DEMONSTRATION TEST FOR A SHIPPING CASK TRANSPORTING HIGH BURN-UP SPENT FUELS -THERMAL TEST AND ANALYSES-

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SUMMARY

The thermal test stipulated by the IAEA transport regulations was carried out for a test package, which has the same structural features as the packages used for the actual transportation from nuclear power plants to the reprocessing plant at Rokkasho-mura in Aomori prefecture in Japan. In order to ensure the safe transport of high burn-up spent fuels, the thermal test which formed a part of demonstration tests was carried out in the Central Research Institute of Electric Power Industry (CRIEPI). This paper describes the thermal test using a furnace.

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INTRODUCTION

TEST PACKAGE

The test package designed as a Type B package is NFT-14P which is a wet type package containing 14 PWR spent fuel assemblies (total heat generation : 54 kW). Total weight of the package is about 115 tons. A perspective view of the package is shown in Fig.1.

In order to hold the weight and decay heat, the fuel elements were simulated in this test by electrical heaters. These heaters have the same weight, heat generating length (4060 mm) and heat generation as an actual spent fuel assembly.

Main dimensions of a packaging are as follows

Total weight	: 101.2 tons(without fuel assemblies and cooling water)
Total length	: 6250 mm (in case of attaching shock absorbers)
Diameter	: 2600 mm

THERMAL CHARACTERISTICS OF TEST PACKAGE

The packaging body consists of three cylinders. The main body members in radial direction are inner shell (stainless steel), gamma shielding (lead), intermediate shell (carbon steel), neutron shielding, outer shell (carbon steel) and fins (stainless steel). There is resin filled as neutron shielding, and heat removal cooling fins are welded between the intermediate shell and the outer shell. Disc shaped fins are welded on the outer shell. Top and bottom shock absorbers and the fins were deformed by the impact force in the 9 m horizontal drop test.

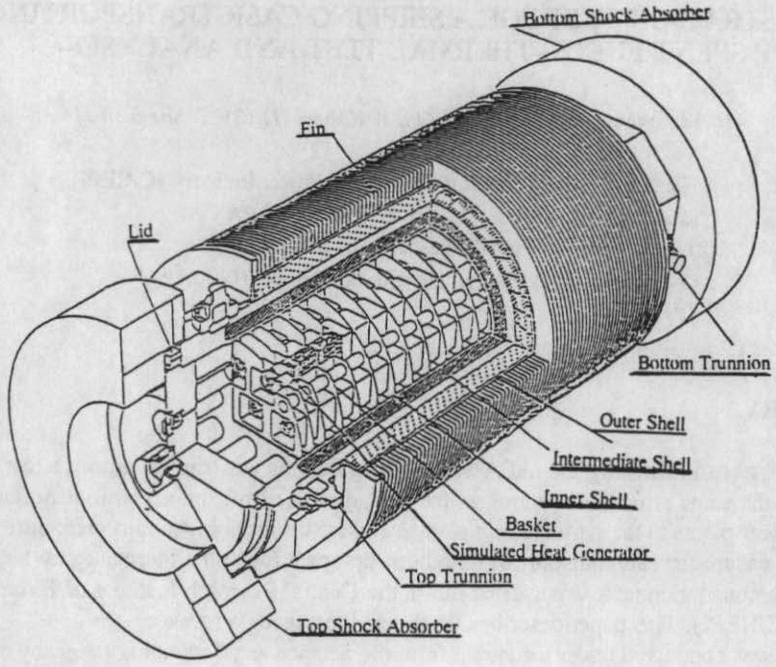

Fig. 1 Perspective view of Test Package

Basket tubes (altogether fourteen) used as housing spent fuel assemblies are made of stainless steel and sustained at the end points including a few intermediate portions by the supporting grids plates. The lid is made of stainless steel. The configuration of top and bottom shock absorbers are as like as doughnuts, and they are respectively fastened to the lid and a bottom plate of the packaging with bolts via stiffeners attached at each hollow part of those.

TEST METHOD

The thermal test was carried out after the 9 m horizontal drop test and 1 m penetration test. Therefore the packaging of which fins had been partially destroyed, and the shock absorbers had been damaged at the loctation of the impact. The package attached with the damaged shock absorbers and containing the simulated fuel elements with the fixed heat generation(decay heat : 54 kW) had been horizontally placed at an average ambient temperature of 23 ℃ prior to the thermal test. After the temperature of the package reached to a steady state, it had been promptly carried into an 800 ℃ furnace and held for 30 minutes, in accordance with the IAEA transport regulations. Moreover, the package was placed at the same ambient temperature of 23 ℃ after the test until the new steady state was reached. The temperature of the simulated fuel elements, cavity water, packaging body and the seal part (O-ring) etc., and the pressure in the cavity of the packaging were measured. The thermal integrity of the packaging was confirmed by the maximum temperature of the components etc.. Temperature data (around 140 points for the package and around 50 points for the ambient) which was utilized for the thermal analysis were also measured.

TEST RESULTS

CHARACTERISTICS OF INITIAL TEMPERATURE DISTRIBUTION

The initial temperature distribution in the circumferetial direction of the package is shown in Fig.2. The temperature at the inner surface of the inner shell was almost constant between 0 degree direction which is equal to a roof of the test equipment and 90 degree direction of the packaging. Moreover, the inner surface temperature of the inner shell at 45 degree direction is nearly equal to that at 0 degree and 90 degree directions. The inner surface temperature at the inner shell tend to decrease from 90 degree direction to 180 degree direction which is equal to the low side of the package due to the effect of the stratified cavity water in the packaging. The temperature in the horizontal direction are uniform at each part of the packaging body. The temperature difference between the inner surface of the inner shell of the packaging and O-ring located at the lid was about 15 ℃ and judged to be small. According to this test result, and because the cavity temperature in the packaging was approximately uniform in the horizontal direction, the effect on longitudinal natural convection of the cavity water is very significant for wet type packages. The temperature of the void region at 0 degree direction in the cavity was almost constant, and the temperature difference between the free surface of the cavity water and the inner surface of the packaging was small. It was shown that the void region in the cavity was filled with steam which caused repetitive phenomenon of evaporation and condensation and this region was also considered to be in a good heat transfer condition.

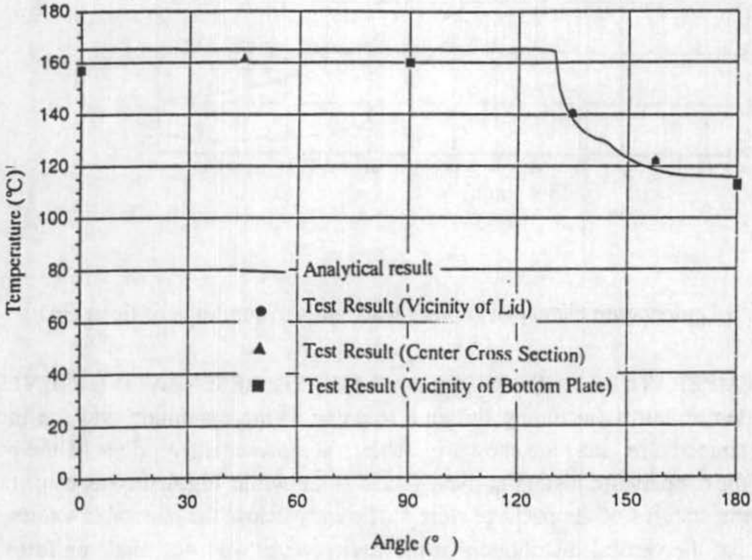

Fig.2 Initial temperature distribution at inner surface of inner shell in circumferentiual direction

TEMPERATURE IN THE FURNACE AND THE PACKAGE SURROUNDINGS

The temperature in the furnace at the thermal test was controlled by the surface temperature of the furnace wall. That temperature, shown in Fig.3, reached 800 ℃ in about 10 minutes after the test package was carried into it. The temperature at the control point in the furnace has been held constantly at 800 ℃ for about 30 minutes, i.e., the condition prescribed in the transport regulations for radioactive materials was satisfied . The ambient temperature close by the fins of the packaging shown in Fig.3 was almost equal to the temperature at the control point in the furnace. Combustion caused by thermal decomposition of the neutron shielding material was observed near the end plates, but it did not give large influence on the furnace temperature. It was confirmed by the results of quantitative analysis and observed cross section view of it that the loss of the neutron shielding material due to the thermal decomposition was about 10 %.

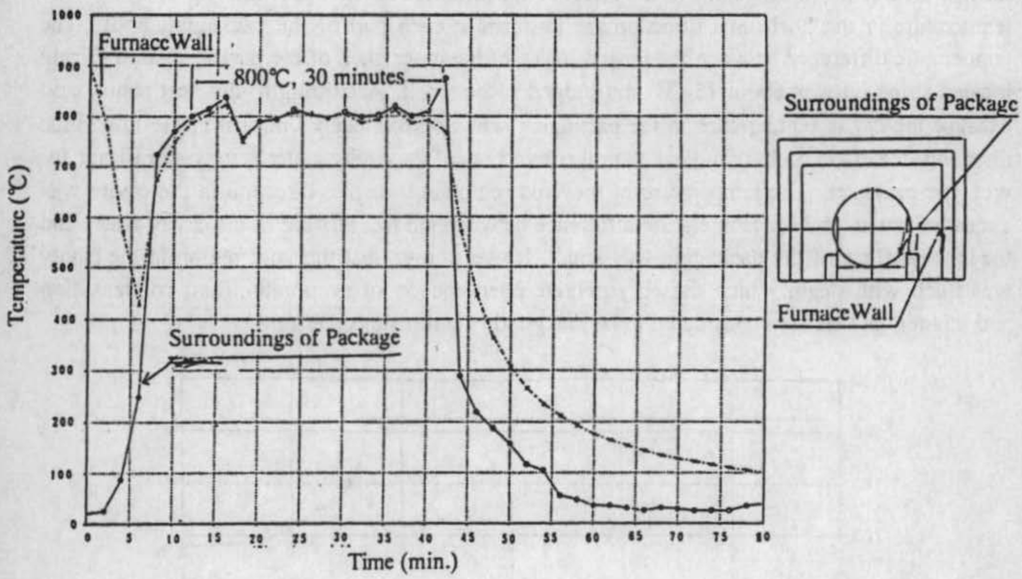

Fig. 3 Temperature history of furnace wall and surroundings of tip at fin.

MAXIMUM TEMPERATURE AND HISTORY AT THE REPRESENTATIVE POINTS

The maximum temperatures (including the time reaching to the maximum and the increment from the initial temperature, etc.) are shown in Table 1 at representative points of the package. An example of the temperature history at those points is shown in Fig.4. It was confirmed that the maximum temperatures of the package were sufficiently below the allowable values. It was also observed that the vertical distribution of the cavity water was not made uniform by the external heat input during the thermal test. Moreover, the maximum temperatures of the seal (O-ring) and the gamma shielding which both were very important with regard to the thermal integrity were 188 ℃ and 178 ℃ respectively. It was confirmed that these values were below the allowable temperatures equivalents of 300 ℃ for the O-ring and 327 ℃ for melting point of lead under the accident condition . Therefore, it was demonstrated that this type of package has sufficient safety margin under thermal test conditions.

Table 1. Maximum Temperature of High Burn-up Shipping Cask for Test

Measured Elements	Maximum Temperature (℃)	Arrival time* (minute)	Initial Temperature (℃) **	Increment of Temperature (℃)
Cavity Water	186.7	454	164.1	22.6
Inner Surface of Inner Shell	183.2	454	161.6	21.6
Inner Part of Gamma Shielding	177.5	107	151.0	26.5
Outer Part of Gamma Shielding	178.0	97	145.0	33.0
Inner Surface of Intermediate Shell	182.8	85	143	39.8
Inner Part of Heat Removal Cooling Fin	201.3	59	133.6	67.7
Outer Part of Heat Removal Cooling Fin	226.3	55	126.5	99.8
Inner Part of Neutron Shielding	180.6	111	140.7	39.9
Outer Part of Neutron Shielding	644.8***	39	118.8	526.0
Outer Surface of outer Shell	492.6	31	105.7	386.9
Vicinity of Tip at Fin	726.5	31	69.4	657.1
Seal Part of Lid	188.0	53	140.2	47.8

* : Elapsed time after the thermal test started (The furnace temperature reached 800 ℃).

** : Ambient temperature was 23 ℃ before and after the thermal test.

*** : This value was affected by partial loss of neutron shielding material for measurement in the drop test.

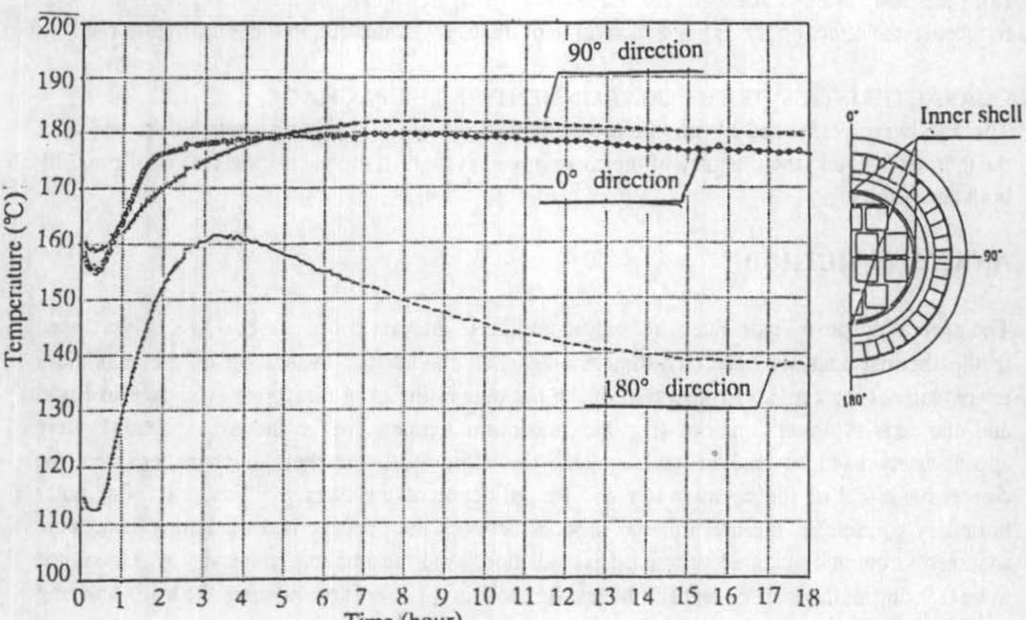

Fig. 4 Temperature history at inner surface of inner shell (0, 90 and 180 degree direction of the package)

PRESSURE IN THE CAVITY

The maximum pressure in the cavity was observed 377 minutes after the thermal test was started. The maximum value was 1.28 MPa and sufficiently lower than 4.3 MPa which is the the allowable value. According to safety analysis of the package, the pressure in the cavity was considered to be the sum of the vapor pressure of the water in it and the increase pressure (according to the Boyle-Charles law) of the void region due to the volumetric expansion of the water in it. However, it was shown that the observed cavity pressure during the thermal test and the time reaching the initial temperature prior to it was fairly good agreed with the saturated vapor pressure which was calculated at the supposed free surface temperature of the cavity water (as shown in Fig.5). Judging from this test result, it was supposed that the thermal expansion of the packaging body, etc. reduceded the effect on the expansive volume of the cavity water due to the temperature rise.

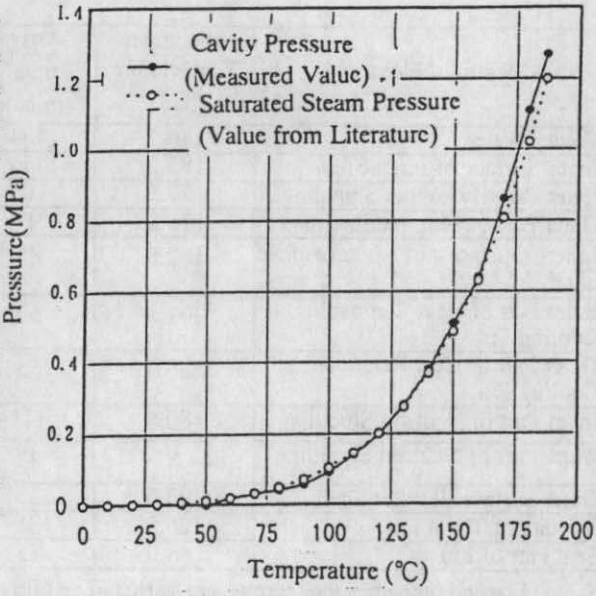

Fig. 5 Relations between cavity pressure and free surface temperature of the cavity water (before and after thermal test)

CHARACTERISTICS OF THE CONTAINMENT OF THE PACKAGE

The tests were performed by leaving a containment system in a vacuum state before and after the thermal test, and the integrity of the containment system of the packaging was confirmed by both test results.

ANALYSIS METHOD

The general purpose Finite Element Method nonlinear analysis code "ABAQUS" was used in the thermal analysis. The two-dimensional shell model (for evaluation of the maximum temperature at the center cross section of the package in the axial direction) as shown in Fig.6 and the axis-symmetric model (for the maximum temperature at the seal portion) were appropriately used to analyze and evaluate the aforementioned thermal characteristics, the convective effect of the cavity water and the influence of the damaged fins, etc.. For outer boundary conditions, the heat transfer process between the package and the atmosphere were assumed to be natural convection and heat radiation. And the ambient emissivity was assumed to be 0.9 during the thermal test (in the test furnace) and 1.0 before and after the test according to the IAEA transport regulations. The effect of the damaged fins (caused by the drop test) was considered by decreasing the heat transfer coefficient at the damaged portions of the fins. For inner boundary conditions in the thermal analysis of the package, the temperature dependent heat conductivities of packaging materials were considered, and moreover, the influence of the stratified water including the natural convection in the cavity and the cyclic effects of evaporation and condensation in the void region were evaluated by taking into account of the equivalent heat transfer coefficients using the proper Nusselt's numbers according to the observed phenomena.

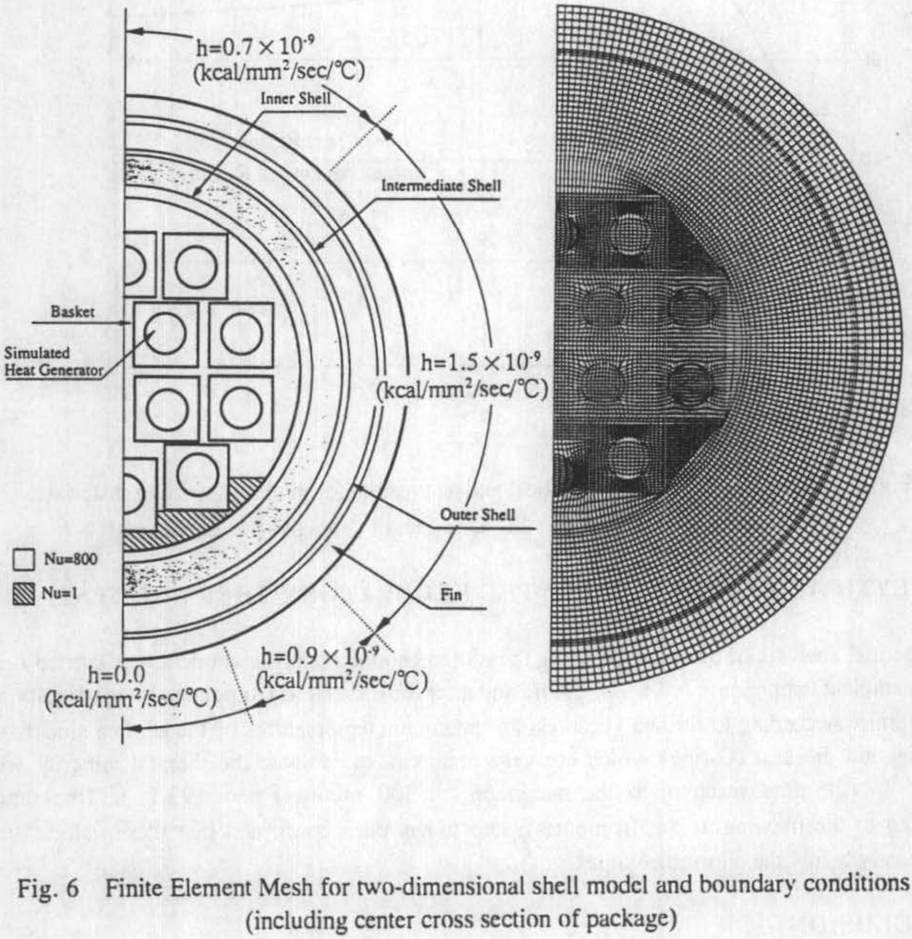

Fig. 6 Finite Element Mesh for two-dimensional shell model and boundary conditions (including center cross section of package)

ANALYTICAL RESULTS OF THE TEST

The thermal test analysis (including about ten minutes until the furnace temperature reaching to 800 ℃) was carried out considering an ambient temperature of 23 ℃ before and after the thermal test. The history of the temperature at the lead portion of the packaging is shown in Fig.7 as a representative result. It was confirmed that the agreement between the test and the analysis was fairly good during and after the thermal test. Therefore, the thermal integrity of actual wet type packages can be evaluated sufficiently by the simulation of thermal test conditions with those analysis models.

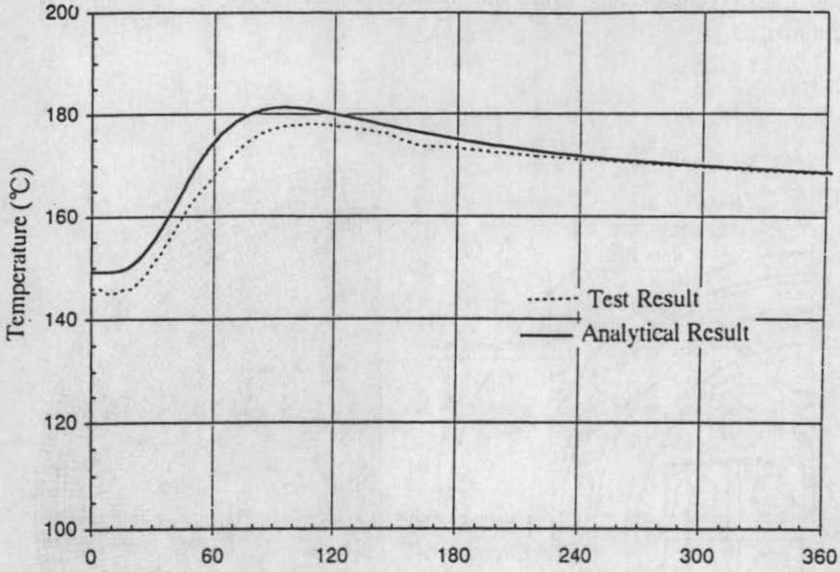

Fig. 7 Comparison between analytical and test results for gamma shielding material (ambient temperature : 23 ℃, effect of damaged fins considered)

ANALYTICAL RESULTS UNDER THE REGULATORY THERMAL TEST

The thermal analysis of the package using the aforementioned analysis models was carried out for an ambient temperature of 38 ℃ before and after the thermal test stipulated by the transport regulations. According to the analytical results, maximum temperatures of the gamma shielding material and the seal (O-ring) which are very important to evaluate the thermal integrity are 190.3 ℃ (the time reaching to the maximum : 300 minutes) and 197.1 ℃ (the time reaching to the maximum : 50 minutes), and it has been confirmed that these values are sufficiently below the allowable values.

CONCLUSION

It was observed that both the maximum temperature at each portion of the package during and after the thermal test is sufficiently below the allowable value. Therefore, the thermal integrity of the transport packages was demonstrated for regulatory thermal test conditions. Fairly good agreements between the analysis and the thermal test were obtained, and it was confirmed that the methodology for the thermal analysis established on the basis of the demonstration tests using various types of full scale package was available for the present package.