Thermal Test and Analysis of a Spent Fuel Storage Cask

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INTRODUCTION

The surface temperature of the fuel rod is one of the most important subjects for the safety evaluation of the integrity of the dry type cask storage system at reactors. This report presents the results of thermal tests on the full scale cask model and thermal analysis by precise estimation of the surface temperature of spent fuel rods to contribute to the safety evaluation of the fuel rods during storage.

CHARACTERISTICS OF TEST CASK

The test cask is a MSF-IV type cask configured to hold 21 PWR spent fuel assemblies after 5 years of cooling (total heat generation rate 23 kW). The bird's eye view of the cask is shown in Figure 1.

The test cask, a multiple layer structure with an outer shell surrounding the basket was used based on following points of view:
(1) It is possible to estimate conductance, convection and radiation, respectively, which dominates heat transfer in the cask.
(2) The thermal estimation for other types of storage casks is possible by the established method of analysis.

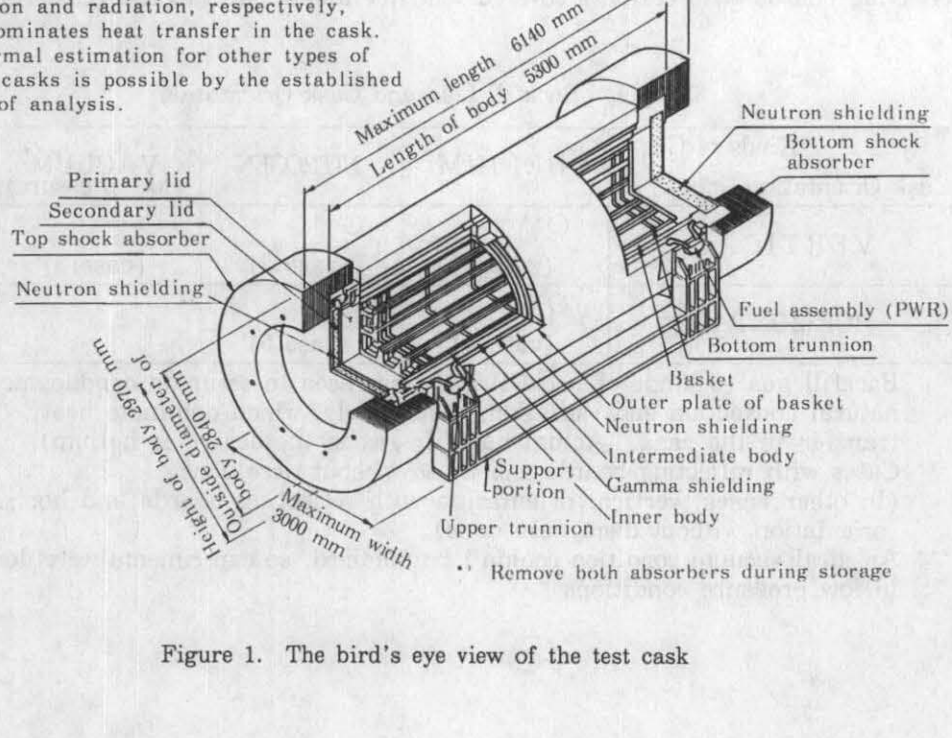

Figure 1. The bird's eye view of the test cask

The body of this cask is of three-layer construction as SUS-Lead-SUS. And there is a layer of polyester resin as neutron shielding and cooling fins made of copper welded between the outer shell and the cask body. Moreover, the lid has a double structure to maintain the efficiency of the containment system over long-term storage.

THERMAL TEST

Test Condition

(1) Condition of the simulated spent fuel assembly and its location in the basket
To simulate the decay heat of 21 spent fuel assemblies after 5 years of cooling, one simulated spent fuel assembly with an equivalent shape and generating heat was housed in the center of the basket. 20 simulated objects with the equivalent generating heat and thermal capacity were housed in other tubes in the basket.

(2) Ambient temperature and wind speed
In this test, according to the concept design of the storage building, the thermal test equipment (7m × 10m × 8m) was used, where the same ambient temperature and wind speed could be simulated.

To simulate the temperature and the wind speed conditions around the cask located in the center of the storage building, the temperature and the wind speed at the inlet of the house were set at 45℃ and 0.4 m/sec. The test conditions of the temperature and the wind speed were determined according to the estimation by another thermal fluid analysis.

Test Cases

The summary of the test case is shown in Table 1. The kind of backfill gas in the cavity (helium/nitrogen/vacuum) and the cask orientation (vertical/horizontal) were chosen as test parameters.

The cask located in the center of the storage building was subjected to the influence of radiation from the surrounding casks. To consider its effect, the cask surface was surrounded with reflecting boards with surfaces covered with the aluminum-vapored resin films (emissivity 0.05).

Table 1. Backfill Gas and Cask Orientation

Kinds of Gas* / Cask Orientation	HELIUM	NITROGEN	VACUUM*** (low pressure)
VERTICAL	○** (case 1)	○ (case 2)	○ (case 3)
HORIZONTAL	○ (case 4)	○ (case 5)	

* Backfill gas (3 kinds of backfill gas were used to estimate conductance, natural convection and radiation, respectively, which dominate heat transfer in the cask. Actual backfill gas in the design is helium).

** Cases with reflecting boards and those without were done.
(In other cases, vertical orientation with reflecting boards and horizontal orientation without them were done).

*** An ideal vacuum condition couldn't be obtained, so experiments were done in low pressure conditions.

Method of Test

After the cask orientation was set, the correct kind of backfill gas was chosen, and the temperature of the test equipment met the test conditions. The cycle of the procedures of checking the seal, raising the temperature, measuring, lowering the temperature, and checking the seal was done in each of the test cases.

Measured Subjects

The measured subjects in this test are shown in the following.
(1) Temperature: cask body, basket, simulated fuel assemblies, ambient in the equipment (totalled about 500 points).
(2) Heat generation: simulated fuel assembly, heat generating objects (totalled 21 points).
(3) Wind speed: neighborhood of the cask and the ambient of the equipment (totalled 10 points).
(4) Pressure: cask cavity (1 point).

Results and Discussion of the Test

(1) Temperature history of the measured points
The representative temperature history is shown in Figure 2. The cask reaches the steady state in about 10 days after the start of the test (heating on).

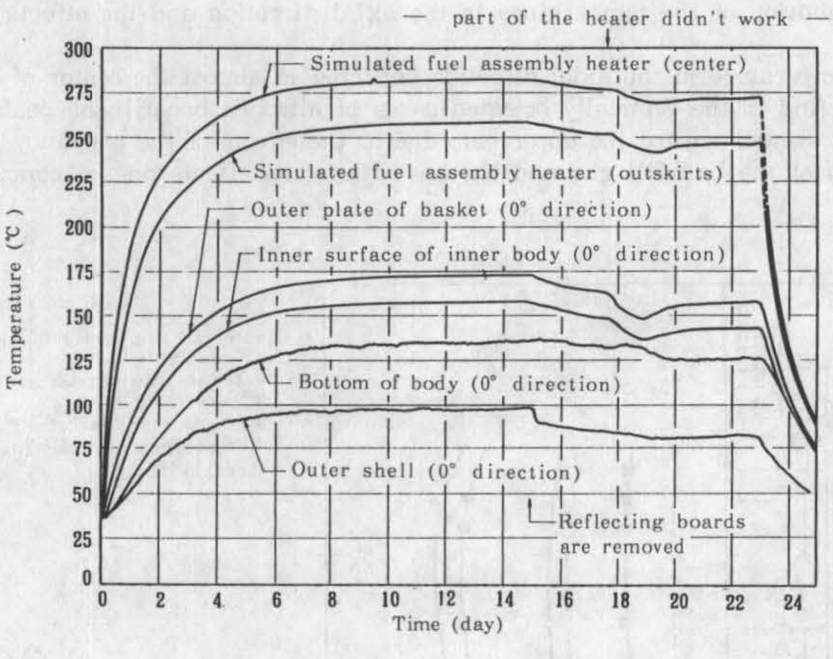

Figure 2. The example of the temperature history of each part at center section in the axial direction. (case 1: He gas backfill. Vertical orientation. Both with and without reflecting boards).

(2) Maximum temperature measured in each part
The maximum temperatures measured in each part in the test in the steady state are shown in Table 2. Maximum temperature of all test cases were lower than those of each allowable temperature (fuel cladding: 380℃, lead: melting point 327℃, lid portion: 180℃).

Table 2. The Maximum Temperature of Each Part (℃)

Measured Elements	case 1* (reflecting boards) with	case 1* (reflecting boards) without	case 2**	case 3***	case 4****	case 5*****	ALLOWABLE TEMPERATURE
FUEL CLADDING	282	274	316	338	324	265	
LEAD	154	143	151	153	150	149	327 (melting point)
PRIMARY LID SEAL	118	113	123	113	115	108	180
SECONDARY LID SEAL	94	91	97	91	96	92	180

* Backfill gas is He. in Vertical orientation.
** Backfill gas is N_2. in Vertical orientation. With reflection boards.
*** Vacuum (low pressure) in Vertical orientation. With reflection boards.
**** Backfill gas is N_2. in Horizontal orientation. Without reflecting boards.
***** Backfill gas is He. in Horizontal orientation. Without reflecting boards.

(3) Effect of reflecting boards
The temperature of the cask and its contents when surrounded with reflecting boards was about 10℃ higher than those without them. The radiation effect in the surface of the cask was observed (see Figure 2).

(4) The distribution of the temperature in the axial direction and the effects of the backfill gas
The peak temperature in the axial direction occurred in almost the center of the cask (see Figure 3). And in the vertically oriented cases of nitrogen backfill the peak temperature was slightly skewed toward the upper part due to the effects of the buoyancy force (thermal fluid effect) of the backfill gas and the heat radiation effects on the concrete floor.

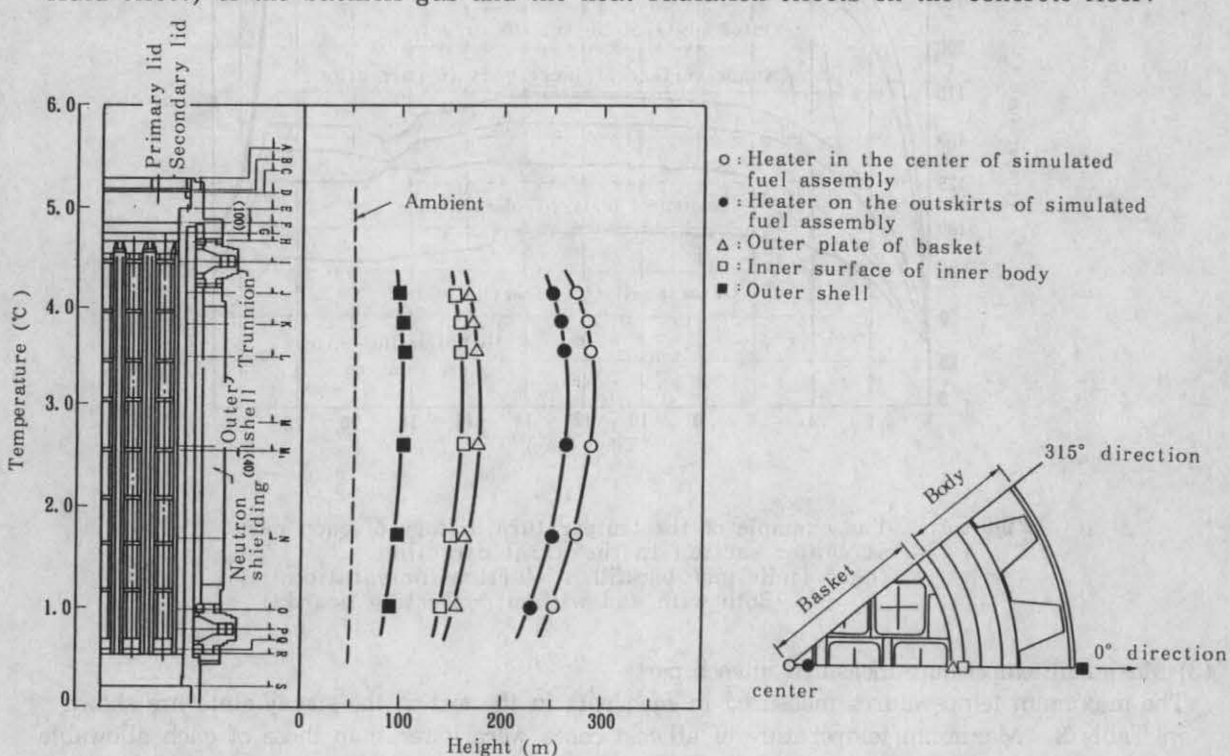

Figure 3. Representative temperature distribution in the axial direction
(case 1: He gas backfill. Vertical orientation.
with reflecting boards).

(5) The temperature distribution in the radial direction and the effects of the backfill gas
The peak temperature in the radial direction occurred in the center of the fuel assembly. The temperatures of the contents were the highest in the vacuum condition (low pressure condition) and the lowest in the helium backfill condition due to its conductivity.

THERMAL ANALYSIS

Thermal analysis was done to precisely estimate the temperature of the fuel cladding and the seal of the cask by heat transfer analysis considering the effects of convection. So the following three type of analysis were performed.

Summary of Analysis

(1) The analysis to estimate the effective heat flux through the cask body
The decay heat generated from the spent fuels is dissipated at both ends of the cask (especially in vertical orientation) and the support portion via trunnions (in horizontal orientation). Therefore, the temperatures of the fuel assemblies in this condition are lower than those in cases without dissipation at the ends.

In present analysis, firstly the temperature distribution for the two models is calculated by steady state heat transfer analysis. Secondly, the decay heat transferred through the cask body is estimated by means of the gradient of the temperature under the condition that both the conductivity and the thickness are known. Finally, the ratio of the heat conducting toward the end part of the cask body to the total heat generation is determined by comparing results of the two cases. The general purpose Finite Element Method nonlinear analysis code "ABAQUS" was improved and utilized in this analysis. The analysis model is shown in Figure 4.

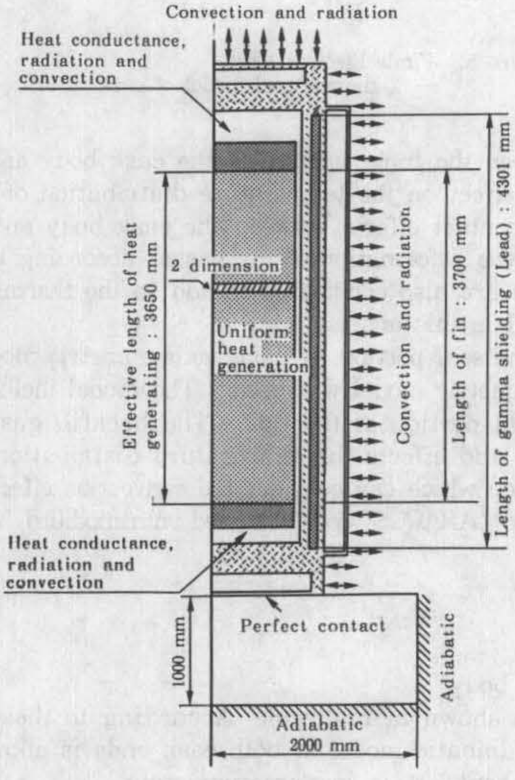

Figure 4. Summary of test condition
— Simple 2 and 3 dimensional model —

(2) Temperature analysis of the cask body by using 2-dimensional model
According to the forementioned ratio of the heat conducting toward the end part of the cask body, the maximum temperature of the fuel assembly in the center cross-section of the cask body was calculated. The 2-dimensional slice model shown in Figure 5 is used in this analysis.

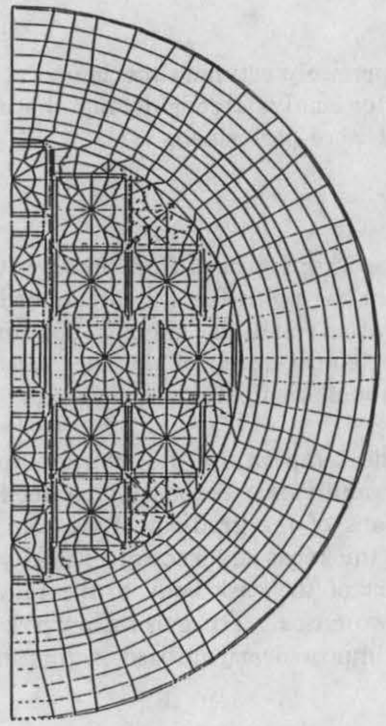

Figure 5. Finite Element Mesh
— 2-dimensional model of cask —

Because the clearance between the inner surface of the cask body and the outer surface of the basket has a strong effect on the temperature distribution of the cask body and spent fuel assemblies, the contact effects between the cask body and the basket at the under part of the cask and the deformation of the basket according to the thermal expansion and the dead weight (20ton) are also considered to add to the thermal gap. The improved "ABAQUS" code is also used in this analysis.

(3) Temperature analysis of the seal portion by using axisymmetric model
In this analysis, the axisymmetric model was used. The model includes the cask body, fuel assemblies and the seal portion at the lids. The backfill gas in the cavity convects around the fuel assemblies and effects the temperature distribution in the axial direction. So an improved ABAQUS code which can consider the convection effects was utilized. In this analysis. The improved "ABAQUS" code was used with modified "SOLA" code as user subroutines.

Results and Discussion

(1) Heat transfer in the cask body
The representative result is shown in Figure 6. According to these results, the effective heat transfer ratio to the adiabatic model at both cask ends is about 90% in the helium and nitrogen backfill and about 80% in low pressure state.

(2) Temperature of the cask and the fuel cladding

The distribution of cask temperature in the radial direction and that of fuel assemblies temperature in the axial direction in the vertical orientation are shown in Figure 7 and Figure 8 compared with the results of the experiments. Good agreements between analysis and measurements are shown in these results. So the propriety of the analysis model and the method are shown.

CONCLUSION AND REMARKS

A thermal test simulated with full-scale cask model for the normal storage was performed to verify the storage skill of the spent fuels of the cask.
The maximum temperature at each point in the test was lower than the allowable temperature. The integrity of the cask was maintained. It was observed that the safety of containment system was also kept according to the check of the seal before and after the thermal test. Therefore it was shown that using the present skill, it is possible to store spent fuels in the dry-type cask safely.

Moreover, because of the good agreement between analysis and experimental results, it was shown that the analysis model was successfully established to estimate the temperature distribution of the fuel cladding and the seal portion.

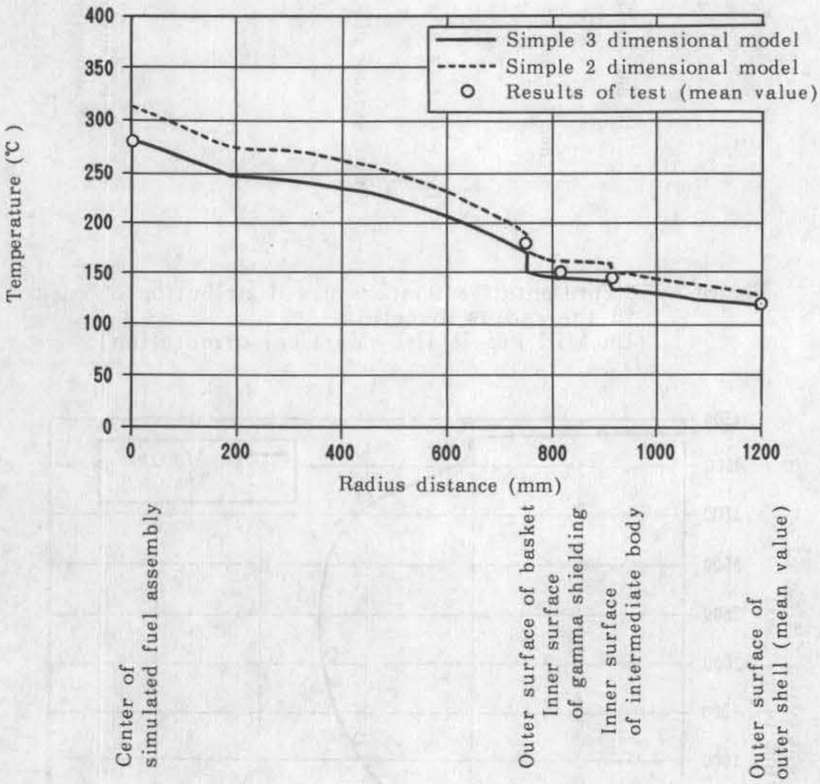

Figure 6. Example of passing heat flux through the body by simple analytical model (He backfill. Vertical orientation).

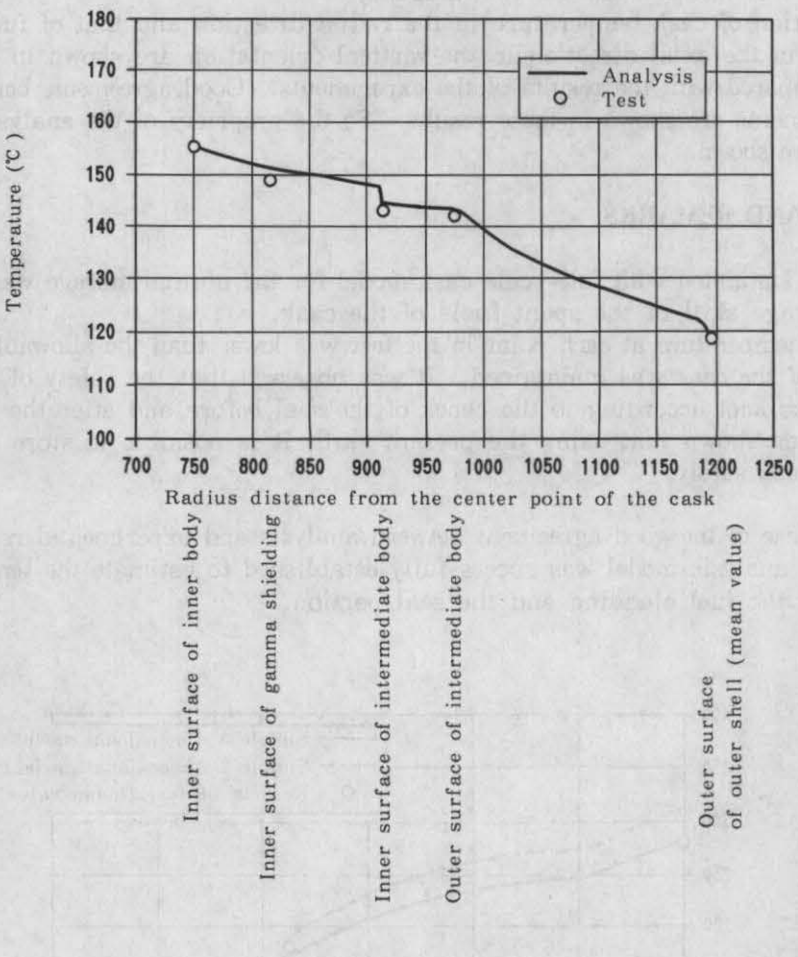

Figure 7. Representative temperature distribution of cask in the radius direction (Backfill gas is He. Vertical orientation).

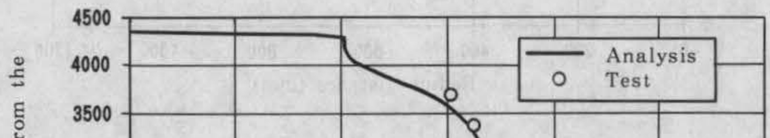

Figure 8. Representative temperature distribution of fuel cladding in the axial direction (Nitrogen backfill. Vertical orientation).