Thermal Test and Analysis for KSC-7 Cask Development

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INTRODUCTION

All shipping casks for spent nuclear fuels should be evaluated for their thermal integrity in accordance with the design criteria prescribed in IAEA (IAEA a and b) and Korea internal regulations. The objective of this paper is to verify the thermal integrity for dry shipment of the KSC-7 cask under normal transport conditions. The cask was designed to transport seven PWR spent-fuel assemblies with a burnup of 50,000 MWD/MTU and a cooling time of 1.5 years.

A slice model was designed and fabricated to compare the analytical results with those of an actual thermal test, the slice model having the identical dimensions in cross-section and approximately 1/8th length of the prototype cask. The dry cavity was filled with air and helium gas, respectively. Test conditions were based on an environment temperature of 38℃. Dummy heater rods, which convert the original 17 x 17 rods array into a lumped 6 x 6 array, were used in simulating PWR assemblies. The temperatures of the slice model were measured by thermocouples located in the heater rod, inner shell, gamma shield, neutron shield, and outer surface, respectively. The measured temperatures were compared with the analysis results from computer models of the same condition, and configuration as the test.

DESCRIPTION OF THE KSC-7 CASK

Fig. 1 shows the configuration of the KSC-7 cask which is designed to load seven PWR spent-fuel assemblies. The decay heat load for seven PWR assemblies is 32 kilowatts. The cask has multi-layer structures, such as stainless steel shells, lead for a gamma shield, and silicone mixture for a neutron shield. Longitudinal internal cooling fins made of copper are attached between the neutron shield layer, and external cooling fins made of stainless steel are welded at the cask surface in order to improve the heat transfer. The inner cavity containing fuel assemblies of the KSC-7 cask is filled with gas (dry cavity) or water (wet cavity) as a cooling medium.

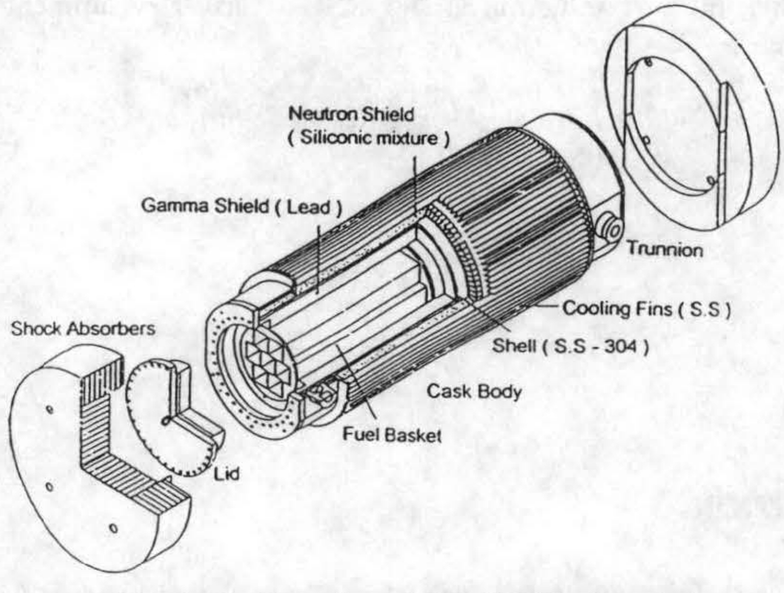


Fig. 1. Configuration of KSC-7 Shipping Cask

THERMAL TEST

Test Model

Fig. 2 shows the slice model for the thermal test, which consists of electric heater rods simulating spent-fuel assemblies and cask body. The slice model has real scale in cross-section and 0.5 m in length. Both ends of the model are covered with an insulation layer to prevent axial heat transfer. K type thermocouples are instrumented at various points in the direction of 0, 90, and 180 degrees to measure the temperatures of each center point. The dummy heater rods simulating spent-fuel assemblies are housed within the slice model, which is composed of seven assemblies. One assembly has a 6×6 rods array, and total thermal power of the dummy heater rods is 4 kilowatts.

Test Equipment

The environment test facility was designed and constructed to simulate ambient temperatures of -40℃ to 38℃. The measurement system consists of thermocouples, scanner, A/D converter, personal computer, and controller. Each component of the measurement system is shown in Fig. 3. Thermocouples installed on the major components of the model are connected to the thermocouple scanner, which can measure temperature up to 40 points. Temperatures measured by thermocouples are stored and analyzed by software in the personal computer after passed A/D converter through each channel of the thermocouple scanner.

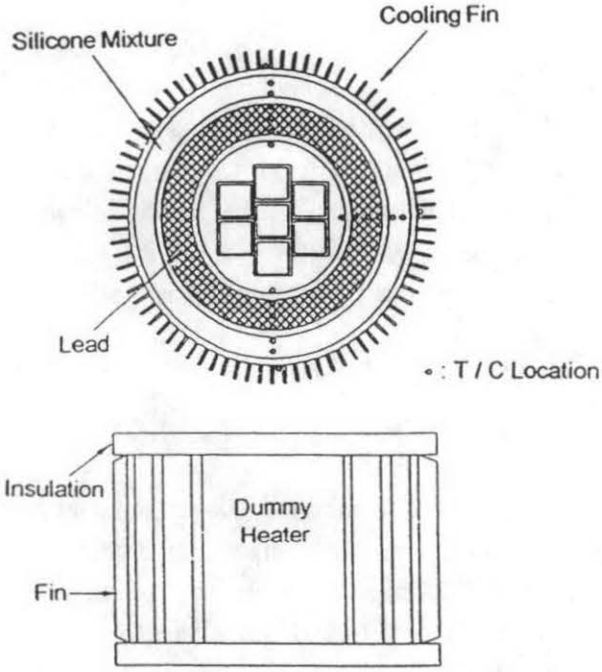


Fig. 2. Slice Model of KSC-7 Cask

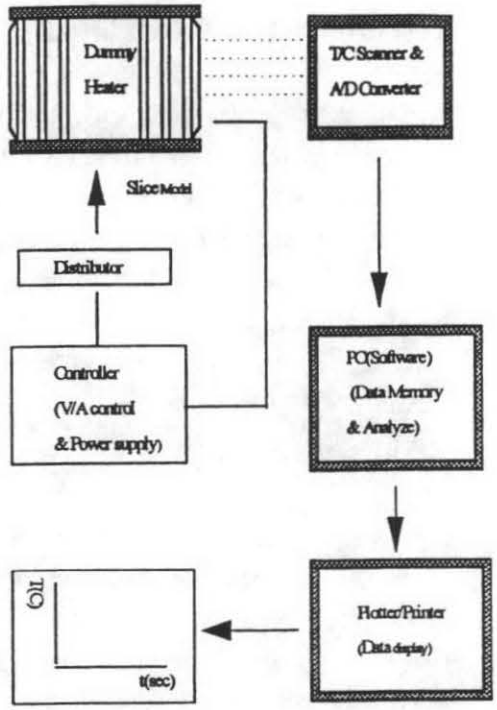
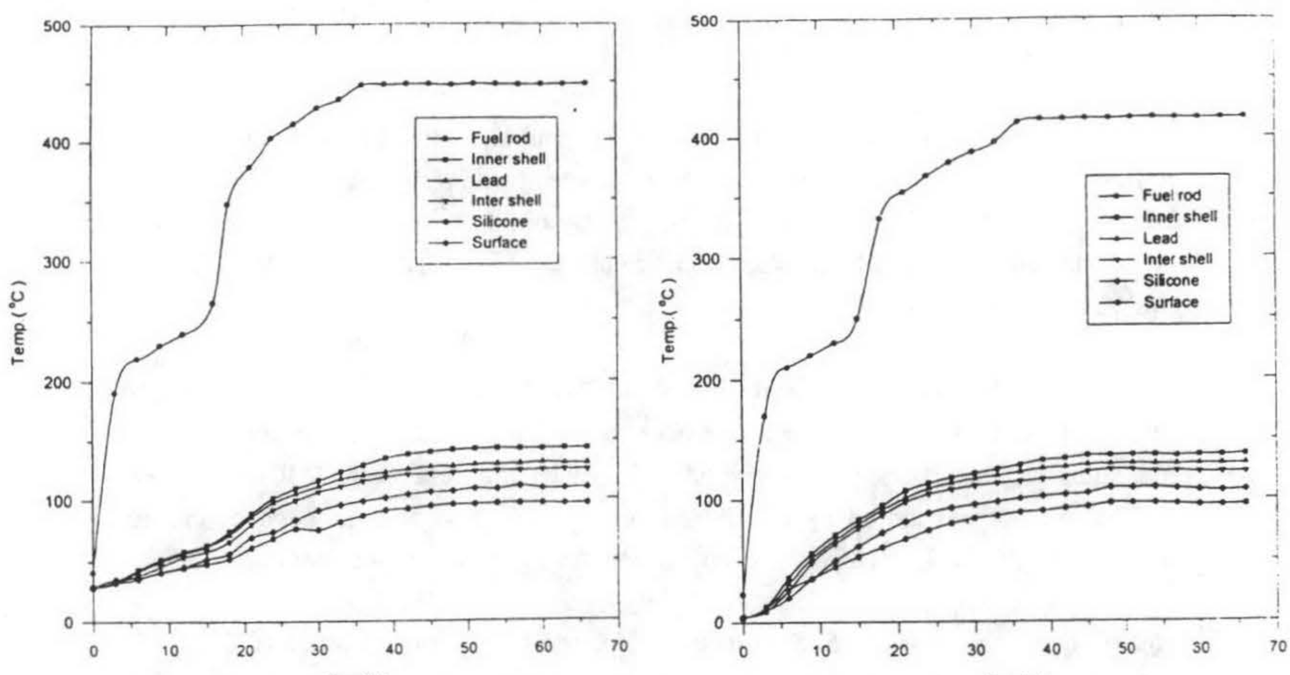


Fig. 3. Temperature Measuring System



<Air cavity>

<Helium cavity>

Fig. 4. Temperature Profiles for Slice Model during the Test

Test Method and Conditions

A thermal test was conducted by placing the slice model horizontally in the test room with an environment temperature of 38℃. Before and after the test, a leakage test was performed with 4.3 kg/cm^2 of air for the model cask cavity in order to confirm it's leak tightness. After the temperature of the cask reached a steady state, it was allowed to stand for 1 week. The test was carried out in two ways: at first, the cavity was filled with air, and then, the cavity was filled with helium gas, which is normally used in the dry type transport cask.

Results of the Test

Fig. 4 shows the temperature profiles of the slice model. It required about 60 hours to reach steady state after the start of raising the temperature. The temperature distribution of the cask body is almost identical when the cavity is filled with air or helium gas. However, the temperature of the fuel rod is higher by about 30℃ when the cavity is filled with air. This is due to the fact that the thermal conductivity of air is lower than that of helium gas by about one-fifth.

THERMAL ANALYSIS

Analysis Method

Thermal analysis was conducted to compare with test results. The analysis was performed in two stages. In the first stage, the temperatures of the cask body were calculated by HEATING-7.2f code (Childs 1993) under steady state. In the second stage, the temperatures of fuel rods were calculated by COBRA-SFS code (Rector et el. 1986).

Fig. 5 shows the two-dimensional HEATING-7 analysis model. In this analysis model, decay heat is removed from fuel assembly to the inner wall by conduction, convection, and radiation, and conduction is considered through the cask body. At the cask exterior surface, heat is transferred by a combination of convection and radiation to the air surrounding the cask. Analysis conditions are the same as test conditions.

Fig. 6 shows the COBRA-SFS analysis model for subchannel analysis of fuel assemblies. COBRA-SFS is a computer code designed and specialized to predict fluid and rod temperatures as well as the fluid velocities for spent-fuel storage systems. Only the inner cavity is considered in the COBRA-SFS analysis model, and boundary conditions are applied with the inner shell temperature calculated by HEATING-7

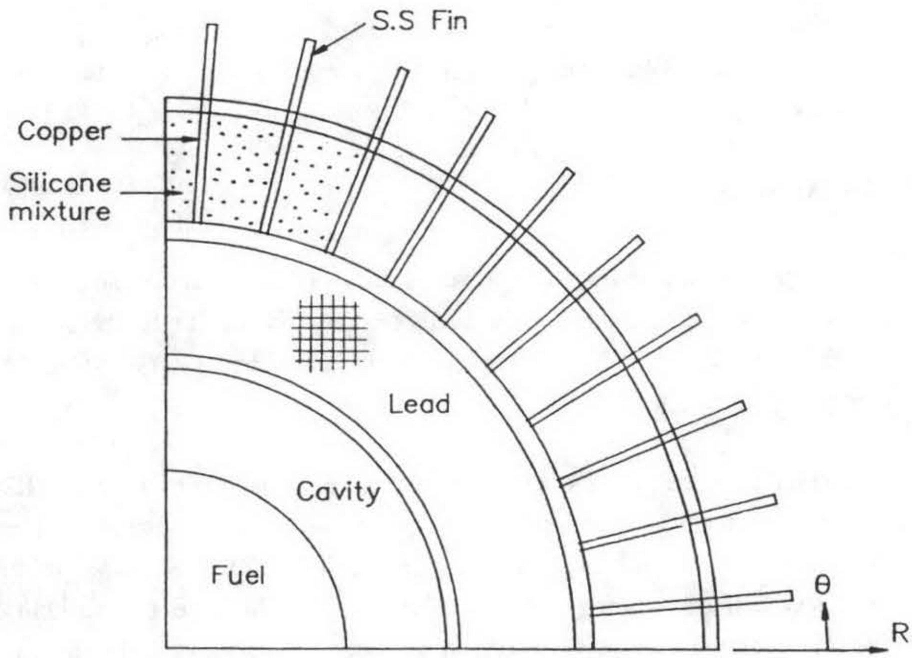


Fig. 5. Thermal Analysis Model for Slice Model

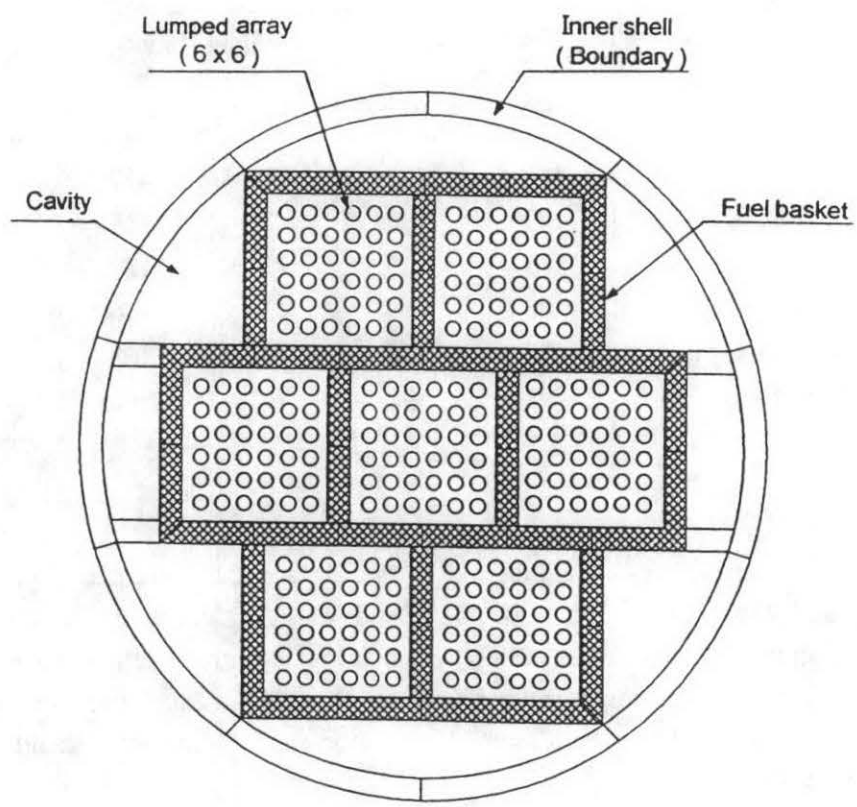


Fig. 6. Subchannel Thermal Analysis Model for Fuel Assemblies

analysis. A 6 x 6 array of fuel bundles is considered in the analysis. The lumped fuel bundles have the same volumetric heat generation rate, fuel cross-sectional areas, and pitch-to-diameter ratio as the real PWR fuel assembly.

Results of Analysis

Figs. 7 and 8 present the temperature distributions of fuel rods in the cavity of air and helium gas which are calculated by the COBRA-SFS code. The temperatures of fuel rods range from 356℃ to 451℃ in the air cavity and from 315℃ to 437℃ in the helium cavity, respectively.

The comparisons between the test and analysis results are shown in table 1. As shown in table 1, the test results are slightly higher than the analysis results. A pure helium gas is considered in the analysis, but it is next to impossible to charge in the cavity with helium gas perfectly during the test. Therefore, in rhe case of the helium cavity, the temperature difference between test and analysis is higher than in the case of the air cavity.

Table 1. Comparisons of Temperatures between the Thermal Test and Analysis

Temp.(℃) / Location	Air cavity		Helium cavity		Allowable values
	Test	Analysis	Test	Analysis	
Max. fuel rod	448	451	416	437	532
Inner shell	129	136	126	136	
Lead	115	129	112	129	327
Intermediate shell	108	116	106	116	
Silicone mixture	102	108	101	108	
Cask surface	97	98	97	98	
Ambient	38		38		38

The maximum temperatures of a fuel rod in the air and the helium cavity, respectively, are 448℃ and 416℃ in the test, and 451℃ and 437℃ in the analysis. These values are lower than 532℃ (Abe et al. 1989) which is the beginning temperature of fuel rod cladding oxidation. Therefore, it was shown that no fuel rod cladding rupture could occur under normal transport conditions. The temperature of the lead shield is lower than the allowable value.

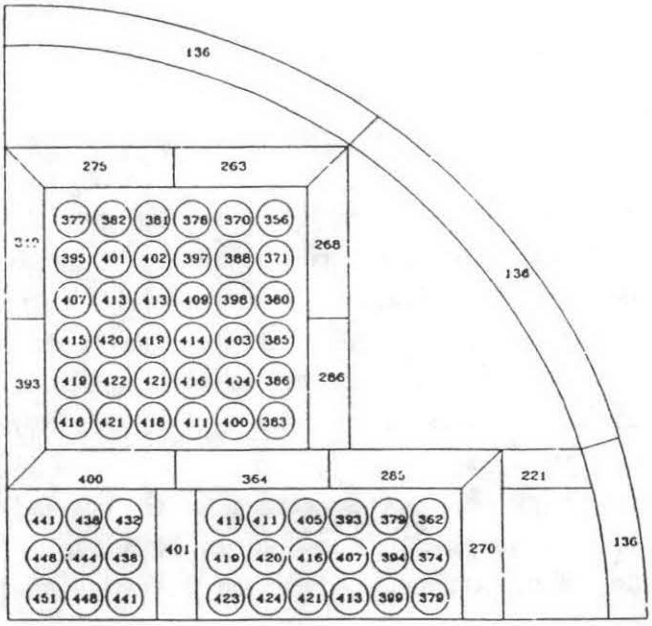


Fig. 7. Temperature Distributions of Fuel Assemblies in Air Cavity

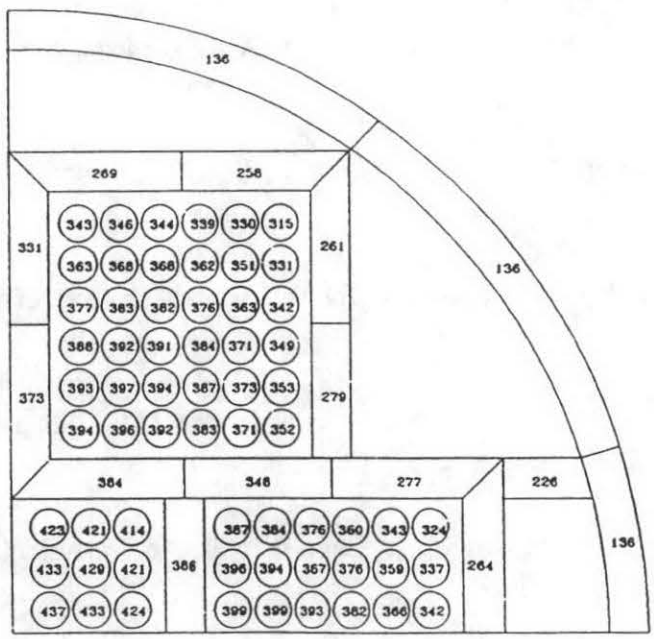


Fig. 8. Temperature Distributions of Fuel Assemblies in Helium Cavity

CONCLUSIONS

The thermal test and analysis were performed to verify the thermal integrity of the spent-fuel shipping cask under normal transport conditions. The maximum temperatures at each part were lower than the allowable values. Especially, the fuel rod temperature was below the specified temperature of 532℃. It was observed that the safety of the containment system was also kept according to the check of the seal before and after the thermal test. Therefore, it was shown that the thermal integrity of the KSC-7 cask was maintained under dry transport conditions.

Moreover, because of the good agreements between the analysis and the test results, it was shown that the test methods were successfully established to estimate the temperature distribution of the shipping cask and the fuel rod.

REFERENCES

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