity. Therefore, heat transfer fins are embedded to enhance heat transfer from the cask body to the outer-shell.

The heat transfer fin, which is embedded to enhance the heat transfer due to the low thermal conductivity of the NS-4-FR, is very thin. Therefore, accurately simulating the heat transfer fin in the thermal analysis is also difficult.

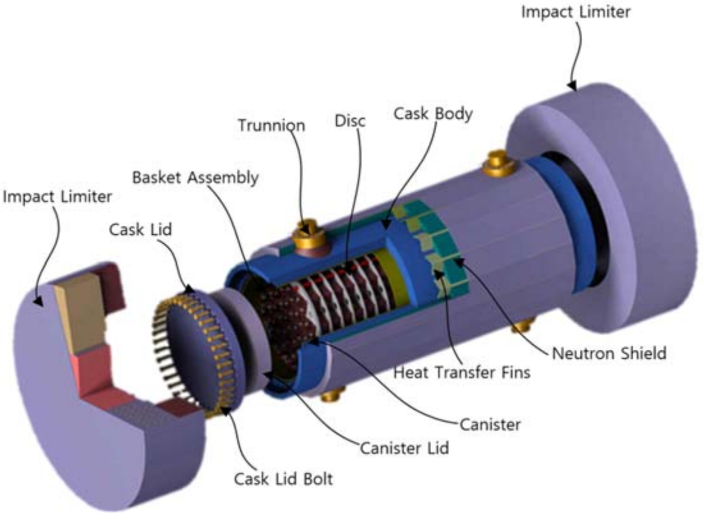

Fig. 1. Configuration of the metal cask

When wood and resin such as NS-4-FR are heated, they produce pyrolysis products such as a char, tars, and gases. The remaining pyrolysis products of the wood and resin are gases consisting of a mixture of hydrocarbons [4]. These gases, generated due to pyrolysis of the resin and wood, are burned. However, accurately simulating the combustion effect of the resin and wood in the thermal analysis is very difficult. Therefore, if material such as wood and resin are used as the components of the metal cask, evaluating thermal integrity of the metal cask using the fire test would be desirable [5].

The fire test can be carried out in summer or winter depending on various circumstances such as the fabrication method of the test model and the conditions of the institution wherein the test was conducted. Therefore, this paper presents an experimental approach used to estimate the effect of the season on the flame temperature and the thermal integrity of the metal cask at a temperature of 800 °C for a period of 30 min.

2. OPEN POOL FIRE TESTS

2.1 Description of the Test Model

Two test models were fabricated to evaluate the effect of the season on the flame temperature and the thermal integrity of the metal cask. The test models are a one-sixth in the length of a real metal cask where the thermal conditions could potentially be the most severe. Fig. 2 shows the configuration of the fire test model. The test models had an outer diameter of 2,384 mm and an axial length of 850 mm. Insulators were installed at both ends of the test models to prevent the high-temperature heat from entering the flame in the axial direction.

The test models contained 72 thermocouples, which were located in the basket, canister, body, neutron shielding, and surface (Fig. 3). All thermocouples were of a Type *K*, sheathed in inconel tubing, ungrounded, and insulated using magnesium oxide. All thermocouples were selected and calibrated at 100, 300, and 800 °C. In addition, their uncertainty was found to be ± 1.0 °C at a 95 % confidence level.

In an actual metal cask, a relief valve is used to prevent an explosion caused by the increase in pressure due to the combustion of the neutron shielding. Therefore, a relief valve was also installed at the bottom of the test models to prevent an explosion during the fire test.

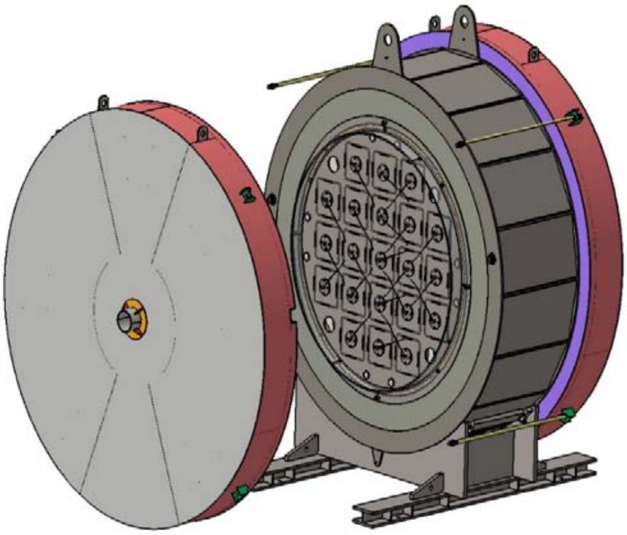

Fig. 2. Configuration of the fire test model

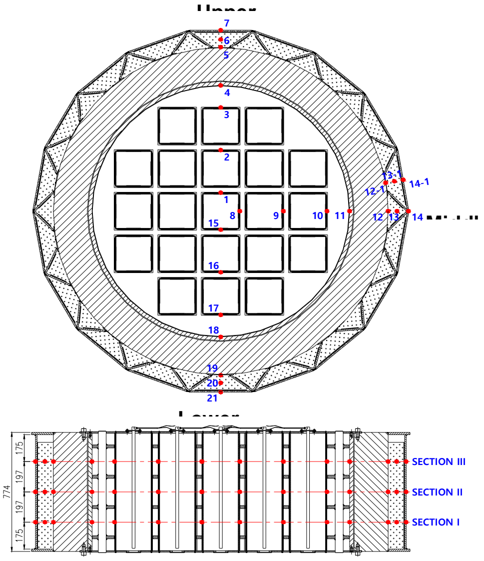

Fig. 3. Thermocouple location

The decay heat from the 21 PWR spent fuel assemblies was 16.8 kW. However, it is very dangerous to use the electric heater in order to simulate the decay heat from the spent fuel assemblies, because the fire can happen. Therefore, no internal heat was simulated in the fire tests.

2.2 Measurement System

The temperature data acquisition system used in the fire test consisted of three thermocouple scanners, three signal conditioners, an analogue-to-digital (A/D) converter, and a personal computer (PC). The thermocouple scanner can connect 32 thermocouples. The signal from the thermocouple scanner was filtered and amplified through the signal conditioner. The analogue signal was then converted to a digital signal through the A/D converter. The digital signal was stored and analyzed using the software (LabView) installed in the PC. In addition, a change in temperature caused by transient was monitored through the PC.

2.3 Open Pool Fire Tests

Fire test may be performed either as a pool fire or in a furnace. The open pool fire test generates a great deal of smoke and soot and is therefore difficult to perform because of strict environmental regulations. A smokeless fire test method was used where the smoke and soot was eliminated. Therefore, the open pool fire tests were carried out in a smokeless fire test facility with dimensions of 3.5 m(W) × 4.0 m(L) × 3.0 m(H).

The open pool fire tests were performed as follows:

- A supporter used to secure the test model within the smokeless fire test facility was installed.
- The test model was horizontally installed onto the supporter.
- Nineteen thermocouples were installed to measure the flame temperature inside the fire test facility (Fig. 4.)
- To protect the fire test facility from the flame, water was filled to the pit at a height of 5 cm.
- Kerosene was filled at a height of 10 cm above the water surface.
- The test model was allowed to be fully engulfed in flames for a period of at least 30 min with an average flame temperature of at least 800 °C.
- Upon completion of the thermal test, the test model was allowed to naturally cool down.

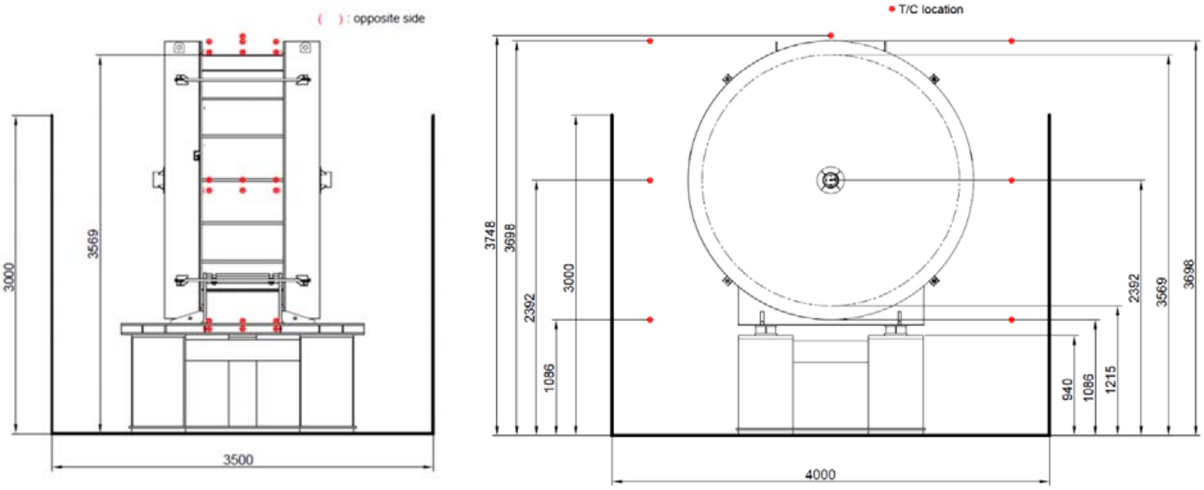

Fig. 4 Thermocouple location in the fire test facility

2.4 Test Results and Discussion

Fig. 5 shows a photograph of the test model fully engulfed in flames in the fire test conducted in summer. Fig. 6 shows the change in the flame temperature during the fire test conducted in summer. Table 2 lists the average ambient temperature before fire test, the average flame temperature during the fire test, and the average ambient temperature during cooling period after the fire test. In the fire tests conducted in winter and summer, the environmental temperatures in the fire test facility before ignition were measured at approximately 5 °C and 25 °C, respectively. The average flame temperature during the fire test conducted in winter and summer was 834 °C and 851 °C, respectively. The average ambient temperature during cooling period after the fire test conducted in winter and summer was 3 °C and 21 °C, respectively.

Fig. 5. Photograph of the test model engulfed in flames (summer).

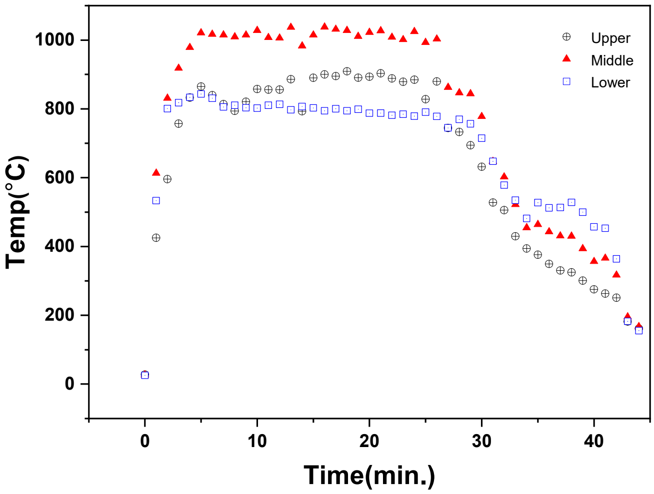

Fig. 6. Flame temperature during the fire test (summer)

Table 2. Flame temperature measured during the fire test

Location (mm)	Winter			Summer		
	Before Fire	Fire	Natural Cooling	Before Fire	Fire	Natural Cooling
Upper (3748 & 3698)	5 °C	695 °C	3 °C	25 °C	810 °C	21 °C
Middle (2392)	5 °C	844 °C	3 °C	25 °C	959 °C	21 °C
Lower (1086)	5 °C	917 °C	3 °C	25 °C	784 °C	21 °C
Average	5 °C	834 °C	3 °C	25 °C	851 °C	21 °C

According to the requirements prescribed in the related regulations, a test model must be exposed to thermal conditions with an average flame emissivity coefficient of 0.9, and an average flame temperature of at least 800 °C for a period of 30 min.

Zabetakis and Burgess recommended that the following expression be used to predict the mass burning rate (kg/m^2·s) of liquid pools with diameters of more than 0.20 m [6]:

$$\dot{m}''= \dot{m}_{\infty}''(1 - \exp(-k\beta D)) \tag{1}$$

where $\dot{m}''$ is the mass loss rate per unit area, $\dot{m}_{\infty}''$ is the mass loss rate per unit area in a larger diameter pool, k is the absorption extinction coefficient, and β is the mean beam length corrector.

The flame emissivity is expressed as [7]:

$$\varepsilon_f = 1 - \exp(-k\beta D) \tag{2}$$

Substituting Eq. (2) into Eq. (1) yields,

$$\varepsilon_f = \frac{\dot{m}''}{\dot{m}_{\infty}''} \tag{3}$$

The flame emissivity can be computed if $\dot{m}_{\infty}''$ is known. Babrauskas proposed the mass loss rate of kerosene in a large pool fire to be 0.039 kg/m^2·s [8]. In the fire tests conducted in winter and summer, the mass burning rate was calculated as 0.038 and 0.0385 kg/m^2·s, respectively. Accordingly, the emissivity of the flame was computed by Eq. (3) to be 0.97 and 0.987, respectively. In general, if the flame is thick and luminous (e.g., hydrocarbon flames), black-body behavior is commonly assumed, i.e., $\varepsilon = 1$ [7]. Therefore, the calculated flame emissivity of 0.97 and 0.987 was considered to be adequate.

In the fire tests conducted in winter and summer, the average flame temperature measured during the steady-state period was 834 °C and 851 °C, respectively. The average flame emissivity was calculated to be 0.97 and 0.987, respectively. Therefore, the thermal conditions given in the regulatory guidelines were satisfied.

The maximum temperatures measured in the test model during the fire tests conducted in winter and summer are listed in Table 3 and Table 4. Figure 7 shows the temperature profile of the test model in fire test conducted in summer.

In the fire tests conducted in winter and summer, the maximum surface temperature was 897 °C after 24 min in the middle part of Section 3 and 957 °C after 24 min in the middle part of Section 2, respectively. The surface temperature was very high because the flame temperature was at the maximum of 984 °C and 1005 °C during this time, and the conductive heat transfer coefficient of the neutron shielding was not good, leading to the accumulation of thermal energy at the model surface. The maximum surface temperature where the heat transfer fin was installed was 634 °C and 624 °C, respectively.

Table 3. Maximum temperatures measured during the fire test (winter)

Location		T/C No.	Section 1		Section 2		Section 3	
			Temp.(°C)	Time(h)	Temp.(°C)	Time(h)	Temp.(°C)	Time(h)
Middle	Basket	8	27	19.0	28	19.0	28	19.0
		9	29	18.8	29	19.0	28	19.0
		10	31	18.8	30	19.0	30	19.0
	Canister	11	40	9.5	39	9.8	39	9.8
	Body	12	62	2.6	59	3.3	62	2.7
		12-1	103	0.6	92	2.4	73	2.6
	NS-4-FR	13	100	1.3	107	0.6	155	0.5
		13-1	153	0.6	183	0.6	170	0.5
	Surface	14	409	0.6	432	0.6	634	0.4
		14-1	789	0.4	764	0.4	897	0.4

Table 4. Maximum temperatures measured during the fire test (summer)

Location		T/C No.	Section 1		Section 2		Section 3	
			Temp.(°C)	Time(h)	Temp.(°C)	Time(h)	Temp.(°C)	Time(h)
Middle	Basket	8	52	29.6	52	28.0	52	30.0
		9	52	28.0	52	28.0	52	28.0
		10	53	22.4	53	22.4	52	28.0
	Canister	11	62	9.4	62	9.4	62	9.25
	Body	12	83	3.25	83	3.6	83	3.25
		12-1	141	0.3	136	0.3	132	0.3
	NS-4-FR	13	136	1.0	132	1.0	146	1.0
		13-1	143	1.4	149	1.25	151	1.25
	Surface	14	532	0.4	608	0.4	624	0.5
		14-1	926	0.4	957	0.4	917	0.4

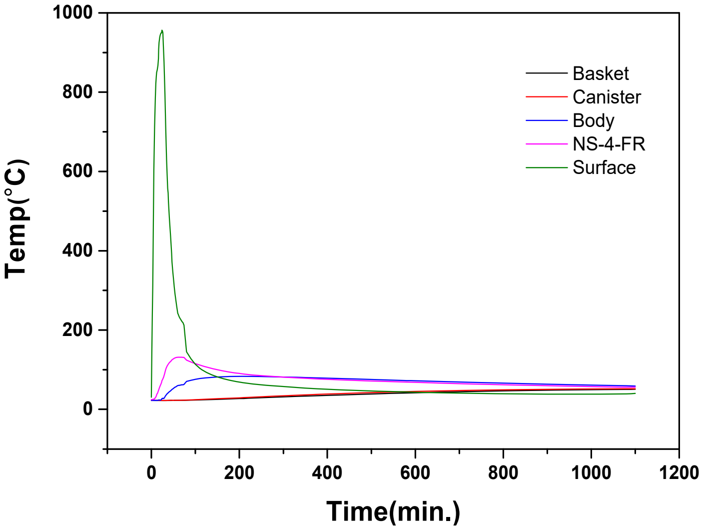

Fig. 7. Temperature history during the fire test (summer, Section 3)

In the fire test conducted in winter, the surface temperatures at the part where the heat transfer fin was installed were 409 °C in Section 1, 432 °C in Section 2, and 634 °C in Section3. However, those in the part where the heat transfer fin was not installed were 789 °C in Section 1, 764 °C in Section 2, and 897 °C in Section 3. Comparing the surface temperature at the part where the heat transfer fin was installed with the surface temperature at the part where the heat transfer fin was not installed in the fire tests conducted in summer showed the same trend as in the fire test conducted in winter. The surface temperatures at the part where the heat transfer fin was installed were 532 °C in Section 1, 608 °C in Section 2, and 624 °C in Section3. However, those in the part where the heat transfer fin was not installed were 926 °C in Section 1, 957 °C in Section 2, and 917 °C in Section 3. From these results, we can determine that the surface temperatures were lower in the presence of the heat transfer fins because the high heat generated by the flame was transferred to the body of the test model through the heat transfer fin.

We now compare the temperature at the surface and the neutron shielding in the fire test conducted in winter. In the upper part, the surface temperature (516 °C) in Section 2 was lower than that (619 °C) in Section 3. However, the temperature of the neutron shielding (101 °C) in Section 2 was higher than that (78 °C) in Section 3. In the middle part, the surface temperature (764 °C) in Section 2 was lower than that (897 °C) in Section 3. However, the temperature of the neutron shielding (183 °C) in Section 2 is higher than that (170 °C) in Section 3. In the lower part, the surface temperature (370 °C) in Section 1 is higher than that (340 °C) in Section 2. However, the temperature of the neutron shielding (70 °C) in Section 1 is lower than that (174 °C) in Section 2. Comparing the temperature at the surface and the neutron shielding in the fire tests conducted in summer showed the same trend as in the fire test conducted in winter. In the upper part, the surface temperature (767 °C) in Section 1 was lower than that (786 °C) in Section 3. However, the temperature of the neutron shielding (124 °C) in Section 1 was higher than that (114 °C) in Section 3. In the middle part, the surface temperature (917 °C) in Section 3 was lower than that (957 °C) in Section 2. However, the temperature of the neutron shielding (151 °C) in Section 3 is higher than that (149 °C) in Section 2. In the lower part, the surface temperature (524 °C) in Section 3 is lower than that (594 °C) in Section 2. However, the temperature of the neutron shielding (83 °C) in Section 3 is higher than that (80 °C) in Section 2.

According to the results of a study by Bang et al. (2015), that is because the neutron shielding absorbed the surrounding latent heat as the neutron shielding burned. Accordingly, an opposite trend occurred.

In the fire test conducted in winter, the initial temperature of the basket before the pool fire test was 4 °C. The maximum temperature was 33 °C after the fire was extinguished and when 19 h had passed. In the fire test conducted in summer, the initial temperature of the basket before the pool fire test was 22 °C. The maximum temperature was 57 °C after the fire was extinguished and when 20.4 h had passed. Accordingly, the temperature rise in the basket during the fire tests was 29 °C and 35 °C, respectively. Therefore, the temperature rise of the spent nuclear fuel rod can be anticipated to be within this range.

From the results of the open pool fire tests, the thermal integrity of the metal cask can be maintained at a temperature of 800 °C for a period of 30 min.

Table 2 shows the comparison of the average ambient temperature before fire tests, the average flame temperature during the fire tests, and the average ambient temperature during cooling period in the fire tests conducted in winter and summer.

In the fire test conducted in winter, when the ambient temperature was low, it took a considerable time to ignite, and it took about 3 minutes for the flame to become an engulfed flame. However, in the fire test conducted in the summer, when the ambient temperature is relatively high, the time taken to ignite was not as long as in winter, and it took about 2 minutes for the flame to become an engulfed flame. This is because the flash point of kerosene used as a fire source in the fire test is 38 °C or higher [9].

Table 5 shows the average temperature of the test model measured in the fire tests conducted in winter and summer. From Table 3 ~ Table 5, comparing the maximum and average temperatures of the test model measured in the fire tests conducted in winter and summer, both the maximum and average temperatures were higher in the fire test conducted in summer.

During fire test, the test model receives energy via convection and radiation heat transfer from the flame. Therefore, the heat input for the 1/6 slice model of the metal cask can be calculated as follows [10]:

$$q = hT_F + \sigma\alpha\varepsilon F{T_F}^4 \tag{4}$$

where h is the convective heat transfer coefficient (10 $\mathrm{W{\cdot}m^{-2}{\cdot}{}^{\circ}K^{-1}}$ [11]), T_F is the flame temperature (°K), σ is the Stefan-Boltzmann constant ($\mathrm{W{\cdot}m^{-2}{\cdot}{}^{\circ}K^{-4}}$), α is the package absorptivity (0.8), ε is the flame emissivity, and F is the view factor for a fully engulfing fire.

In the fire tests conducted in winter and summer, the test models were estimated to have received 47 and 51 kW/m^2 of heat from the flame, respectively. Therefore, the temperature of the test model was higher in the fire test performed in summer than it was in the one in winter.

In the fire test conducted in summer, it took longer for the high-temperature flame to transfer inside than it did for the flame in the fire test conducted in winter. This is because the temperature of the test model itself was higher due to the higher ambient temperature in summer than in winter, and the thermal resistance was a little greater. In addition, in the fire test conducted in summer, it is estimated that the test model received more heat from the flame and took a little longer to transfer heat to the inside. Accordingly, a more conservative test result can be obtained if the fire test is carried out in the summer than in winter. Therefore, it is desirable to conduct fire tests in summer to evaluate the thermal integrity of the transport cask, if possible.

Table 5. Comparison of the average temperature of the test model measured in the fire test conducted in winter and summer

Location		T/C No.	Winter		Summer	
			Temp. (°C)	Amb.(°C)	Temp. (°C)	Amb.(°C)
Middle	Basket	8	28	5	52	25
		9	29		52	
		10	30		53	
	Canister	11	39		62	
	Body	12	61		83	
		12-1	89		136	
	NS-4-FR	13	121		138	
		13-1	169		148	
	Surface	14	492		588	
		14-1	817		933	

3. Conclusion

Open pool fire tests were conducted to estimate not only the effect of the season on the flame temperature but also the thermal integrity of the metal cask at a temperature of 800 °C for a period of 30 min. The main results are described below.

i) The test model received more heat from the flame in the open-pool fire test performed in summer than it did from the one in winter. Therefore, both the maximum and the average temperatures of the test model were high in the fire test conducted in summer.
ii) In the fire test conducted in the summer, it took longer for the high-temperature flame to transfer inside than it did for the test conducted in winter due to the higher temperature of the test model, resulting from the higher ambient temperature. Additionally, the overall testing period was longer.
iii) Performing the open-pool fire test in early summer rather than in winter could produce more conservative test results, owing to the high ambient temperature. Therefore, it is more desirable to conduct an open-pool fire test in summer than in winter if possible.
iv) In the fire tests conducted in winter and summer, it was evaluated that the metal cask can maintain its thermal integrity under a fire accident condition (800 °C for a period of 30 min).

ACKNOWLEDGMENTS

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