Proceedings of the 19th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019, New Orleans, LA, USA

Confirmation of heat removal performance of spent fuel storage and transport metal cask HDP-69B by heat transfer inspection

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ABSTRACT

As completion inspection of a spent fuel storage and transport metal cask, heat transfer inspection is carried out by measuring temperature of the cask by inserting electric heaters in the metal cask, and this inspection is conducted for every manufactured cask in Japan. This paper reports the temperature measurement data in the heat transfer inspection of the spent fuel storage and transport package HDP-69B. By analyzing the temperature measurement data, it is confirmed that the thermal analysis model for evaluating heat removal performance of the package HDP-69B has sufficient design margin. Therefore, obtained inspection data is very useful to improve thermal analysis model of the package HDP-69B rationally. In addition, the package HDP-69B is sure to perform designed heat removal capability as long as the dimension/material/welding/visual inspection results of the component related to the heat transfer characteristics meet design requirement. It is concluded that heat transfer inspection for the package HDP-69B can be eliminate or reduce to appropriate frequency.

INTRODUCTION

Japan has about 60 years commercial nuclear power plant history and the most of spent fuels have been cooled in the spent fuel pool at those power plants for certain period of time until being transported. Dry storage systems using metal casks have attracted attention for the purpose of transportation and/or storage of spent fuel for reprocessing, in particular, storage and transport metal cask which does not need to replacing spent fuel between storage and transportation has been developed.

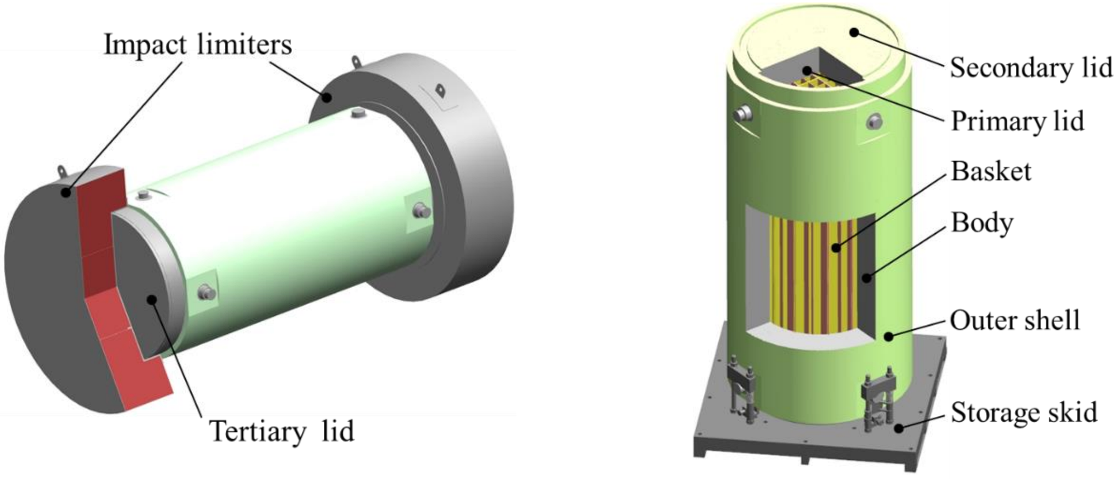
HDP-69B is a BWR spent fuel storage and transport metal cask developed by Hitachi-GE Nuclear Energy [1]. HDP-69B were manufactured 18 units from 2013 to 2017, and have been loaded and operated with spent fuels. During production of HDP-69B, heat transfer inspection is performed to confirm the heat removal performance of the cask. In Japan, a method of measuring temperature by inserting an electric heater into the inside of the metal cask is specified as heat transfer inspection, and this heat transfer inspection was performed for all HDP-69B.

This paper reports the temperature measurement data in the heat transfer inspection of HDP-69B done by now, and indicates that all HDP-69B has sufficient heat removal performance. In addition, it is presented that the heat removal performance of HDP-69B manufactured in future can be evaluated without measuring the temperature by the specified heat transfer inspection method by analyzing temperature measurement data of 18 units of HDP-69B. Furthermore, it is shown that the thermal analysis methods for evaluating heat removal performance of HDP-69B has sufficient design margin.

OUTLINE of HDP-69B

Outlines of HDP-69B is shown in Fig.1. The size of HDP-69B is 5.4 m in length and 2.5 m in diameter, and it can store 69 BWR spent fuels. During storage, it is placed vertically on the storage skid, and when transported, tertiary lid and impact limiters are attached and placed horizontally on the transport skid.

Fig. 2 shows the heat transfer concept of HDP-69B. The basket plates with notches are cross-inserted to each other like the dividers in an egg carton and inserted into the grooves on the inner surface of the body. The basket plates support the fuel assemblies, and the decay heat of the spent fuel is transferred to the basket plates mainly by radiation and heat conduction via helium enclosed in the cask. The heat of the basket plates is transferred to the body by heat conduction. The outer shell is provided on the outside of the body. Thermal fins are attached and welded to the body and outer shell, and the most of heat is transferred to the outer shell by heat conduction through the thermal fins. Resins as neutron shielding material are filled between the body and the outer shell. The heat of the outer shell is transferred to the external environment mainly by natural convection heat transfer and radiation.



(a) Transport condition (b) Storage condition

Figure 1. Outlines of HDP-69B.

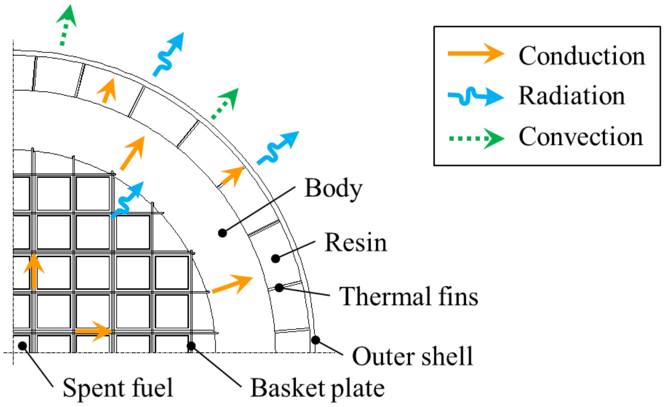


Figure 2. Heat transfer diagram of HDP-69B.

THERMAL TEST for INSPECTION

The thermal tests were conducted on 18 HDP-69B units in the condition of both transportation and storage as heat transfer inspection. In these tests, electric heaters were loaded into the basket, and the design heat load was given. The inside of the body and the space between the lids were filled with helium as in the operation. In addition, mock-up lids and impact limiters were used for heat transfer inspection and both lids and impact limiters have holes for the cable of the electric heaters and thermocouples. In the storage condition, HDP-69B was placed vertically on the storage skid. On the other hand, in the transport condition, HDP-69B was mounted horizontally on the transport skid after the tertiary lid and the impact limiters were attached.

Temperature measurement

The temperature at the points shown in Fig. 3 was measured using sheathed thermocouples. The thermocouples for the center of basket and body were attached by pressing against the measurement point using the jig so as not to damage the components. The thermocouples attached to the outer shell were fixed with aluminum tape.

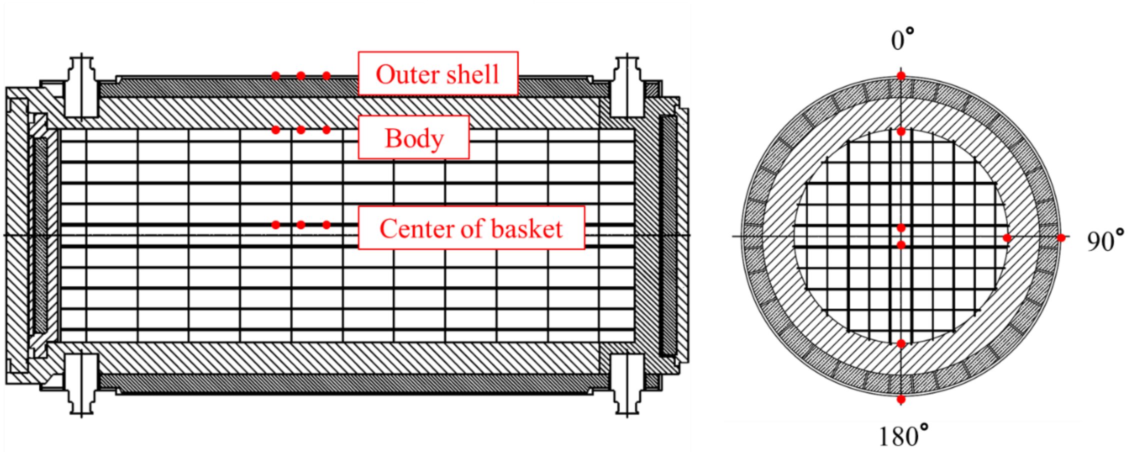


Figure 3. Temperature measurement point.

THERMAL ANALYSIS in DESIGN

The temperatures of each component of HDP-69B on design are evaluated by static analysis using Abaqus code with appropriate analysis margin. The validity of the calculation method had been verified by the thermal test using the radial slice mock-up model [2]. The temperatures of each component of HDP-69B in the thermal test conditions were calculated using similar calculation method.

The calculation method uses the combination of two 2-D analysis models. These models simulate the axial and radial cross sections of HDP-69. Although HDP-69B basket plates are cross inserted, the basket was modeled as non-contact structure in this calculation in order to give conservatism on design. For the same reason, the non-contact condition was given to the boundary between the basket plates and the grooves on the inner surface of the body. Radiation heat transfer and natural convection heat transfer were taken into account as the boundary conditions of the outer shell surface. It is considered that the natural convection heat transfer coefficient of the outer shell surface has a circumferential distribution in the transport condition due to HDP-69B being in horizontal position [3]. However, in this calculation, the smallest natural convection heat transfer coefficient in the circumferential distribution was given as uniform value.

RESULT of THERMAL TESTS

Angular distribution of measured temperature

Fig. 4 shows the comparison of the temperature of the horizontal and vertical conditions between the thermal test result of Unit #1 and the calculation result. The measurement values in the thermal test were corrected by the following equation using the measured heat quantity and environment temperature prescribed Japanese standards [4].

$$T_\mathrm{c} = (T_\mathrm{m} - T_\mathrm{me}) \times \frac{Q_\mathrm{d}}{Q_\mathrm{m}} + T_\mathrm{de} \qquad (1)$$

T_c : Corrected temperature [°C]

T_m : Measured temperature [°C]

T_me : Measured environment temperature [°C]

T_de : Environment temperature on design [°C]

Q_m : Measured heat quantity [W]

Q_d : Heat quantity on design [W]

The instrument error of the combination of the power meter and the thermocouple was approximately ± 2 °C.

As shown in Fig. 4, the thermal test results were lower than the calculation results at all measurement points. In the outer shell, the measurements and the calculation result show relatively close. The difference between the measurements and the calculation result became larger as it gets closer to the center of HDP-69B, and the measurements were much lower than the calculation result of the center of basket.

As mentioned above, the natural convection heat transfer coefficient of the outer shell surface is considered to have circumferential distribution under transport conditions in which the HDP-69B is in the horizontal position. Similar circumferential temperature distribution appears in the thermal test results of the body under the horizontal condition. On the other hand, there is no influence of the temperature distribution of the outer shell on the temperature of the center of basket because the temperature of the center of basket was equally affected by the circumferential temperature distribution.

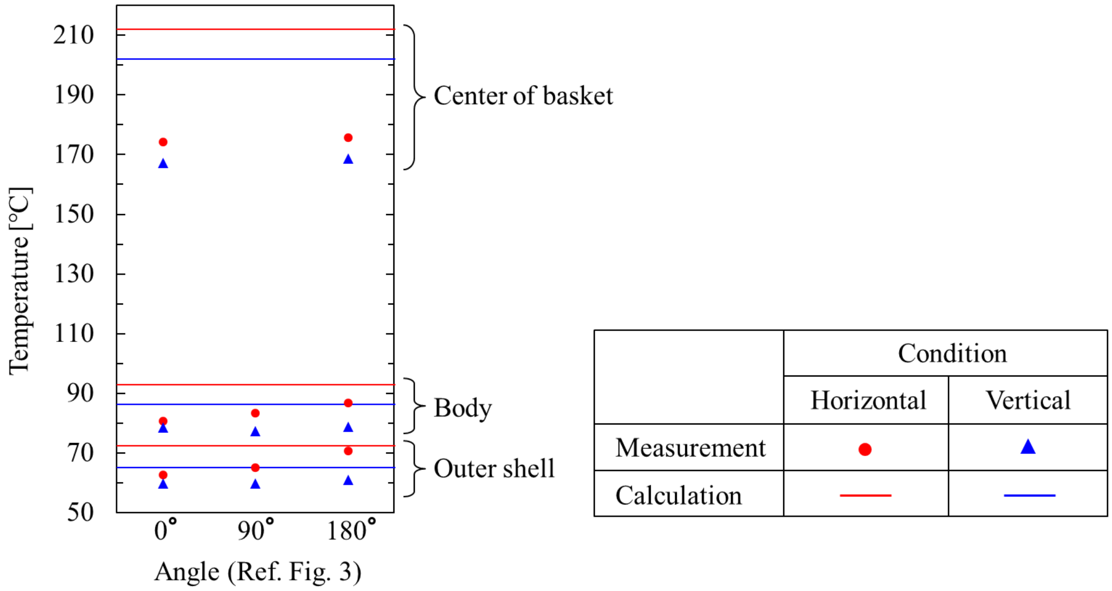


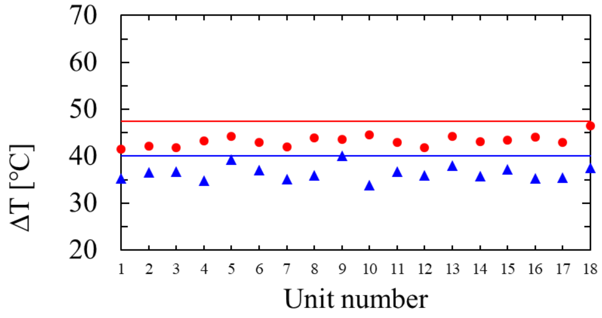
Figure 4. Comparison between the thermal tests and the calculation results (Unit #1).

Temperature differences between units

Fig. 5 shows the comparison of the temperature between the thermal test results and the calculation results of Units #1 to #18. In Fig. 5 (a), the vertical axis ΔT indicates the temperature difference between the outer shell and the environmental. As shown in Fig. 5 (a), the differences of ΔT between Units #1 to #18 were relatively small (approximately ± 3 ° C), which are larger than the instrument error ± 2 ° C. Since there were no differences between the HDP-69B units in the shape and the state of painting of the outer surface of HDP-69B, it is considered that the differences of ΔT were caused by convection state on the outer shell surface.

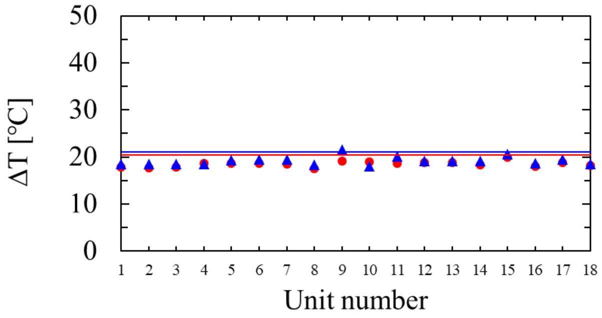
In Fig. 5 (b), the vertical axis ΔT indicates the temperature difference between the body and the outer shell. As shown in Fig. 5 (b), ΔT did not change significantly between Units #1 to #18. This means that the influence of individual differences in manufacture from the body to the outer shell on the temperature can be negligibly small.

In Fig. 5 (c), the vertical axis ΔT indicates the temperature difference between the center of basket and the body. As shown in Fig. 5 (c), the differences of ΔT were relatively large, which means that the influence of individual differences in manufacture from the center of basket to the body on the temperature is large. For example, the basket plates are inserted into grooves on the inner surface of the body and these are not welded or bolted. Therefore, the temperature of the center of basket are greatly influenced by thermal resistance of the joints due to individual differences in manufacturing such as the thickness of the basket plates and the width of the grooves on the inner surface of the body.

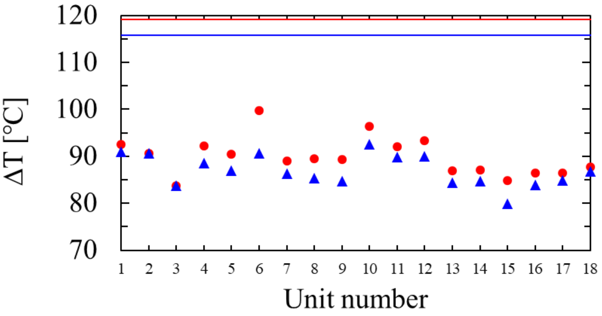


	Condition	
	Horizontal	Vertical
Measurement	●	▲
Calculation	—	—

(a) ΔT = (Outer shell) – (Environment)



(b) ΔT= (Body) – (Outer shell)



(c) ΔT= (Center of basket) – (Body)

Figure 5. Comparison between the thermal test results and the calculation results (Units #1 to #18, circumferential average).

Temperature correlation

Fig. 6 shows the correlation of the temperature of the center of basket and the body against the outer shell without correction by equation (1). The all measurement results at 0, 90, 180 ° in the horizontal and vertical conditions are plotted in this figure. According to Fig. 4, temperature of the center of basket has no circumferential distribution unlike the outer shell, so temperature of the center of basket was plotted against the average value of temperature of the outer shell of 0, 90, 180 °. The thermal test results ± 3σ are also shown in Fig. 6.

According to Fig. 6, the temperature between the body and the outer shell is in proportional relationship. This result is attributed to the fact that the heat transfer from the body to the outer shell is conductive heat transfer. In addition, the temperature of the center of basket and the outer shell is also in proportional relationship. This indicates that heat transfer from the center of basket to the body is mainly heat conduction rather than radiation. Furthermore, it was shown that these correlations do not depend on the horizontal or vertical conditions.

The open plots in Fig. 6 show the calculation results in the horizontal and vertical conditions. At the center of basket and the body, the approximate straight line of the thermal test results are almost parallel to the calculation results.

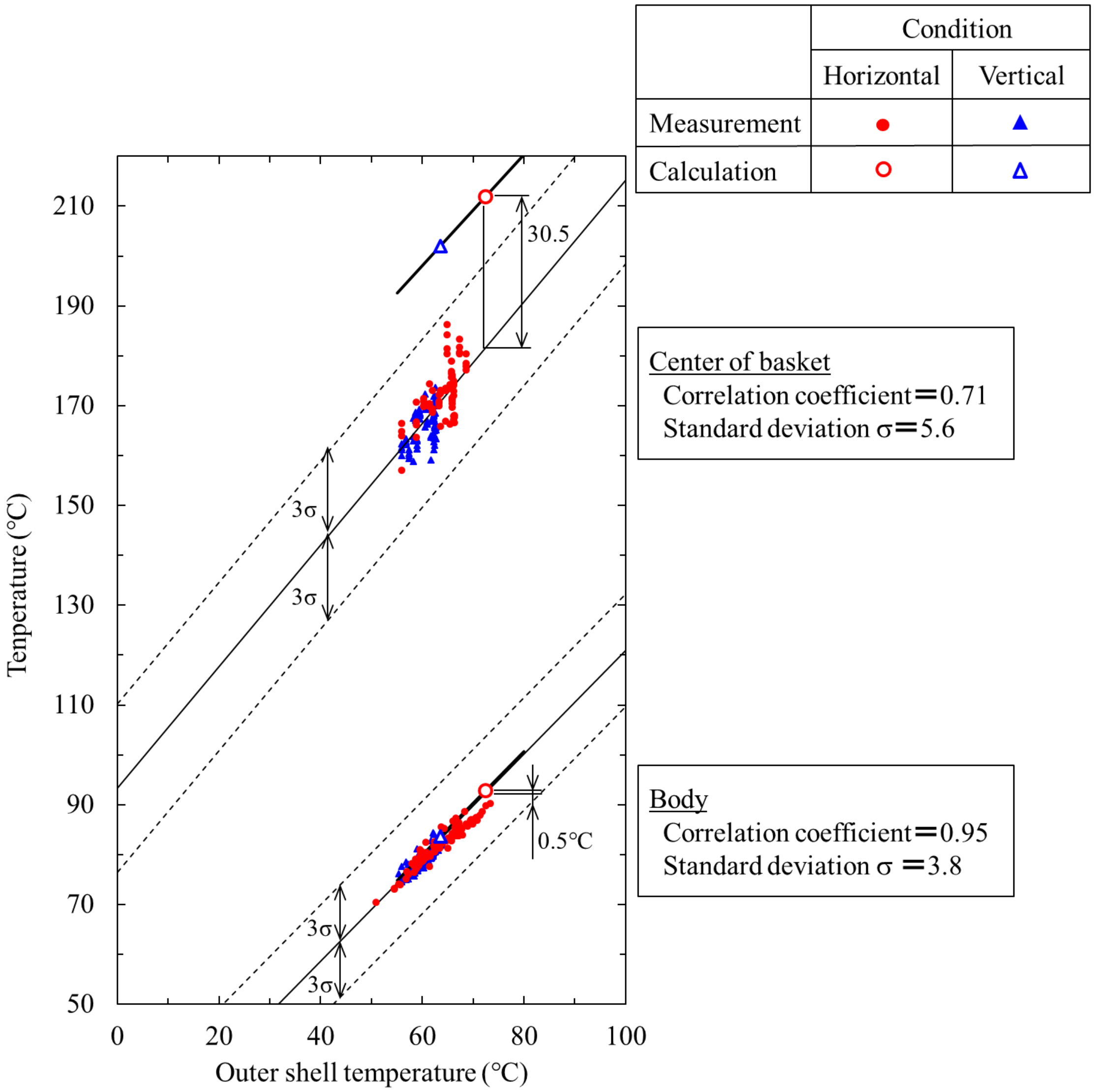


Figure 6. Correlation to temperature of the outer shell.

DISCUSSION

Heat removal performance of HDP-69B

According to Fig. 6, it became clear that both temperature correlations between the center of basket and the outer shell, and the body and the outer shell of Units #1 to #18 are similar. Also, it is considered that there would be almost no difference in temperature of the outer shell between the units when the thermal test condition is same. These two facts were obtained under the condition that HDP-69B were manufactured as designed. In other words, temperature of the center of basket, the body and the outer shell of HDP-69B will have the same correlation as long as carrying out the same inspection which have been performed on Units #1 to #18. From the above, it is concluded that HDP-69B manufactured in the future by the current manufacturing control and inspection will have the same heat removal performance as before.

Improvement of thermal analysis model of HDP-69B

Table 1 compares the temperature between the thermal test results and the calculation results. Since the difference between the calculation result and the thermal test result is only 0.5 ° C, This represents that temperature of the body is accurately calculated. In case of the center of basket, the difference between the calculation result and the thermal test result is 30.5 ° C. This represents that the analysis margin in temperature of the center of basket is very large compared with thermal test results. From the above, HDP-69B thermal analysis model can be improved rationally in the future by reducing the analysis margin for temperature evaluation of the center of basket.

Table 1. Comparison of thermal test results and calculation results.

Item	**Temperature (° C)**		
	Outer shell	**Body**	**Center of basket**
(A) Calculation [*1]	72.5	93.0	212.0
(B) Thermal test [*2]	－	92.5	181.5
(A)－(B) Deviation	－	0.5	30.5

*1: Horizontal condition shown in Fig. 6.

*2: calculation results using the approximate straight line of the heat test results shown in Fig.6.

CONCLUSIONS

It was confirmed that HDP-69B has sufficient heat removal performance by conducting thermal test on 18 Units of HDP-69B as heat transfer inspection. Furthermore, it concluded that HDP-69B manufactured in the future by current manufacturing control and inspection is expected to have similar heat removal performance. In addition, it concluded that HDP-69B thermal analysis model can be improved rationally in the future by reducing the analysis margin.

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