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Development Status of Hybrid Heat Pipe-Integrated Spent Fuel Dry Storage Cask - UCAN

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1. Introduction

Spent fuel dry storage cask, has been operated as a interim storage of nuclear wastes to manage the issues on saturation of the storage capacity of spent fuel pool. However, the required decay heat removal rate increases continuously as spent fuel assemblies keep accumulated. despite the cooling capacity is limited due to its inefficient heat transfer manner. To enhance cooling performance of dry cask, a new design of dry storage cask, UCAN (UNIST CANister) was proposed [1]. The UCAN is equipped with hybrid heat pipe-control rod module, which is a passive heat removal device, combining the function of heat pipe and control rod. Through the integration of the hybrid heat pipe-control rod module to the dry cask, additional heat removal capacity could be secured and subcriticality could be maintained.

The dry storage cask should be designed to meet the safety acceptance criteria provided by US NRC in terms of structural integrity, heat removal, confinement, shielding, maintaining subcriticality, and material during operation period. To evaluate the performance of dry cask, numerical simulations including CFD analysis have been performed based on several assumptions. They require high computational resources, and predicted results are highly dependent on many parameters such as mesh cell number, boundary conditions, and applied models [4, 5]. In addition, experimental works with scaled-down test facilities were not designed with logical scaling methodology [2, 3].

To overcome the shortcomings of previous design works, 1/5 test facility was constructed to represent both conventional dry cask and UCAN, based on the Ishii and Kataoka`s scaling law. Besides, MARS code was selected as a safety analysis tool to evaluate thermal performance of UCAN with hybrid heat pipe-control rod module with reasonable accuracy. The structural integrity of UCAN design is being analyzed using ANSYS. In this paper, the development status of UCAN design including physical insights observed by experiments and numerical simulation with analysis codes are presented.

2. Experimental Works

In this section, scaling methodology to design scaled test facility for dry cask and validation simulation results are presented. It is scaled down as length scale of 1/5, by modeling heat and fluid flow as single phase natural circulation of helium gas charged inside sealed canister and major heat transfer mechanism as both natural convection and radiation heat transfer of helium inside. Reference design of conventional dry cask is a dual-purpose metal cask with 10-year cooled 21 PWR SNF developed by KORAD, assuming 1 kW decay heat generation per each fuel assembly.

2.1 Scaling Methodology

Ishii and Kataoka's scaling law for the single-phase natural circulation loop and ANL scaling law developed for RCCS of VHTR was adopted to design 1/5 length scale test facility of dry cask [6, 7]. Especially, ANL scaling law for RCCS of VHTR can be adopted to dry cask system, where natural convection and radiation heat transfer of gas take important roles to determine overall thermal performance of the system.

First, the geometrical similarity should be satisfied to match ratio of model to prototype for major parameters as unity. By using same fluid and solid materials of model with those of prototype, reference velocity ratio u_{oR} and reference temperature ratio, ΔT_{oR} can be expressed in terms of length scale, l_{oR}, shown in (1) and (2). And then, energy similarity is made to have ΔT_{oR} as unity by selecting proper design. Table I shows the derived scaling ratio for scaled test facility for dry cask.

$$u_{oR} = \left\{ \dot{q}_{oR} \left(\frac{\beta}{\rho C_p} \right)_R \frac{\delta_{oR}}{d_{oR}} l_{oR}{}^2 \right\}^{1/3} \quad (1)$$

$$\Delta T_{oR} = \dot{q}_{oR} \left(\frac{1}{\rho C_p} \right)_R \frac{l_{oR}}{u_{oR}} \frac{\delta_{oR}}{d_{oR}} \quad (2)$$

Table I Derived scaling ratio for test facility

Parameter	Expression	Value
Length	l_{oR}	0.20
Velocity	$u_{oR} = \sqrt{l_{oR}}$	0.45
Temperature difference	$\Delta T_{oR} = 1$	1.00
Heat transfer coefficient	$h_R = \sqrt{l_{oR}}$	0.45
Total heat input	$Q_{oR} = l_{oR}$	0.20

2.2 Test facility

1/5 UCAN test facility can represent both conventional dry cask and UCAN by changing operation mode of hybrid heat pipe module. 4 heater rods assembly with guide tube at the center represents each fuel assembly. Total 84 cartridge heaters and 21 basket ducts are installed in same arrangement of actual SNF assemblies. 3 thermocouples (TCs) are attached on each basket wall in axial direction and 5 TCs are installed near canister wall in axial direction for each side. Helium gas is filled in canister to 1 bar initially. And then, power for cartridge heaters turned on and temperature and pressure data are measured until reaching steady state. Fig. 1 shows the design of the test facility and Table II shows test range for 1/5 scaled test facility

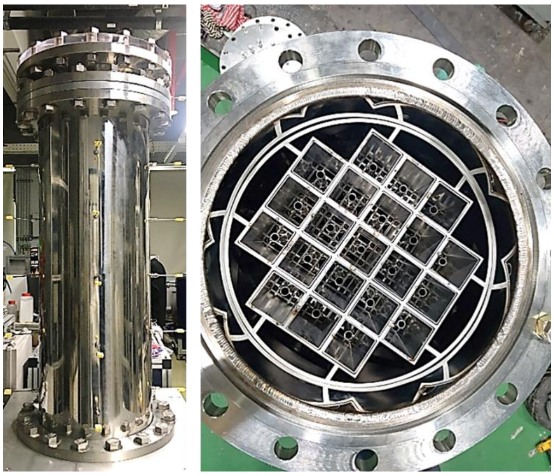


Fig. 1. Photo of 1/5 Scaled UCAN test facility

Table II Test range of 1/5 scaled UCAN facility

Parameter	Value
Heat input	1050 – 8400 W
Q_{oR}	1.0 – 2.0
Internal pressure of He	1 – 2 bar
External air condition	22 °C constant
Working fluid	Water
Operation pressure of hybrid heat pipe module	0.5 – 1.5 bar

2.3 Experimental results and discussion

Temperature distributions and evolutions of the helium and baskets at the steady states according to dry storage cask designs (UCAN and general metal cask) were analyzed to deduce the effects of improved cask design with integration of hybrid heat pipes on thermal safety criteria quantitatively.

Basket wall temperature distributions of 1/5 scaled general metal cask and UCAN at steady states were plotted in Figs. 2 and 3. The maximum basket temperature of the general cask was 270 ºC, which is observed at near the center. The basket temperature is decreased as the distance from the center increases because heat removal boundary is cask wall. In addition, temperature difference between maximum and minimum value of the general metal cask design was 120 ºC. In case of UCAN design, the maximum basket temperature and the average temperature difference between center basket and baskets at the peripheral position were 200 ºC and 40 ºC, respectively.

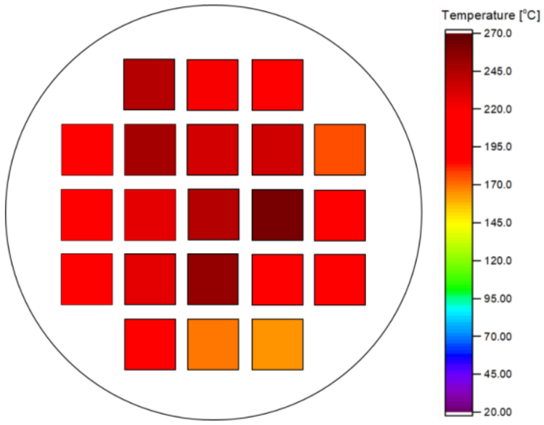


Fig. 2. Basket wall temperature distribution of 1/5 scaled general metal cask at steady state (Q=1050 W, z=0.455 m).

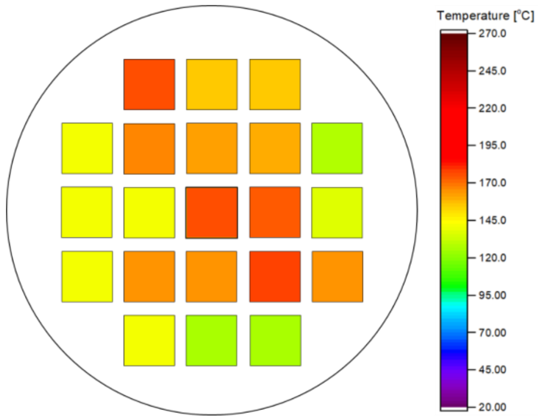


Fig. 3. Basket wall temperature distribution of 1/5 scaled UCAN at steady state (Q=1050 W, z=0.455 m).

Through the comparison of the basket temperature distributions according to cask designs, it was confirmed that the hybrid heat pipe module reduces the temperature gradient in radial direction as well as maximum basket temperature by providing additional heat removal path. UCAN design can reduce basket temperature at steady state providing more temperature margin.

The axial temperature distributions of the helium and basket temperature are important parameter in thermal analysis of dry storage casks because the axial temperature gradient can impose the thermal stress on baskets and fuel rods. Additionally, analysis on axial temperature distribution can represent the quantitative heat removal rate in the axial direction through the hybrid heat pipes or natural circulation.

For both cask designs, the helium temperature was continuously increased as the elevation increases due to the buoyancy as shown in Fig. 4. Comparing helium temperature inside the with that of general cask, lower helium temperature and axial temperature gradient were observed with UCAN. In case of the basket temperature, middle elevation showed the highest wall temperature for both cask designs as shown in Fig. 5 due to the sine-shape heat flux distribution in axial direction. The axial temperature gradient and absolute value of the basket wall temperature of UCAN were also lower than general cask. From data, the additional heat removal path through the hybrid heat pipes of UCAN is provided in axial direction with reducing the thermal stress on baskets and fuel rods. The reduction of thermal stress is expected to decrease thermal degradation of structures for the long-term operation.

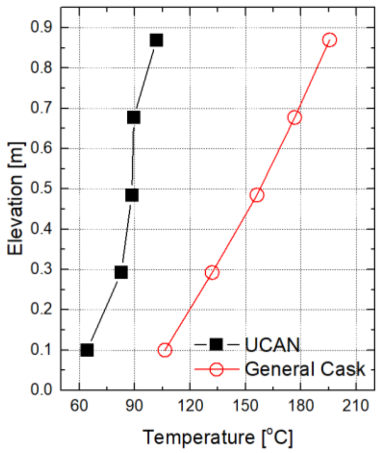


Fig. 4. Comparison of measured helium temperature distributions inside the scaled UCAN and general metal cask.

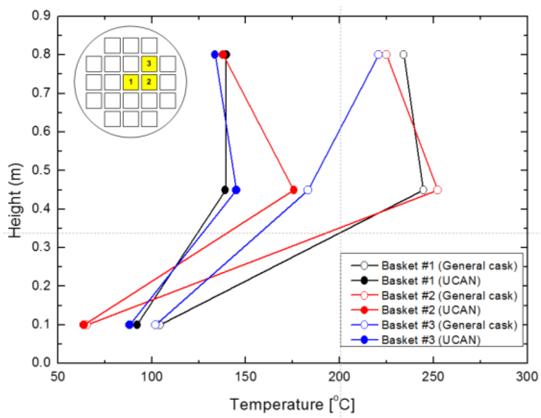


Fig. 5. Comparison of measured axial basket wall temperature distributions of scaled UCAN and general metal cask.

3. Safety Analysis

The effects of UCAN design on cask operation was observed through the experimental works with scaled test facility. However, the safety of the cask design must be proved under various off-normal and accident scenarios. Therefore, safety analyses are conducted using MARS code, which is a one-dimensional thermal-hydraulics system analysis code, for a thermal safety and ANSYS for structural analysis. In this section, research progress on the system analysis of UCAN are presented.

3.1 Deterministic safety analysis using MARS code

For the use of MARS code on safety analysis of UCAN under accident conditions, analysis methodology and predictability of the MARS code on cask analysis must be validated. The experiment conducted with 1/5 scaled test facility was simulated as a benchmark case.

Initial and boundary conditions of MARS analysis were modeled equal to experimental conditions. The specific analysis methodologies used in the simulation are heat transfer models related to the natural convection of helium gas, and evaporation and condensation inside the hybrid heat pipes. The details on analysis method are discussed in Ref. [8].

The calculated axial temperature distributions of basket and helium by MARS were compared with experimental data as shown in Fig. 6.

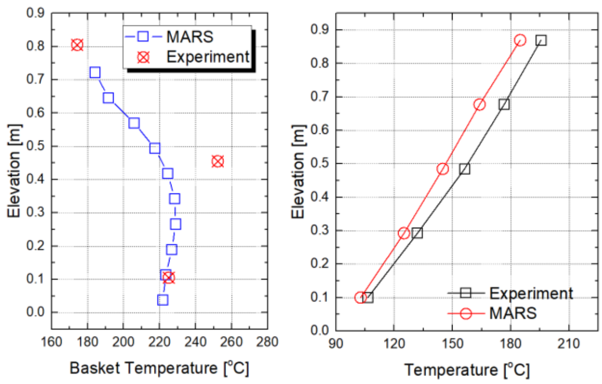


Fig. 6. Comparison of analyzed basket wall and helium temperature distributions with experimental data.

Predicted temperature from MARS analysis showed reasonable agreement with measured data for both basket and helium. The deviations between experimental data and analyzed results were attributed to the bundle effect and neglection of view factor in radiation heat transfer. However, the overall temperature behavior inside the cask were negligibly influenced by the deviation contributors. Although there will be additional verification works, it seems that the MARS has sufficient prediction ability to the thermal analysis of cask. Thus, performances of the cask designs under postulated accident conditions, suggested by US NRC, will be analyzed by MARS code with established analysis methodology for the optimization of cask design and its design approval.

3.2 Mechanical integrity analysis

The drop accident was simulated to evaluate the mechanical integrity of the UCAN component by using the ANSYS explicit dynamic method. To analyze the weakness point of the UCAN such as rupture, stress and strain, the simplified fuel assembly and the hybrid heat pipe component were modelled. The detail information of simulation domain is shown in Fig. 7.

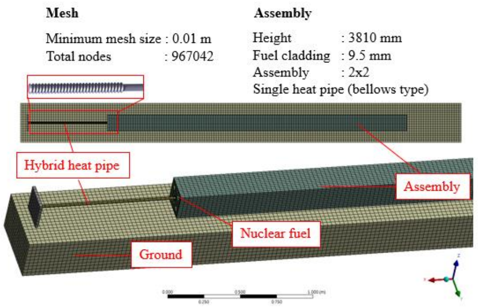
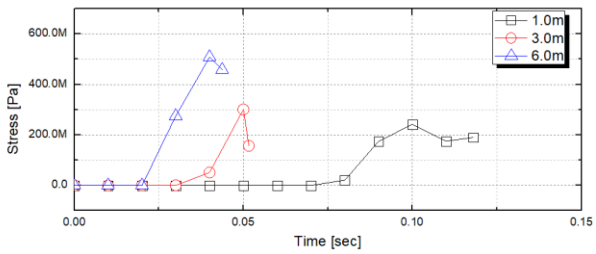
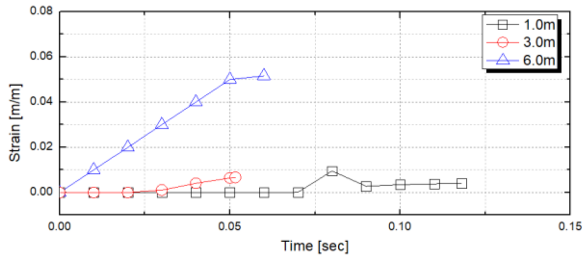


Fig. 7 Generated mesh and fuel assembly information



(a) Stress curve according to the drop height



(b) Strain curve according to the drop height

Fig. 8 Stress and strain curve under 6m side drop accident

In case of the side drop, the hybrid heat pipe is possible to have mechanical damage and deformation due to the its long and thin shape. For all cases the drop heights (1m, 3m, 6m), the hybrid heat pipe had small plastic deformation and maximum stress. In case of the 6m side drop, maximum stress loaded on the hybrid heat pipe was lower than stress limit. The maximum strain of the UCAN was 0.005, and 0.024m of the plastic deformation were predicted from drop accident analysis. The stress and strain behavior under 6m drop accident are shown in Fig. 8.

4. Conclusions

To improve the design safety of spent fuel dry storage cask, UCAN, which is integrated with hybrid heat pipe-control rod module, was proposed. onTo demonstrate the thermal performance of UCAN, 1/5 scaled test facility was designed based on Ishii and Kataoka`s scaling law. Through the experimental work with scaled test facility, the improved decay heat removal rate and extended temperature margin of the UCAN was expected compared to that of general metal cask design.

For the safety analysis for postulated accident conditions, MARS code was selected as a thermal analysis tool. By simulating the experimental work conducted with scaled test facility, MARS analysis method for dry cask was established, and reasonable predictability was proved. In addition, ANSYS analysis showed that the UCAN components have sufficient mechanical integrity in severe drop accident conditions.

In the future, the thermal safety of UCAN design under steady operation and various off-normal conditions will be conducted in both experimental and numerical approach.

ACKNOWLEDGEMENTS

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