⟨Technical Notes⟩

HEAT REMOVAL TEST USING A HALF SCALE STORAGE CASK

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Spent nuclear fuel generated at nuclear power plants must be safely stored during interim storage periods. A dry storage cask to safely store the spent nuclear fuel should be able to adequately emit the decay heat from the spent nuclear fuel. Therefore, heat removal tests using a half scale dry storage cask have been performed to estimate the heat transfer characteristics of a dry storage cask under normal, off-normal, and accident conditions. In the normal condition, the heat transfer rate to an ambient atmosphere by convective air through a passive heat removal system reached 83%. Accordingly, the passive heat removal system is designed well and works adequately. In the off-normal condition, the influence of a half blockage in the inlet on the temperature appears minimal. In the accident condition, the temperature rose for 12 hours after the accident, but the temperature rise steadied after 36 hours.

KEYWORDS : Spent Nuclear Fuel, Interim Storage, Dry Storage Cask, Decay Heat, Heat Removal, Heat Transfer

1. INTRODUCTION

The management of spent nuclear fuel generated at nuclear power plants has become a major policy issue due to continued delays in obtaining a safe, 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 storage of spent nuclear fuel is essential if the nuclear power plants are to be allowed to continue operation.

Dry storage casks are one possible solution for solving the interim storage problem. The dry storage cask system consists of three separate components: an over-pack, a canister, and a transfer cask. The spent nuclear fuel assemblies are loaded and sealed inside the canister. Then, the canister is transferred using the transfer cask into a cylindrical over-pack for on-site dry storage. The canister may be removed from the over-pack at any time and transferred into the transport cask for movement to a permanent disposal facility.

Figure 1 shows the schematic of the dry storage cask. The structural casing of the over-pack is made of carbon steel, and the inner cavity of the casing is filled with concrete, which acts as a radiation shield. The dry storage cask must ensure that the temperatures of the spent nuclear fuel assemblies are maintained within the allowable values for normal, off-normal, and accident conditions. Therefore, the dry storage cask must be designed including heat removal capabilities with an appropriate reliability[1].

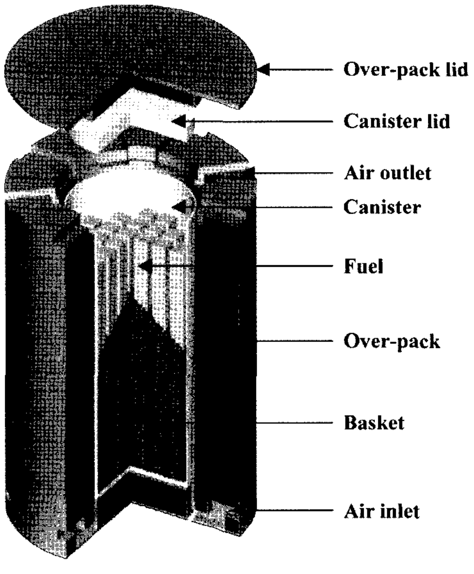

Fig. 1. Schematic of the Dry Storage Cask

Table 1. Description of the Dry Storage Cask

Item	Description
Storage Capacity	24 PWR Assemblies
Components	Concrete Over-pack Canister
Dimension	Concrete Over-pack : 3550 mm x 5885 mm Canister :1840 mm x 4845 mm
Weight	Storage Cask : 154.5 tons (Loaded Canister) Canister: 38.2 tons (Loaded Fuels)
Material	Over-pack : Carbon Steel & Concrete Canister : Stainless Steel &Boral (B_4C + Al)
Design Basis Fuel	Burn-up: 50,000 MWD/MTU Cooling Time: 7 years Enrichment: 5.0 wt% ^{235}U Decay Heat: 25.2 kW"

However, the thermal conductivity of concrete is not good and the allowable temperature of concrete is lower than that of steel. Therefore, a passive heat removal system was designed so that the temperatures of the fuel assembly cladding material and the dry storage cask components remain within the allowable limits. The passive heat removal system consists of eight inlets and eight outlets [2].

A description of the dry storage cask is provided in Table 1. The outer diameter of the dry storage cask is 3,550 mm and its overall height is 5,885 mm. It weighs approximately 135 tons. The dry storage cask accommodates 24 PWR spent fuel assemblies with a burn-up of 55,000 MWD/MTU and a cooling time of 7 years. The decay heat from the 24 PWR spent fuel assemblies is 25.2 kW".

This paper discusses the experimental approach used to evaluate the heat transfer characteristics of the dry storage cask.

2. HEAT REMOVAL TEST

2.1 Description of the Test Model

The test model is a one-half scale model of the dry storage cask. Figure 2 shows a cross section of the thermal test model. During actual storage, the lid of the canister is welded to the body of the canister to maintain the confinement. However, during the thermal tests, the lid of the canister was only bolted to the body of the canister to allow the opening of the lid after the test. The lid of the canister had 24 holes for electric heaters and 24 holes for thermocouples. The electric heaters, which were used to simulate 24 PWR spent fuel assemblies, were accommodated within the baskets and fixed onto the top of the lid of the canister with a swage lock.

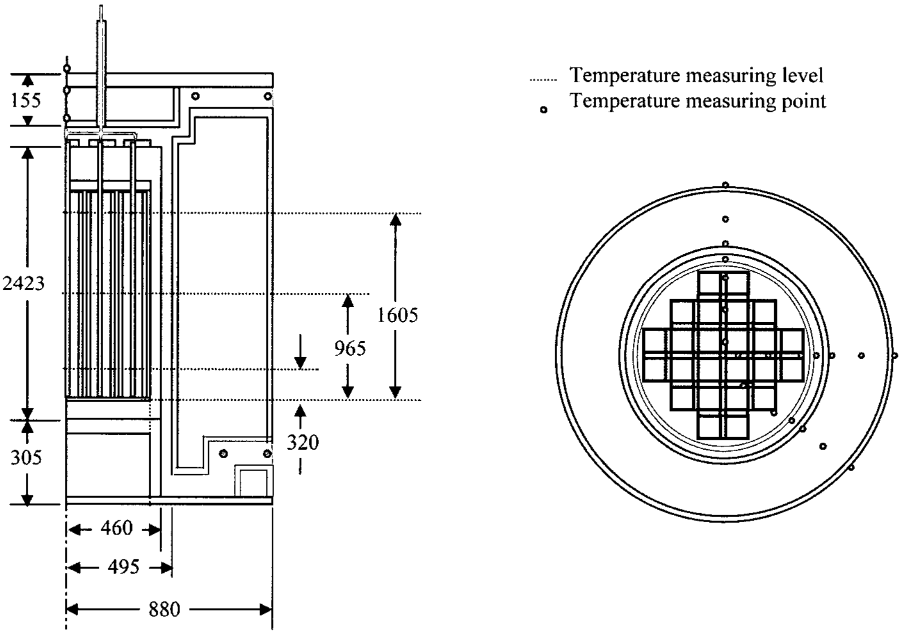

Fig. 2. Cross Section of the Thermal Test Model

2.2 Heat Transfer Mode and Measurement System

Heat is generated by the spent nuclear fuel assemblies within the canister and transferred to the surface of the canister via conduction, convection, and radiation. This heat is then transferred from the surface of the canister to the inner surface of the over-pack through convection and radiation. The over-pack is designed to dissipate the heat from the canister through a passive heat removal system. This mechanism involves a natural convective air flow through the annular area between the canister and the inner surface of the over-pack. Therefore, heat transfer from the over-pack to the ambient atmosphere is accomplished through two mechanisms: the heat, which is conducted through the over-pack body, is dissipated from the exterior surface of the over-pack to the ambient atmosphere by convection and radiation, and the air, which is heated in the annular area, is vented to the ambient atmosphere through the outlets of the passive heat removal system.

The heat transfer from the exterior surface of the over-pack to the ambient atmosphere is [3,4]:

$$q_s = hA(T_s - T_a) + \sigma\varepsilon A(T_s^4 - T_a^4),$$

where q_s is the heat flow rate from the exterior surface of the over-pack to the ambient atmosphere, h is the natural convective heat transfer coefficient, A is the surface area, T_s is the temperature at the surface, T_a is the ambient temperature, σ is the Stefan-Boltzmann constant, and ε is the emissivity.

Heat transfer to the ambient atmosphere through the passive heat removal system can be related to the inlet and outlet fluid temperatures through an energy balance [5]:

$$q_A = \dot{m}C_p\Delta T,$$

where q_A is the heat transfer into the air, $\dot{m}$ is the mass flow rate, C_p is the specific heat of the air, and ΔT is the differential air temperature from the inlet to the outlet.

Therefore, it is important to estimate the energy balance in order to evaluate the heat transfer characteristics of the dry storage cask. Accordingly, two measurement systems were used in the heat removal test. One was the temperature data acquisition system, which consists of a thermocouple scanner, a signal conditioner, an A/D converter, and a P/C. The other was the velocity data acquisition system, which consists of an anemometer scanner, a data logger, an A/D converter, and a P/C.

2.3 Heat Removal Test

As shown in Fig. 3, the heat removal tests were carried out in a structure with dimensions of 5.0 m x 5.0 m x 5.0 m under normal, off-normal, and accident conditions [6]. The structure was made from sandwich panels to avoid wind and rain, as well as to decrease the influence of ambient temperature fluctuations. Also, the roof of the house had two exhausts in order to prevent a stratification boundary at the outlet level of the dry storage cask during

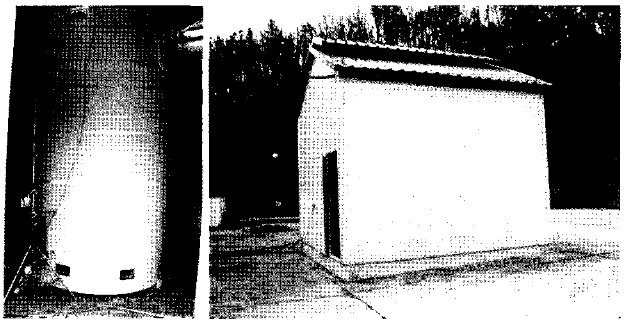

Fig. 3. Test Model and Thermal Test Structure

Table 2. Measurement Parameters

Item	Sensor		Subject and Number
Temperature	Thermocouple		Inside of the Over-pack: 18 Surface of the Over-pack: 9 Surface of the Canister: 12 Basket: 24 Inlet: 6 Outlet: 6 Ambient: 26
Air Velocity	Anemometer	Hot Wire	Inlet: 3
		Vane	Outlet: 3

the heat removal tests.

During the heat removal test, the test model was located in the center of the house, cold air entered the house through six louvers at ground level, and the heated air was vented through the roof. The total heat power from the 24 electric heaters was 4.5 kW.

Table 2 shows the measurement parameters and Fig. 2 shows the measuring points of the temperature in the test model. A total of 105 thermocouples were installed: 79 to measure and monitor the temperature of the test model and 26 to measure and monitor the ambient temperature of the thermal test structure.

There were two types of sensor used to measure the air velocity at the inlet and outlet. Hot wire anemometers were used to measure the air velocity at the inlet duct. As the temperature of the exhaust from the outlet duct is very high, the air velocity at the outlet duct was measured with a vane anemometer.

3. TEST RESULTS AND DISCUSSION

3.1 Normal Condition

In the normal condition, the thermal equilibrium of the test model was reached after approximately 120 hours and that state was maintained for two days. Table 3 shows the maximum temperatures measured under normal conditions. The average ambient temperature in the house was maintained at approximately 27 °C during the normal conditions test. Figure 4 shows the temperature distribution of the dry storage cask under normal conditions.

The heat transferred from the dry storage cask to the ambient atmosphere was accomplished using the air in the passive heat removal system and heat transfer on the dry storage cask surface. In order to evaluate the energy balance, the heat transfer rate into the air and the heat transfer rate on the dry storage cask surface were calculated using the temperature and velocity data at the inlet and outlet. The difference of the temperature between the inlet and the outlet was considerably large. The average temperature at the inlet and outlet was measured at 27 °C and 73 °C, respectively. The average velocity at the inlet and outlet was measured at 0.49 m/s and 0.72 m/s, respectively. Therefore, the mass flow rate of the air was calculated to be 0.0104 kg/s. Accordingly, the heat transfer rate to the ambient atmosphere by the air was estimated as 83% of the heat transferred from the dry storage cask to the environment. This shows that the passive heat removal system was designed well and worked adequately.

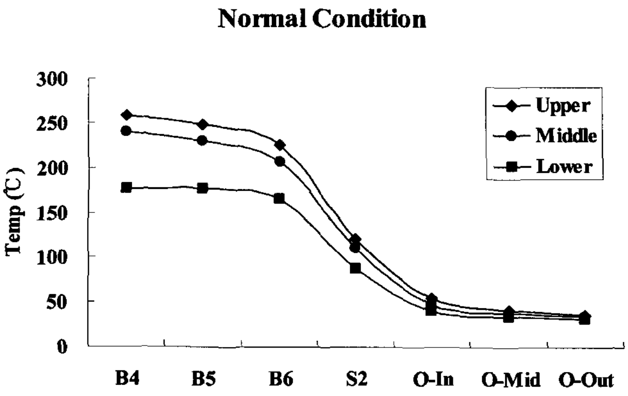

Fig. 4. Temperature Distribution of the Dry Storage Cask under Normal Conditions

3.2 Off-normal Condition

In the off-normal condition, half of the inlet was blocked. The thermal equilibrium of the test model was reached after approximately 120 hours, as in the normal condition, and that state was also maintained for two days. The average ambient temperature in the house was maintained at approximately 27 °C during the off-normal condition test. Table 4 and Fig. 5 show the temperatures from the off-normal condition compared with the normal condition.

Table 3. Test Results for Normal Conditions

Location		Maximum temperatures (°C)					
		Basket	Canister	Over-pack		Inlet	Outlet
				Inside	Outside		
0°	Upper	259	116	53	36		70
	Middle	240	105	46	34		
	Lower	177	-	39	32	27	
90°	Upper	259	121	54	36		76
	Middle	239	110	47	34		
	Lower	176	88	40	32	27	

Table 4. Test Results for Off-Normal Conditions

Location		Maximum temperatures (°C)					
		Basket	Canister	Over-pack		Inlet	Outlet
				Inside	Outside		
0°	Normal	259	116	53	36	27	70
	Off-normal	263	123	56	38	27	78
90°	Normal	259	121	54	36	27	76
	Off-normal	263	125	58	38	27	84

As can be seen in the table and figure, the temperatures for off-normal conditions are slightly higher than those for normal conditions, but the temperature of the air at the outlet increases compared with the normal conditions. The average velocity at the inlet was measured at 0.69 m/s; however, the average velocity at the outlet was measured at 0.58 m/s, lower than that at the inlet. This is due to the mass flow rate of the air decreasing at the inlet. As can be seen in the temperature distribution, a drift flow in the flow area that could increase the local temperature of the dry storage cask has not occurred. As the temperature increase is between 2°C ~ 8°C, the influence of the half blockage of the inlet on the temperature appears to be minimal.

3.3 Accident Condition

In the accident condition, after the thermal equilibrium of the test model was reached, all inlets were blocked. The test was continued for 48 hours. During the test period, the air did not leave the outlet. Table 5 shows the temperatures at 12 h, 24 h, 36 h, and 48 h after all inlets were blocked. Figure 6 shows the temperature profile for the dry storage cask under the accident condition. The temperature rose for 12 hours after the accident. This is because convection heat transfer weakens and radiation heat transfer occurs mainly due to the blockage of the all inlets. The temperature rise steadied after 36 hours, but the temperature of the test model did not reach a thermal equilibrium.

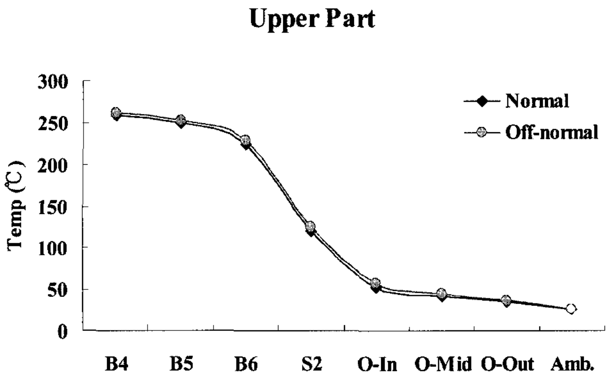

Fig. 5. Temperature Comparison between Normal and Off-normal Conditions

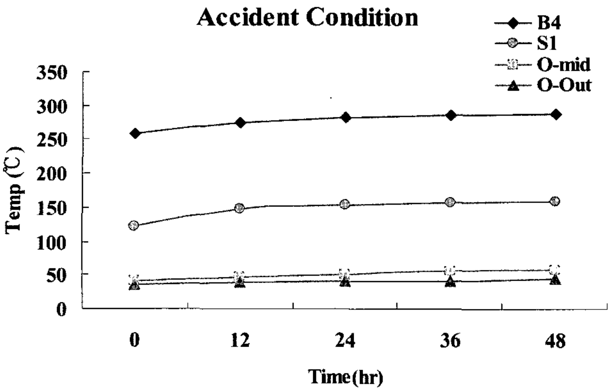

Fig. 6. Temperature Profile for the Dry Storage Cask under Accident Conditions

Table 5. Test Results for Accident Conditions

Location	temperatures (°C)					
	0h	12h	24h	36h	48h	Ambient
Basket	259	275	282	287	288	31
Canister	116	144	150	154	156	31
Over-pack	43	46	51	55	58	31

4. CONCLUSIONS

A heat removal test was carried out to evaluate the heat transfer characteristics of a dry storage cask. The main results are as follows:

(i) In the normal condition, the heat transfer rate to the ambient atmosphere by convective air through a passive heat removal system reached 83%. Accordingly, the passive heat removal system was well designed and worked adequately.

(ii) In the off-normal condition, the influence of a half blockage of the inlet on the temperature appeared to be minimal.

(iii) In the accident condition, the temperature rose for 12 hours after the accident, but the temperature rise steadied after 36 hours.

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NOMENCLATURE

A	surface area [m^2]
C_p	specific heat of the air [kJ/kg·K]
h	convective heat transfer coefficient [W/m^2·K]
$\dot{m}$	mass flow rate [kg/s]
q_A	heat flow rate to the air [W]
q_s	heat flow rate at the surface [W]
T_s	temperature at the surface [K]
T_a	ambient temperature [K]
σ	Stefan-Boltzmann constant [5.669 x 10^{-8} W/ m^2·K^4]
ε	emissivity
ΔT	differential air temperature from the inlet to the outlet [K]

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