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Experimental Evaluation of the Thermal Integrity of a Large Capacity Pressurized Heavy Water Reactor Transport Cask

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The safety of a KTC-360 transport cask, a large-capacity pressurized heavy-water reactor transport cask that transports CANDU spent nuclear fuel discharged from the reactor after burning in a pressurized heavy-water reactor, must be demonstrated under the normal transport and accident conditions specified under transport cask regulations. To confirm the thermal integrity of this cask under normal transport and accident conditions, high-temperature and fire tests were performed using a one-third slice model of an actual KTC-360 cask. The results revealed that the surface temperature of the cask was 62°C, indicating that such casks must be transported separately. The highest temperature of the CANDU spent nuclear fuel was predicted to be lower than the melting temperature of Zircaloy-4, which was the sheath material used. Therefore, if normal operating conditions are applied, the thermal integrity of a KTC-360 cask can be maintained under normal transport conditions. The fire test revealed that the maximum temperatures of the structural materials, stainless steel, and carbon steel were 446°C lower than the permitted maximum temperatures, proving the thermal integrity of the cask under fire accident conditions.

Keywords: Pressurized heavy water reactor, High-temperature test, Fire test, Thermal integrity, Transport cask

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1. Introduction

Spent nuclear fuels discharged from the reactor after burning in a pressurized heavy water reactor (PHWR) of the Wolsong nuclear power plants were stored in dry storage facilities located at the Wolsong nuclear power plant site; most dry storage facilities here have reached their maximum capacities. Even if the additional dry storage facility currently under consideration is constructed and operated, the need to transport spent nuclear fuel to an interim storage facility is expected to emerge after 2035, when the facility is built and operated.

Currently, the HI-STAR 63 transport cask, developed to transport CANDU spent nuclear fuel from the wet storage pool to the dry storage facility which is called the MACSTOR/KN-400, has a transport capacity of 120 bundles, which is unfavorable when considering transportation costs and other related aspects. According to the 'Basic Plan for High-Level Radioactive Waste Management (draft)', the total amount of CANDU spent nuclear fuel is expected to be approximately 660,000 bundles. To safely and efficiently transport this amount to interim storage facilities, it is essential to develop a large-capacity transport cask.

Therefore, we have been developing a large-capacity PHWR spent nuclear fuel transport cask, called the KTC-360 transport cask. Fig. 1 shows a schematic of the KTC-360 transport cask. It consists of a thick-walled cask body, cask lids, and impact-limiters. The KTC-360 transport cask accommodates 360 CANDU spent nuclear fuel bundles with a burn-up of 7,800 MWd/MTU and cooling time of 6 years. The decay heat from these bundles was approximately 2.3 kW. A description of the KTC-360 transport cask is presented in Table 1. Its outer dimensions and overall height are 1,810 × 3,528 mm and 2,233 mm, respectively, and it weighs approximately 28 tons. The cask body and lid were made of forged carbon and stainless steel, respectively. The impact limiters were made of stainless steel and the inner space was filled with balsa wood.

According to the transport-cask related regulations

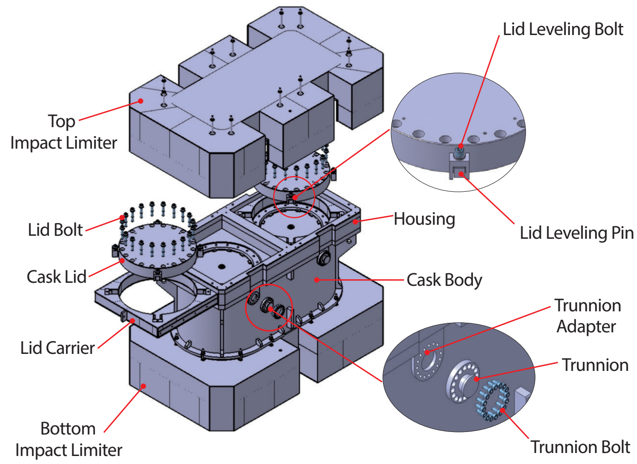

Fig. 1. Configuration of the KTC-360 Transport Cask.

(Korea Nuclear Safety Security Commission Act 2021-2, 2021 [1]; IAEA Safety Standard Series No. SSR-6, 2018 [2]; US 10 CFR Part 71, 2005 [3]), the KTC-360 transport cask was classified as a Type B package, and such packages need to maintain integrity under the normal transport and accident conditions described in these regulations.

Table 1. Description of the KTC-360 Transport Cask

Item	Description
Capacity	6 Fuel Baskets (360 CANDU Bundles)
Components	Cask Body Impact Limiters
Dimension	Cask Body: 1,810 × 3,528 × 2,233 mm (H) Top Impact Limiters: 2,604 × 4,322 × 1,218 mm (H) Bottom Impact Limiter: 2,604 × 4,322 × 968 mm (H)
Weight	Cask Body: 4.4 tons Fuel Baskets (6 EA): 11.4 tons Impact Limiters: 12.2 tons (Top + Bottom)
Material	Cask Body: Carbon Steel & Stainless Steel Impact Limiters: Stainless Steel Housing & Balsa Wood
Design basis fuel	Burn-up: 7,800 MWD/MTU (per Fuel Basket) Min. Cooling Time: 6 years Initial Enrichment: 0.711wt% ^{235}U Max. Decay Heat: 378 W (per Fuel Basket)

The purpose of this study is to evaluate the surface temperature limit of the KTC-360 transport cask under high-temperature conditions and to evaluate whether the maximum temperature of the components of the cask exceeds the permissible value under fire-accident conditions. Therefore, a high-temperature test under normal transport conditions and a fire test under transport accident conditions were performed to evaluate the surface temperature limit and thermal integrity of the KTC-360 transport cask, respectively. The results obtained in this study can support the approval of the design of KTC-360 transport casks for safely transporting the CANDU spent nuclear fuel.

2. Thermal Test

2.1 Description of the Test Model

Using a prototype model when conducting tests to evaluate the integrity of the transport cask is desirable. However, it is expensive performing tests using a prototype model. Therefore, a one-third slice model of a real KTC-360 transport cask was fabricated as the test model for the high-temperature and fire tests. The cross-sectional shape of this test model was the same as that of a real KTC-360 transport cask, and the height was the shape of a slice of one of the three baskets loaded in the real KTC-360 transport cask. To minimize heat loss through the upper and lower portions of the model and shield it from the intense heat from the flame entering through these portions during the fire test, both ends of the model were covered with an insulator. Additionally, a lug for handling the test model was installed. Fig. 2 shows a picture of the test model. 36 thermocouples were attached to the model body, three each at the top, center, and bottom to measure the temperature of the test model and 18 thermocouples were installed, six each at the top, center, and bottom around the test model, to measure its ambient temperature under the high-temperature test.

Fig. 2. Test Model.

2.2 Measurement System

The data acquisition system for measuring the temperature of the model under the high-temperature and fire tests was obtained from the National Instrument Corporation. This system consists of three thermocouple scanners, three signal conditioners, an analogue-to-digital (A/D) converter, and a personal computer (PC). Each thermocouple scanner could connect 32 thermocouples. The signal sent from the thermocouple scanner was filtered and amplified using a signal conditioner. The analogue signal was then converted into a digital signal using an A/D converter. The digital signal was stored and analyzed using the LabVIEW software installed on the PC. In addition, the change in temperature caused by the transient signal was monitored using a PC.

2.3 High-Temperature Test

In accordance the Korea Nuclear Safety Security Commission Act 2021-2 article 26 para. 4 and IAEA Safety Standard Series No. SSR-6 para. 654, the temperature of the accessible surfaces of a transport cask should not exceed 50℃ in the absence of insolation under the ambient temperature condition of 38℃ unless the cask is transported for exclusive use. Therefore, to evaluate

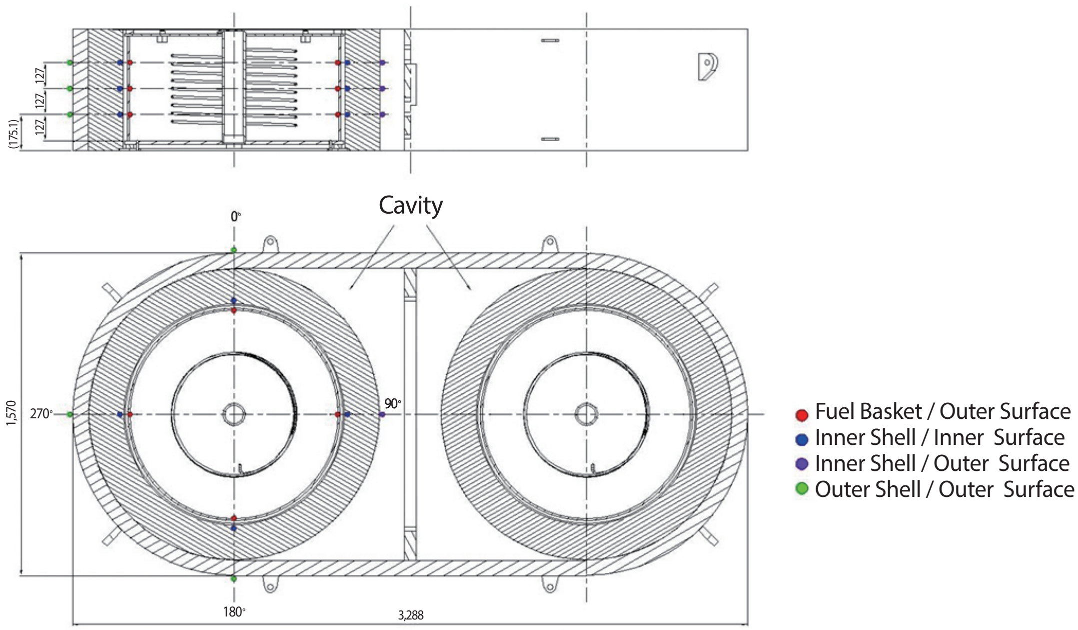

Fig. 3. Locations of thermocouples installed on the test model.

whether the surface temperatures satisfied the temperature limits, a high-temperature test was performed using the model of the KTC-360 transport cask.

The International Atomic Energy Agency (IAEA) Safety Standards Series No. SSG-26, para. 653.4 [4], describes the conditions under which high-temperature tests should be conducted as follows:

653.4. "Practical tests may be used to determine the internal and external temperatures of the package under normal conditions by simulating the heat source due to radioactive decay of the contents with electrical heaters. In this way, the heat source can be controlled and measured. Such tests should be performed in a uniform and steady thermal environment (i.e. fairly constant ambient temperature, still air and minimum heat input from external sources such as sunlight). The package, with its heat source, should be held under test for sufficient time to allow the temperatures of interest to reach steady state. The test ambient temperature and internal heat source should be measured and used to adjust, linearly, all measured package temperatures to those corresponding to a 38℃ ambient temperature."

Therefore, after installing the test model in a uniform and still environment, a high-temperature test was performed by applying heat, with a capacity of 756 W, from two electric heaters, simulating the decay heat released from the CANDU spent nuclear fuel loaded in the two fuel baskets. After the temperature distribution of the test model reached thermal equilibrium, it was maintained for 24 h, and the ambient temperature was measured during the test period using the 18 thermocouples installed around the test model.

2.4 Fire Test

The fire test was performed after installing the test model in a furnace, which had dimensions of 3,500 (W) × 4,000 (L) × 3,000 mm (H), at the Fire Insurers Laboratories of Korea using the furnace test method, as shown in Fig. 4. This test method was one of those recommended by the IAEA Safety Standards Series No. SSG-26.

The furnace was designed to regulate the temperature

Table 2. Temperatures measured in the high-temperature test

Location		Temperature (°C)				
		0°	90°	180°	270°	Ambient
Outer Surface	Upper	38.2		38.4	39.4	14.8
	Middle	37.4		37.8	38.8	
	Lower	37.1		37.5	39.2	
Inner-shell Outer Surface	Upper		49.5			
	Middle		49.2			
	Lower		49.0			
Inner-shell Inner Surface	Upper	43.9	49.8	44.1	42.4	
	Middle	44.1	49.3	44.0	42.4	
	Lower	43.5	49.4	43.1	41.9	
Basket Surface	Upper	94.3	95.5	94.8	94.5	
	Middle	90.7	92.3	90.7	89.9	
	Lower	85.8	88.1	85.6	84.8	

Fig. 4. Photograph of the test model installed in the furnace.

by completely burning heavy oil. After the flame temperature reached 800℃ in the fire test, the test model was exposed for 30 min to fully engulfed flames at an average temperature of at least 800℃ after which the fire test was stopped and the test model was allowed to cool naturally.

The decay heat from the CANDU spent nuclear fuel loaded into the two fuel baskets was 756 W. However, it is very dangerous to use electric heaters to simulate the decay heat from spent nuclear fuel because fires can occur. Therefore, electric heaters were not used in the fire test.

3. Results and Discussion

3.1 High-Temperature Test

Table 2 lists the maximum temperatures measured under the high-temperature test. The thermal equilibrium of the test model was attained after about 140 h, and that state was maintained for one day. The average ambient temperature around the test model was maintained at approximately 15℃ during the high-temperature test.

Comparing the overall temperatures, which are listed in Table 2, the temperature of the components in the upper part of the test model was high in most areas. This is typical because heat flow by convective heat transfer occurs in the space inside the KTC-360 transport cask.

As shown in Fig. 3, there is a considerable space inside the 90° direction. Therefore, comparing the overall temperature distribution, the temperature in the 90° direction was high, whereas the temperature in the 270° direction was low. This is because heat resistance was generated owing to the internal space in the 90° direction, resulting in less heat transfer, while there was more heat transfer in the 270° direction.

In the high-temperature test, the ambient temperature

Table 3. Temperatures of test model compensated for ambient temperature of 38°C

Location		Temperature (°C)				
		0°	90°	180°	270°	Ambient
Outer Surface	Upper	61.4		61.6	62.6	38
	Middle	60.6		61.0	62.0	
	Lower	60.3		60.7	62.4	
Inner-shell Outer Surface	Upper		72.7			
	Middle		72.4			
	Lower		72.2			
Inner-shell Inner Surface	Upper	67.1	73.0	67.3	65.6	
	Middle	67.3	72.5	67.2	65.6	
	Lower	66.7	72.6	66.3	65.1	
Basket Surface	Upper	117.5	118.7	118.0	117.7	
	Middle	113.9	115.5	113.9	113.1	
	Lower	109.0	111.3	108.8	108.0	

of the test model was approximately 15°C. Table 3 shows the linearly adjusted temperatures according to the method described in the IAEA Safety Standards Series No. SSG-26, para. 653.4, considering the temperature measured around the test model as 38°C, which was the ambient temperature prescribed for high-temperature conditions.

As shown in Table 3, the maximum temperature of the outer surface was evaluated to be approximately 62°C, which exceeded 50°C, the surface temperature stipulated by the regulations. This indicated that KTC-360 transport cask should be transported exclusively.

According to William [5], the fuel design acceptance criterion for normal operating conditions is that the local temperature in all parts of the pellet and the sheath remains below the melting point of the material.

As shown in Table 3, the maximum temperature of the basket was approximately 119°C. It can be predicted that the highest temperature of the CANDU spent nuclear fuel would be below the melting temperature (1,852°C) of Zircaloy-4, which is the sheath material. Therefore, if normal operating conditions are applied, the thermal integrity of the KTC-360 transport cask can be maintained under normal transport conditions.

3.2 Fire Test

Fig. 5 shows the change in the average flame temperature measured under the fire test. In the fire test, it took approximately 11 min for the average flame temperature inside the furnace to reach 800°C, and the average flame temperature during this time was 630°C. The average flame temperature for 30 min after reaching 800°C was 805°C, which satisfied the thermal conditions specified in the regulatory guidelines.

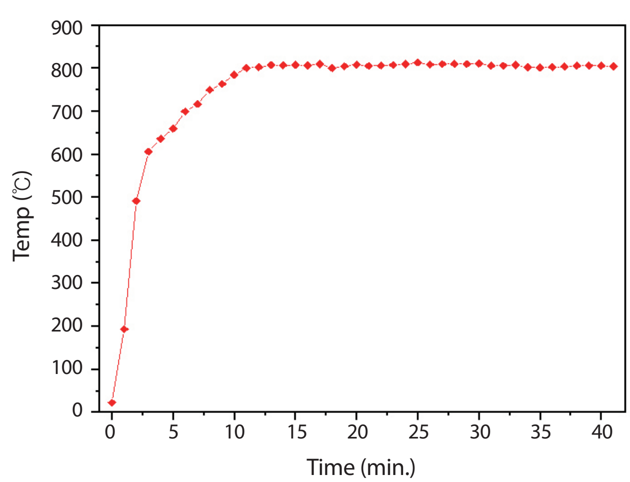

Fig. 5. Average flame temperature during the fire test.

Table 4. Maximum temperatures measured in the fire test

Location		0°		90°		180°		270°	
		Temp. (°C)	Time (h)	Temp. (°C)	Time (h)	Temp. (°C)	Time (h)	Temp. (°C)	Time (h)
Outer Surface	Upper	376.6	0.6			259.8	0.6	446.3	0.6
	Middle	409.4	0.6			273.0	0.6	439.8	0.6
	Lower	416.3	0.6			264.5	0.6	404.0	0.6
Inner-shell Outer Surface	Upper			81.8	12.13				
	Middle			81.6	12.37				
	Lower			81.2	12.67				
Inner-shell Inner Surface	Upper	101.9	3.35	81.6	12.28	101.6	3.55	113.7	2.38
	Middle	100.6	3.35	81.2	12.5	101.9	3.55	110.2	2.67
	Lower	99.9	3.27	81.2	12.88	99.9	3.55	106.7	2.83
Basket Surface	Upper	75.5	12.35	76.1	15.05	76.6	9.7	75.9	11.7
	Middle	75.1	12.83	-		76.0	10.7	75.6	12.48
	Lower	74.5	13.0	75.5	15.85	75.0	11.85	75.0	13.32

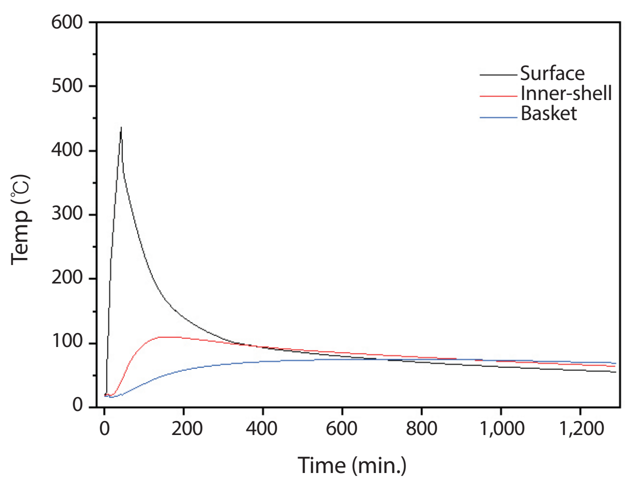

Fig. 6. Temperature history of the test model in the fire test.

Table 4 lists the maximum temperatures measured during the fire test. Fig. 6 shows the temperature history of the test model according to the transient time during the fire test. The maximum temperature of the outer surface measured under the fire test was 446°C after 36 min in the upper part of the 270° direction. The maximum temperature of the inner-shell outer surface was 82°C after 12 h in the upper part of the 90° direction. The maximum temperature of the inner-shell inner surface was 114°C after 2.4 h in the upper part of the 270° direction. The maximum temperature of the basket surface was 77°C after 9.7 h in the upper part of the 180° direction. These were lower than the short-term- exposure permitted maximum temperature of 538°C [6] for stainless steel and carbon steel, which are materials that are components of the KTC-360 transport cask. Therefore, it was proved that the thermal integrity of the KTC-360 transport cask could be maintained under the fire-accident condition at 800°C for 30 min.

Considering the overall temperature distribution, the phenomenon opposite to that observed in the high-temperature test was observed; the temperature in the 90° direction was low and that in the 270° direction was high. This was because heat resistance was created because of the internal space in the 90° direction, and resultantly, less heat transfer occurred, similar to what happened under the high-temperature test.

4. Conclusions

To prove the thermal integrity of the KTC-360 transport cask under high-temperature and fire-accident conditions, high-temperature and fire tests were performed using a one-third slice model of an actual KTC-360 transport cask. The main results of this study are as follows:

(i) The maximum temperature of the outer surface was evaluated to be approximately 62℃, which exceeded 50℃, the surface temperature stipulated by the regulations. Therefore, KTC-360 transport casks should be transported exclusively.

(ii) The highest temperature of the CANDU spent nuclear fuel was predicted to be lower than the melting temperature of Zircaloy-4, which was the sheath material used. Therefore, it was evaluated that the thermal integrity of the KTC-360 transport cask could be maintained under normal transport conditions.

(iii) The maximum temperatures of the components of the KTC-360 transport cask were lower than the permitted maximum temperature limit. Therefore, the thermal integrity of the KTC-360 transport cask could be maintained under fire accident conditions.

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