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COMPARTMENT FIRE TEST USING THE AVIATION FUEL

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ABSTRACT

Compartment fire tests were performed using Jet-A-1 as the fire source under a compartment condition in order to evaluate the flame temperature according to the opening size in the fire from the release of jet fuel involving the collision of an airplane. The compartment fire test was performed using a 1/3 scale down model of the metal storage cask under test condition in which the flame temperature was the highest measured. As the opening and ventilation factor increased, the fuel consumption rate also increased. Therefore, when the size of the opening and ventilation factor was large, the flame temperature was high. When the metal storage cask was stored in the compartment, the flame temperature was decreased by as much as the heat that the metal storage cask received from the flame.

INTRODUCTION

The management of spent nuclear fuel generated at nuclear power plants has become a major policy issue owing to continued delays in obtaining a safe and permanent disposal facility. Most nuclear power plants store their spent nuclear fuel in wet storage pools. However, after decades of use, most storage pools have reached maximum capacity. For the nuclear industry, finding sufficient capacity for the storage of spent nuclear fuel is essential if the nuclear power plants are to be allowed to continue their operation.

In the USA, spent nuclear fuel assemblies are currently stored in various dry storage systems: metal casks, concrete casks, horizontal modules, and vaults. In the EU and Japan, spent nuclear fuel assemblies are mainly stored in metal casks.

The USA has operated various dry storage systems in open air. The EU and Japan store metal casks within storage buildings.

KOREA is planning to construct interim storage facilities using a dry storage method to store spent nuclear fuel discharged from nuclear power plants. Korea is likely to choose the type of dry storage cask within the storage building.

Storage systems should be able to withstand an accident, such as fire from the release of jet fuel after an airplane collision.

Thus far, the evaluation of fire accidents has been mainly evaluated under kerosene conditions. However, the regulatory requirement for a Type C package specifies that the package must be exposed to luminous flames from a pool fire of JP-4 or JP-5 aviation fuel for a period of at least 60 minutes [1-3]. In addition, the need for an evaluation under aviation fuel conditions has been raised since the 9.11 terror attacks. Therefore, Greiner from Nevada University and Lopez from SNL have performed research on fire accidents using jet fuel [4-5]. However, data on aviation fuel fires for a safety analysis remain insufficient.

In this paper, compartment fire tests were performed using Jet-A-1 as the fire source under a compartment condition to evaluate the flame temperature according to the opening size in the fire from the release of jet fuel involving the collision of an airplane. For a metal storage cask stored in a compartment, the flame temperature was also evaluated over a long duration. It is expected that the results obtained in this study can be used as basic data for a cask storage facility as future reference.

COMPARTMENT FIRE TEST

Description of the Fire Test Facility

As shown in figure 1, the test facility for performing the fire test was constructed as a compartment with 4 m (W) × 4 m (L) × 4 m (H) in size using a light concrete of 10 cm in thickness. The openings were made in the front and rear sides of the compartment. The size of the openings was designed to be controlled from 40 cm (H) × 70 cm (W) to 50 cm (H) × 80 cm (W). On the roof, a 30 cm diameter hole was designed with the intention of creating a chimney effect.

All thermocouples used in these tests are a Type *K*, sheathed in inconel tubing, ungrounded, and insulated using magnesium oxide. A total of 63 thermocouples were installed at heights of 80 cm, 200 cm, and 320 cm above the bottom of the inside of the compartment to measure the flame temperature in the compartment. Ten of the 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.

Figure 1. Fire test facility

Heat Transfer Mode and Measurement System

A fire in the compartment may progress in four phases, as shown in figure 2. In addition, a fire in a compartment is affected by the heat release rate, enclosure size, enclosure construction, and enclosure ventilation [6].

The heat transfer in a compartment fire occurs by convection and radiation from the enclosure, and then conduction through the walls. Heat is generated by the fire source within the compartment and transferred from the combustion zone to the upper layer through convection and radiation. This heat is then transferred to the adjacent wall by the radiation and conduction, and the compartment lower layer by the radiation. Also, this heat is transferred to the ambient atmosphere by convection through the openings.

The temperature data acquisition system used in the compartment fire test consists of a thermocouple scanner, a signal conditioner, an A/D converter, and a PC. The signal, which is detected in the thermocouple scanner, is filtered and amplified through the signal conditioner, and converts an analog signal to a digital signal through an A/D converter. This signal is stored and analyzed using the software installed in the PC.

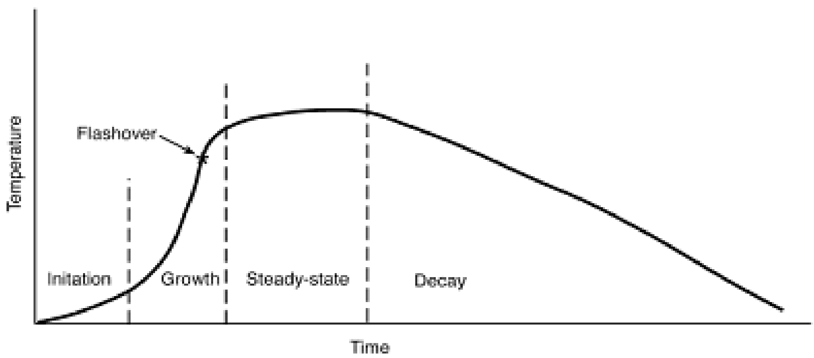

Figure 2. Phases of fire development in the compartment fire

Compartment Fire Test

Compartment fire tests were performed using aviation fuel as a fire source under a compartment condition to evaluate the flame temperature according to the opening size in the fire from the release of jet fuel involving the collision of an airplane.

The compartment fire tests using aviation fuel as the fire source were carried out for three cases in accordance with the size of the opening. JP-4 is very difficult to obtain as it is used by the military. Jet-A-1 may be easier to obtain than JP-4, but only through the refueling team of the Korea Airport Service. In the compartment fire test, Jet-A-1 was therefore used as the aviation fuel.

In the first case, as shown in figure 3, the compartment fire test was performed by filling 50 liters of Jet-A-1 as the fire source in the compartment. The compartment consists of one opening on the front and rear sides, respectively. The size of the opening was 50 cm (H) × 80 cm (W) on both sides.

In the second case, the compartment consists of one opening on the front and rear sides, and on the roof. The size of the opening was 50 cm (H) × 80 cm (W) on both sides, with a 30 cm diameter hole on the roof. 50 liters of Jet-A-1 was then filled in the compartment.

Figure 3. Compartment fire test

In the third case, the compartment consists of one opening on the front and rear sides, and on the roof. The size of the opening was 40 cm (H) × 70 cm (W) on both sides, with a 30 cm diameter hole on the roof. 50 liters of Jet-A-1 was then filled in the compartment.

Compartment Fire Test using 1/3 scale down model of the metal cask

The fourth compartment fire test was performed using a 1/3 scale model of the metal storage cask. Figure 4 shows the 1/3 scale model of the metal storage cask which was installed in the compartment.

The compartment consists of one opening on the front and rear sides, and on the roof. The size of the opening was 50 cm (H) × 80 cm (W) in both sides, with a 30 cm diameter hole on the roof. 170 liters of Jet-A-1 was then filled in the compartment.

Figure 4. A 1/3 scale model of the metal storage cask was installed in the compartment

TEST RESULTS AND DISCUSSION

Table 1 shows comparisons of the average engulfed flame temperature, engulfed flame time, and fuel consumption measured during the compartment fire tests.

In the first case, the engulfed flame time continued for approximately 15 minutes. The average engulfed flame temperature was measured as 618 ˚C in the upper part, 602 ˚C in the middle part, and 551 ˚C in the lower part.

In the second case, the engulfed flame time continued for approximately 12 minutes. The average engulfed flame temperature was measured as 692 ˚C in the upper part, 677 ˚C in the middle part, and 616 ˚C in the lower part.

In the third case, the engulfed flame time lasted for approximately 17 minutes. The average engulfed flame temperature was measured as 618 ˚C in the upper part, 602 ˚C in the middle part, and 551 ˚C in the lower part.

The maximum flame temperatures in the three case were measured as 778 °C, 851 °C, and 779 °C in the near of the opening, respectively. This is because the convective heat transfer is increased as the air flowed into the opening.

The temperature profiles of the flame in the first and second cases are shown in figures 5 and 6, respectively. As can be seen in these figures, the engulfed flame temperature was continuously increased in the compartment fire tests. NUREG-1805 states that the temperature of the flame in the compartment fire increased gradually, and reached 1,260 ˚C after an elapsed time of 8 hours [7].

Table 1. Engulfed flame temperature and time.

	Engulfed Flame Temp. (˚C)			Engulfed Flame Time(min.)	Fuel (liter)
	Upper Part	Middle Part	Lower Part		
1st Case	618	602	551	15	50
2nd Case	692	677	616	12	50
3rd Case	646	623	568	17	50

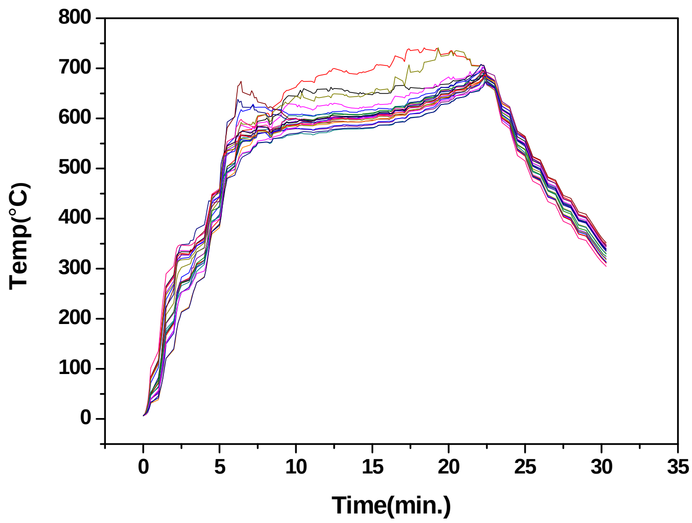

Figure 5. Flame temperature in the first case (upper part)

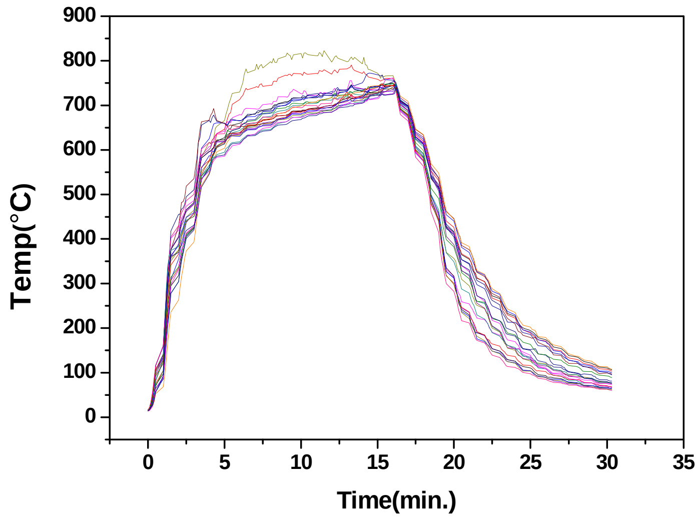

Figure 6. Flame temperature in the second case (upper part)

In the compartment fire, the important factor having an effect on the flame temperature is the heat release rate. The heat release rate in the compartment fire can be calculated as follows [8]:

$$\begin{aligned} \dot{Q} &= \dot{m}_F \Delta H_c, \Phi < 1 \\ \dot{Q} &= \dot{m}_{Air} \Delta H_{Air}, \Phi \geq 1 \\ \dot{m} &= k_0 A_0 \sqrt{H_0} \end{aligned} \quad (1)$$

where, $\dot{Q}$ is the heat release rate(kW), $\dot{m}$ is the mass flow rate(kg/s), ΔH is the effective heat of combustion(kJ/kg), Φ is the equivalence ratio, k_0 is the effective constant(kg/s . $m^{5/2}$) , A_0 is the flow area(m^2), and H_0 is the opening height(m).

The effective heat of combustion of Jet-A-1 was 43,333 kJ/kg, which was calculated based on the results of the quality assurance performance in accordance with the ASTM method by SK energy Co., Ltd [9].

In the compartment fire tests, 50 liters of fuel was used. If the fuel consumption during the fire growth phase and decay phase is considered, the fuel consumption in the steady state phase could be estimated to be about 45 liters. Therefore, the heat release rate and mass flow rate were evaluated by considering the fuel consumption during a steady state.

Table 2. Heat release rate and mass flow rate

	Heat release rate (kJ/s)	Mass flow rate (kg/s)	Effective Constant (k_0)	Combustion time (s)
1st Case	1,728	0.040	0.070	900
2nd Case	2,160	0.050	0.052	720
3rd Case	1,524	0.035	0.058	1020

Table 2 shows the heat release rate and mass flow rate calculated during the compartment fire tests. As can be seen in table 2, the heat release rate and mass flow rate in the second case was the largest at 2,160 kJ/s and 0.050 kg/s, respectively.

In the compartment fire, the mass flow rate depended very strongly on the ventilation factor. The ventilation factor depended on the size, shape, and position of the opening.

For a compartment with more than one opening, the ventilation factor can be calculated as follows:

$$\boldsymbol{A}\sqrt{\boldsymbol{H}} = \sum_i \boldsymbol{A}_i\sqrt{\boldsymbol{H}_i} \qquad (2)$$

For a compartment with a horizontal opening on the roof, the ventilation factor can be determined from the alignment chart in figure 7 [10].

Table 3 shows the ventilation factor according to the area and location of the opening. As can be seen in table 3, the area of the opening in the second case is the largest. The ventilation factor is the largest in the second case, as well. Therefore, we can know that the flame temperature in the second case was the highest.

If the first and third cases are compared, however, the area of the opening in the first case is larger than that of the third case, but the ventilation factor in the third case was larger than that of the first case.

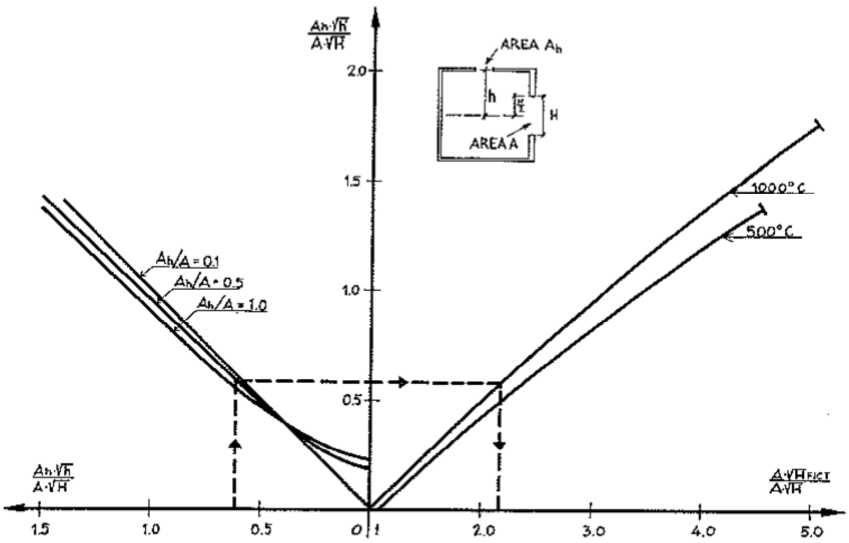

Figure 7. Alignment chart for the calculation of the value of the modified ventilation factor.

Table 3. Ventilation factor according to the area and location of the opening

	Opening Area (m^2)				Ventilation factor ($m^{5/2}$)			
	Front	Rear	Roof	Total	Front	Rear	Roof	Total
1st Case	0.4	0.4	-	0.8	0.283	0.283	-	0.566
2nd Case	0.4	0.4	0.07	0.87	0.283	0.283	0.396	0.962
3rd Case	0.28	0.28	0.07	0.63	0.177	0.177	0.248	0.602

Table 4. Test results of compartment fire using the metal storage cask

Temperature (°C)							Engulfed Flame Time(min.)	Fuel (liter)
Flame			Metal Cask		Canister Surface	O-ring		
Upper Part	Middle Part	Lower Part	Surface	Inside				
701	707	608	357	337	247	171	40	170

As can be seen in table 1, the flame temperature in the third case is higher than that of the first case. When the opening was installed on the roof, even through the area of the opening was small, the ventilation factor was big, the temperature of the flame was high, and the burning time was long.

Therefore, we can know that the position of the opening is an important factor having an effect on the flame temperature.

The fourth compartment fire test was performed using a 1/3 scale model of the metal storage cask under the condition of the second case in which the flame temperature is the highest measured. The fourth compartment fire test results are summarized in Table 4. The engulfed flame time continued for approximately 40 minutes. The average engulfed flame temperature was measured at 701 ˚C in the upper part, 707 ˚C in the middle part, and 608 ˚C in the lower part.

The maximum surface temperature of the metal storage cask was measured as 357 °C. The maximum inside temperature of the metal storage cask was measured as 337 °C. The maximum temperature of the canister surface was measured as 247 °C. The maximum temperature of the seal was measured as 171 °C.

In the three compartment fire tests to evaluate the flame temperature in the compartment, the flame temperature in the upper part was the highest. However, the other trend was shown in the fourth compartment fire test. The flame temperature was the highest in the middle part. It is considered that the convective heat transfer was increased because the 1/3 scale model was installed near the opening.

In the second case, the engulfed flame time lasted for approximately 12 minutes. The average engulfed flame temperature measured in the second case was 692 ˚C in the upper part, 677 ˚C in the middle part, and 616 ˚C in the lower part. However, in the fourth case, the engulfed flame temperature for 12 minutes was evaluated as 633 ˚C in the upper part, 621 ˚C in the middle part, and 510 ˚C in the lower part.

In the compartment fire, heat is generated by the combustion of Jet-A-1 and transferred to the surface of the metal storage cask through convection and radiation. This heat is then transferred from the surface of the metal storage cask to the inner part of the metal storage cask through conduction.

During a compartment fire, the metal storage cask gets the effect by the convection heat transfer and radiation heat transfer from the flame. The specific heat input for the 1/3 scale model of the metal cask can be calculated as follows:

$$Q_M = (hT_F + \sigma F T_F^4) A \frac{\tau_F}{M_M} \quad (3)$$

where, Q_M is the specific heat input per unit mass of the 1/3 scale model, h is the convective heat transfer coefficient, T_F is the flame temperature, σ is the Stefan-Boltzmann constant, F is the view factor for a fully engulfing fire, *A* is the surface area, τ_F is the compartment fire duration, and M_M(2,714 kg) is the mass of the 1/3 scale model.

The 1/3 scale model of the metal storage cask was evaluated to receive 120 kJ/kg of heat from the flame in the compartment fire. Therefore, it is considered that the flame temperature of the compartment is decreased by as much as the amount of calories that the metal cask receives from the flame.

SUMMARY

Compartment fire tests were performed using Jet-A-1 as the fire source under a compartment condition to evaluate the flame temperature in the fire owing to the release of jet fuel involving the collision of an airplane. The main results are as follows:

First, as the opening and ventilation factor increased, the fuel consumption rate also increased. Therefore, when the size of the opening and ventilation factor was large, the flame temperature was high.

Second, the flame temperature gradually increased according to the elapsed time during a compartment fire.

Third, when the opening was installed on the roof, even through the area of the opening was small, the ventilation factor was large, the temperature of the flame was high, and the burning time was long. Therefore, the position of the opening is an important factor affecting the flame temperature.

Fourth, when a metal storage cask is stored in a compartment, the flame temperature of the compartment is decreased by as much as the amount of calories that the metal cask receives from the flame.

ACKNOWLEDGMENTS

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