EXPERIMENTAL STUDY OF HEAT REMOVAL ABILITY AND LEAD SLUMP OF LEAD-TYPE MULTI-WALL CASK

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ABSTRACT

The purpose of this study is to establish the appropriate design of the lead-type cask by experimental method. Firstly, in order to examine heat removal ability, a multi-wall cylinder models composed with three layers (carbon steel – lead – carbon steel) were used. Secondary, in order to examine the lead slump, the above models were dropped, and the transformation of the lead layer surface was measured. The heat transfer characteristics and the amount of lead slump were confirmed from the experimental methods. These results are reflected in more appropriate design of the lead-type multi-wall cask.

INTRODUCTION

Numbers of the lead-type multi-wall casks have been produced. The lead-type cask might be economically advantageous, because it is not so influenced by the price fluctuation as the forged type cask, and economical. However, conservative designs are adopted for the lead-type cask, because the experimental data about heat removal ability and lead slump is insufficient. In this study, experiments were carried out to obtain these data for appropriate design.

The lead layer of the lead type cask works as an insulator against γ-ray. A lead layer is formed by casting. The melted lead is poured into the clearance between two carbon steel cylinders. Thermal expansion coefficient of lead is larger than that of carbon steel. So, without certain treatment, a narrow gap between lead layer and carbon steel wall formed during solidification and cooling of lead. We call this treatment for sticking lead layer to carbon steel shells (or stainless steels) “lead-soldering treatment”. By this treatment, the heat removal ability of the lead-type cask satisfies design specification, and the lead slump is prevented.

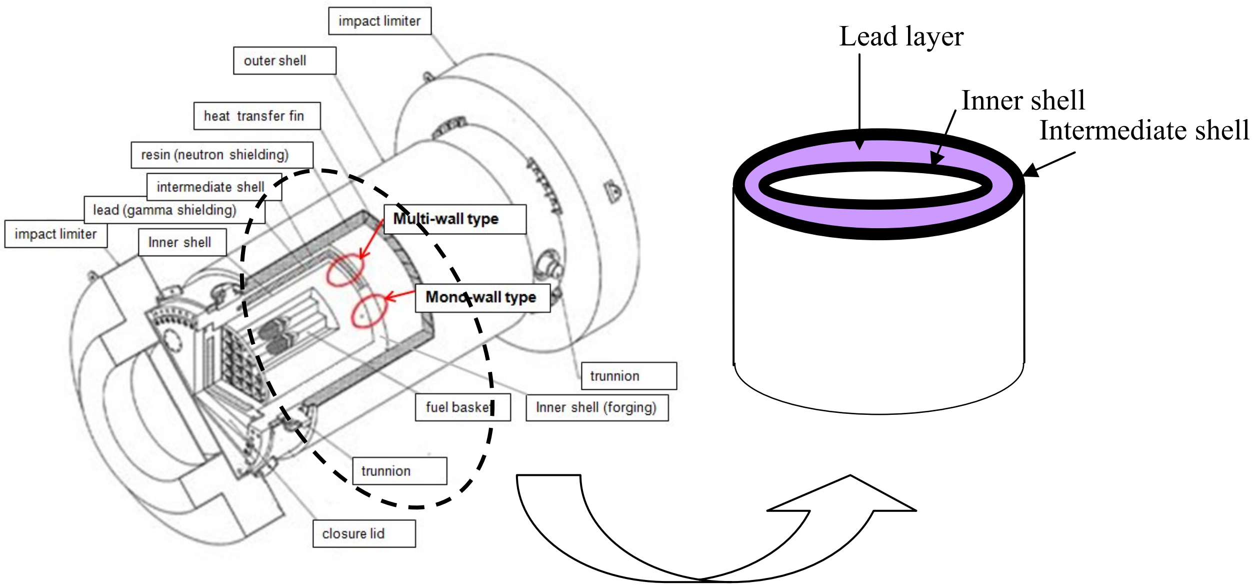
And now, the “lead slump” means the shrinkage of lead layer by drop impact. By the lead-soldering treatment, the lead layer is stuck to the both side walls, and the lead layer should be shrinking during the solidification and the cooling of lead. In spite of the shrinkage of lead layer is restrained by carbon steel walls in the radial direction, we know the fact that the height of the lead layer does not decrease so much. They say that the density of the lead must decrease, or numbers of micro cracks should be induced in the lead layer. If the diminish of density or the existence of numbers of micro crack is true, the heat transfer performance would go down than that from theory, and the lead slump by drop impact is inevitable. But, there's no method to measure the density or to find out the micro cracks for cast lead layer. Therefore, we chose experimental method to confirm them.

HEAT TRANSFER TEST

Heat transfer tests were performed to find out the heat transfer characteristics of the lead-type multi-wall cask, paying attention to the heat transfer of the interface between the lead layer and the steel shell.

Test models

The outline structure of typical transportation cask (Hitz-B54) is shown in Figure 1(a). Hitz-B54 cask (Transport and storage cask containing BWR 54 spent fuel) was developed by HITACHI ZOSEN CORPORATION. Figure 1 (b) shows the schematic diagram of the sliced cask model. Two slice shaped scale models imitating middle part of cask body were prepared. One of them is with lead-soldering treatment, called L-model. Another is without lead-soldering treatment, called S-Model (a little smaller than the L-Model). The dimensional data are shown on Table 1. The thickness of the carbon steel shells of the models was decided by trial and error calculation, to become the pressure peeling the shell from lead layer equal to that of actual cask.



(a) Actual cask (Hitz B54) (b) Slice shaped scale models

Figure 1 Outline structure of cask and schematic diagram of the sliced cask model

Table 1 Dimensional data of test models

Test specimen	Mass (ton)	OD of inner shell (mm)	Thick of inner shell (mm)	Thick of lead layer (mm)	Thick of intermediate shell (mm)	Od of intermediate shell (mm)	Length of test specimen (mm)	Length for test area (mm)	Inner peeling pressure (MPa)	Outer peeling pressure (MPa)
L-model	6.6	990	12	105	25	1250	1290	406	-0.89	14.63
S-model	2.2	650	16	50	25	800	1110	402	1.84	14.4
Actual cask*	135	1592	38	105	80	1962	6800	-	3.11	14.6

* : Transport and storage cask containing BWR 54 spent fuel developed by HITACHI ZOSEN CORPORATION

Test conditions

The internal surface of inner shell was heated by electrical heaters settled on the surface. The temperature of the internal surface of inner shell was kept stable state at four levels, 100°C, 150°C, 200°C, 250°C, and the temperatures at several points in the section were measured. Figure 2 shows external appearance of L-Model. It took about 4-hours to raise the internal surface temperature to the target level, then the temperatures of each points were almost steady state. To ensure the steady state, the temperature kept steady state more than 1-hour was adopted. And the temperature measurement points were on the middle section of the model to avoid the influence of the axial heat flow.

(a) Top view (b) Side view

Figure 2. External Appearance of L-Model

Test results

Figure 3 shows a measured temperature distribution of L-Model, when the heater temperature was at 200°C. Thermocouples were used for the measurement of temperature. Considering the accuracy of thermocouples, it can be said that the heat resistance on the interface between the lead layer and the steel shell is almost negligible. The solid lines in this figure show the temperature distribution estimated from the radial heat flow, and the measured temperatures on the internal surface of the inner shell and the outer surfaces of the intermediate shell. This radial heat flow was calculated using three temperature data in the lead layer. Table 2 shows the measured temperature at each points and heat flow at the four conditions. And the heat resistances at the inner interface (between the lead layer and inner shell) were estimated using the heat flow. The heat flows are also shown in Table 2.

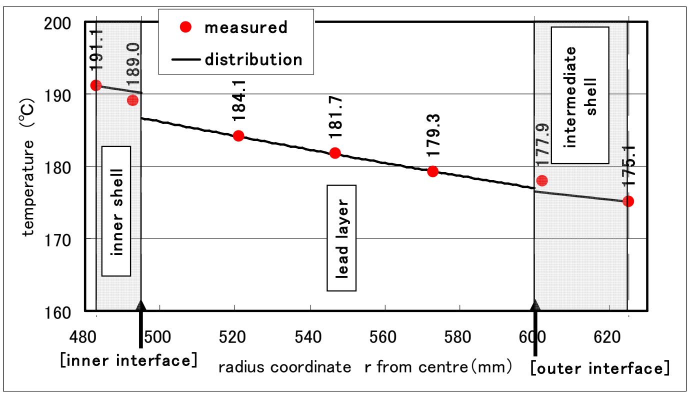


Figure 3 Temperature Distribution of L-Model

Table 2 Heat resistance at interface

Temperture of inner surface of inner shell (°C)	Temperture of outer surface of intermediate shell (°C)	Temperture of circumference (°C)	Heat flow* per unit hight (W/m)	Heat resistance at interface** (m^2K/W)
95.0	90.7	27.1	3539	3.68E-04
143.4	133.9	29.3	6807	8.56E-04
191.1	175.1	29.8	10321	1.23E-03
239.7	215.7	30.3	15639	1.11E-03

*Computed with the heat transfer equation of pipe based on 3 data in lead layer

**Sum of heat resistance at inner and outer interface

Figure 4 shows a measured temperature distribution of S-Model, when the heater temperature was 200°C. The temperature difference between inner shell and intermediate shell is larger than that of L-Mode. In case of S-Model, without lead-soldering treatment, the heat resistance at the interface between lead layer and steel shell should be large. The solid lines in this figure show the temperature distribution estimated from the radial heat flow and the measured temperature on the internal surface of the inner shell and the outer surfaces of intermediate shell. The heat flow on radial direction was calculated at the outer surface of the intermediate steel shell, using the heat transfer coefficient estimated by the results of measurement of L-Model. However, the temperature distribution was calculated on the assumption that the heat resistance at the interface between the lead layer and intermediate shell is negligible, because of no information about the temperatures in the lead layer. In this case of S-Model, the temperature gap at the interface between the lead layer and the inner steel shell is large as 17°C. Therefore, it was confirmed that the lead-soldering treatment works very well to keep the heat transfer ability of cask body.

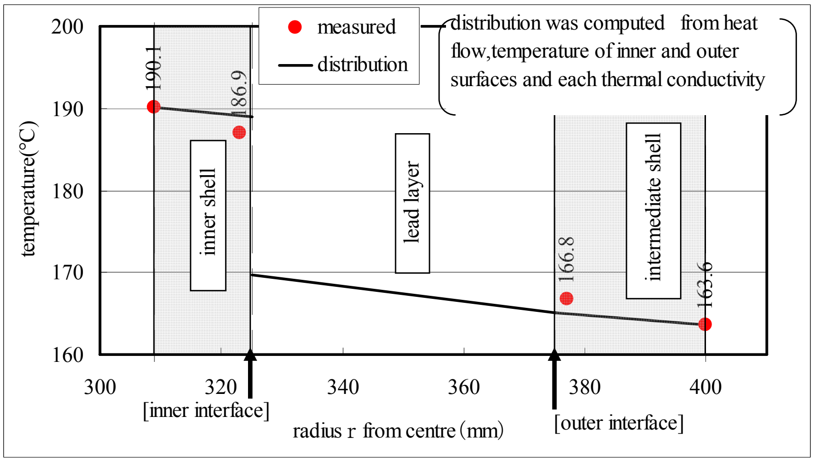
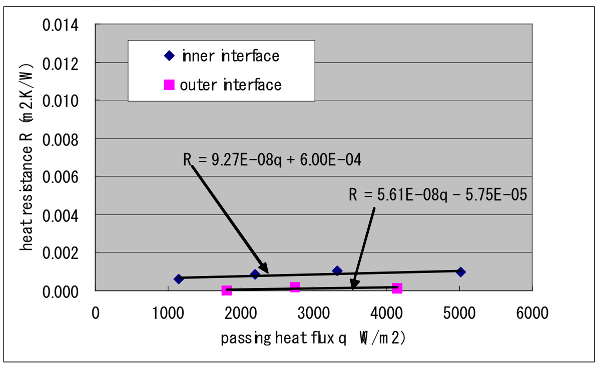


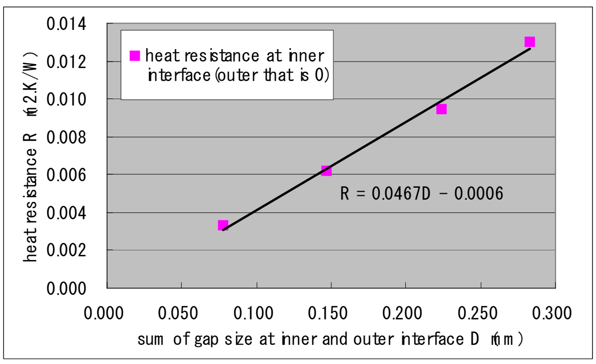
Figure 4 Temperature Distribution of S-Model (radial direction)

Heat Resistance at the Lead-Steel Interface

The calculating formulas for the heat resistance of the interface were defined by the test results mentioned above. In case of L-Model (with lead-soldering treatment), the heat resistance of the interface is negligible. But here, forcibly, the formula is made up as a function of the heat flow. In case of S-Model, the formula is a function of the total size of gaps both side of the lead layer. The total size of the gaps was estimated by FEM analysis reproducing the test. These relations are shown in Figure 5. The effect of the lead-soldering treatment for the heat resistances is evident.



(a) Heat resistance vs. heat flux (L-Model)



(b) Heat Resistance vs. gap (S-Model)

Figure 5 Characteristic of heat resistance

Trial calculation for actual cask

The temperature distribution was calculated by FEM analysis, using the formulas for the heat resistance defined above, under the thermal conditions assumed for actual casks; the heat flux at inner surface of inner shell is 1178W/m^2, the temperature at the outer surface of intermediate shell is 140°C. Figure 6 shows the results of trial calculation for actual cask. The blue lines with rectangle marks showing the temperature distribution without the lead-soldering treatment are far above from the black solid lines showing that in case of the heat resistance of the interface equal to zero. However, the red lines showing that with the lead-soldering treatment are little difference from black solid lines. The effect of the lead-soldering treatment is evident on actual cask, as expected.

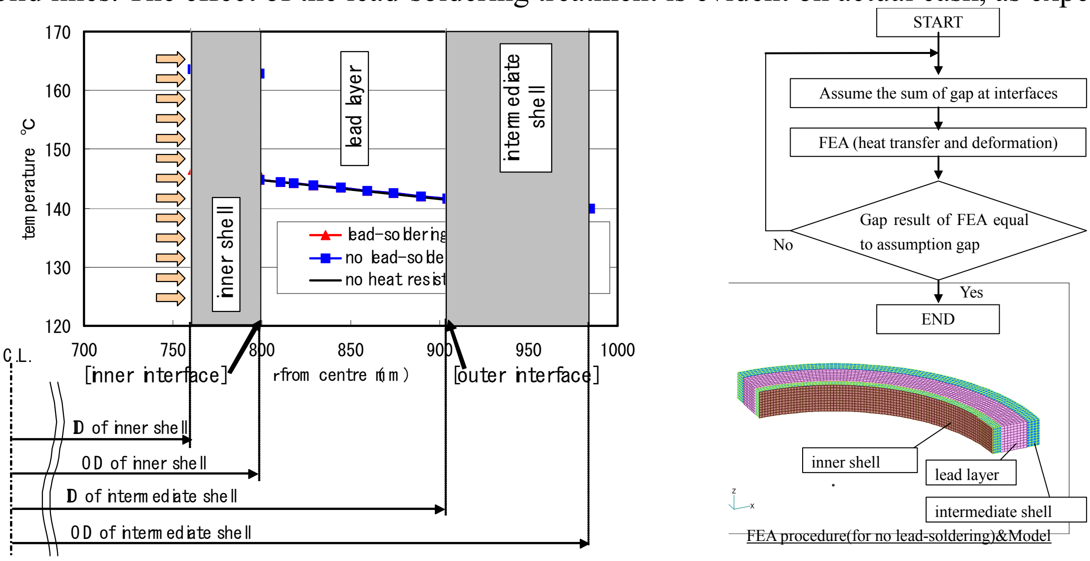


Figure 6 Result of trail calculation for actual cask

LEAD SLUMP TEST

The deformation of lead layer caused by a drop impact (so called "lead slump") would make a small gap on the top end of lead layer. This gap may allow some passage of γ-ray. Two cases of drop impact test were performed to confirm the lead slump phenomena and the effect of lead-soldering treatment.

Test models and conditions

L-Model (with the lead-soldering treatment) and S-Model (without the lead-soldering treatment) were used for the lead slump test as same as the heat transfer test. The drop height and the shock absorbing characteristics of the collision target; depth and the density, were settled to achieve the same impact acceleration as that assumed for the actual casks (Hitz-B54 cask, end drop test in 0.3m height and impact limiters were equipped, 451m/s^2). Table 3 shows the test conditions. Figure 7 shows the appearance of L-Model. Figure 8 shows the sensors for acceleration and strain.

Table 3 Test conditions

Model	Drop height (m)	Target depth (mm)	Target density (ton/m^3)
L-Model	0.3	200	0.2
S-Model	1.0	200	0.15

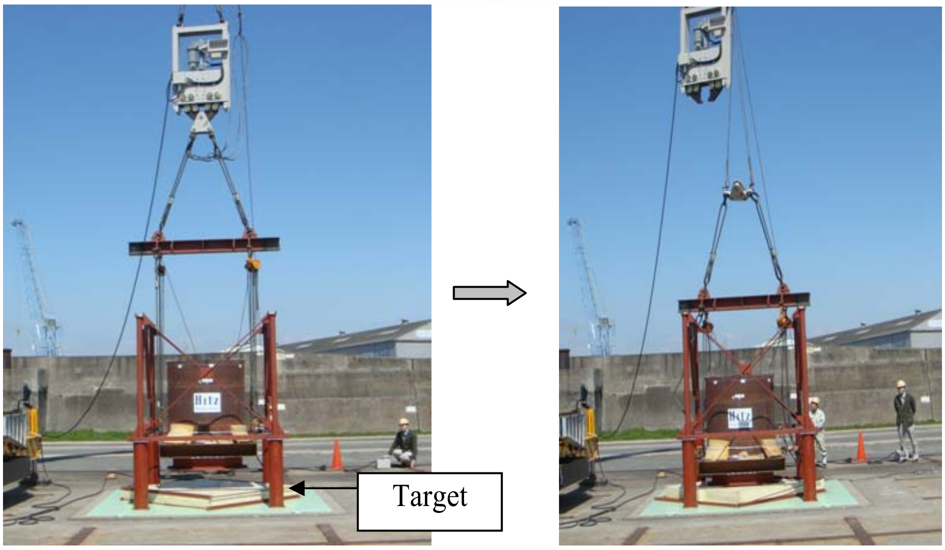


Figure 7 Appearance of L-Model

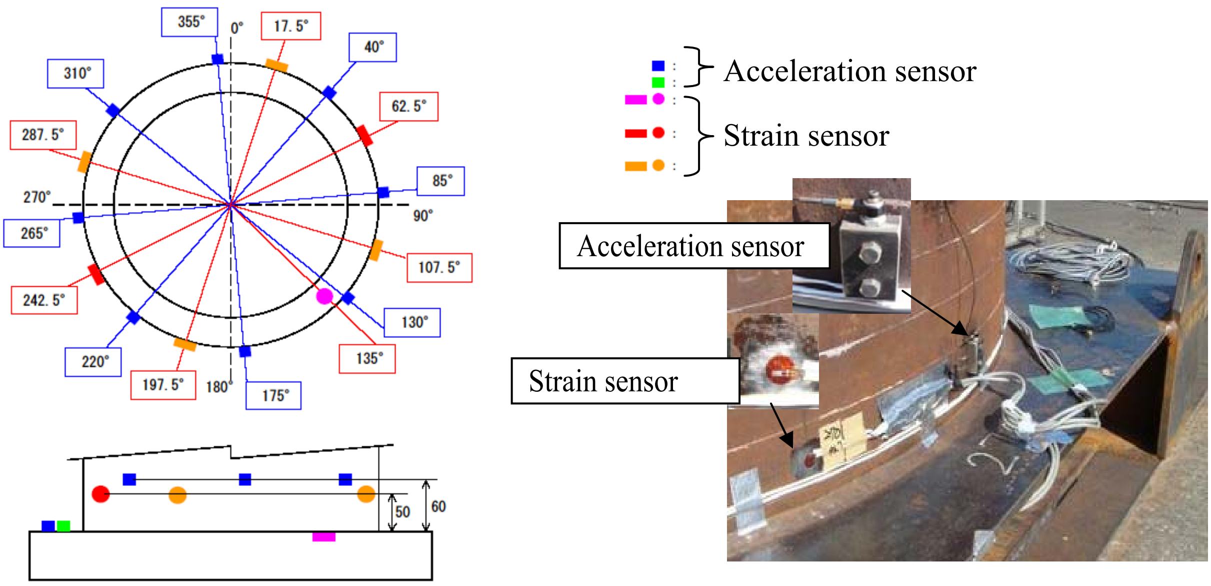


Figure 8 Sensors for the acceleration and the strain

<u>Test results</u>

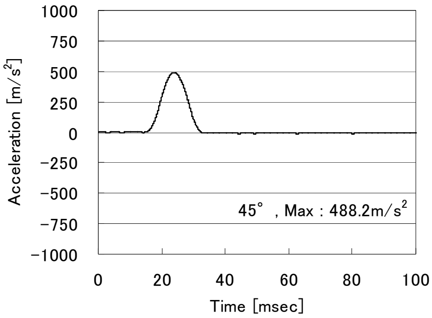
The impact acceleration of the L-Model at the drop test is shown in Figure 9(a). The accelerations were almost equal to that assumed for the actual casks. So, the drop test was performed as intended, and it is confirmed that the setting of condition was effective. Figure 9(b) shows a sample shape of impact acceleration wave. It is smooth and shows that the collision was as expected.

The impact acceleration of the S-Model (without lead-soldering treatment) at the drop test is shown in Figure 10(a). The impact accelerations were far large than that assumed for the actual casks. Figure 10(b) shows a sample shape of impact acceleration wave. It has two peeks. S-Model is without lead-soldering treatment, and the lead layer does not stuck to the steel shells. The cause of the acceleration behavior is presumed that the lead layer and the steel shells move separately.

Monitoring position		Maximum acceleration (m/s²)
Circumferential direction at outer surface of intermediate shell	Height from base plate	
0°	60mm	478.5
45°		488.2
90°		499.2
135°		476.1
180°		469.3
225°		452.6
270°		449.1
315°		462.5

Measured data were processed with the low path filter of 250Hz

(a) Maximum Acceleration



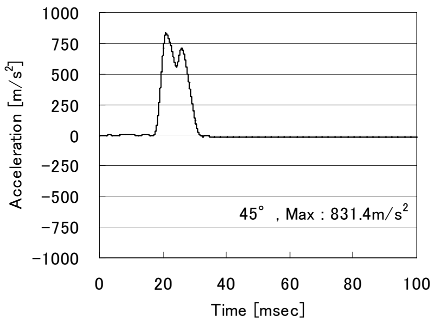
(b) Acceleration wave

Figure 9 Acceleration of L-Model at drop test

Monitoring position		Maximum acceleration (m/s²)
Circumferential direction at outer surface of intermediate shell	Height from base plate	
0°	60mm	826.7
45°		831.4
90°		821.4
135°		748.1
180°		725.9
225°		739.2
270°		767.2
315°		806.7

Measured data were processed with the low path filter of 350Hz

(a) Maximum Acceleration



(b) Acceleration wave

Figure 10 Acceleration of S-Model at drop test

The shapes of the top end of the lead layer of the models were measured before and after the drop test by non-contact displacement sensor. Figure 11 shows the apparatus for the shape measurement. Figure 12 shows samples of the shape measurement results. The blue line shows the shape before the drop test, and red line shows that after the drop test. And the average differences between these two shapes are shown on Table 4. In case of L-Model with lead-soldering treatment, there is almost no difference between two shapes, so it can be said that no lead slump occurred. Contrarily, in case of S-Model without lead-soldering treatment, the top end of the lead layer sank down so much. That is, lead-soldering treatment works to avoid the lead slump, and the treatment prevents the lead slump for the actual casks.

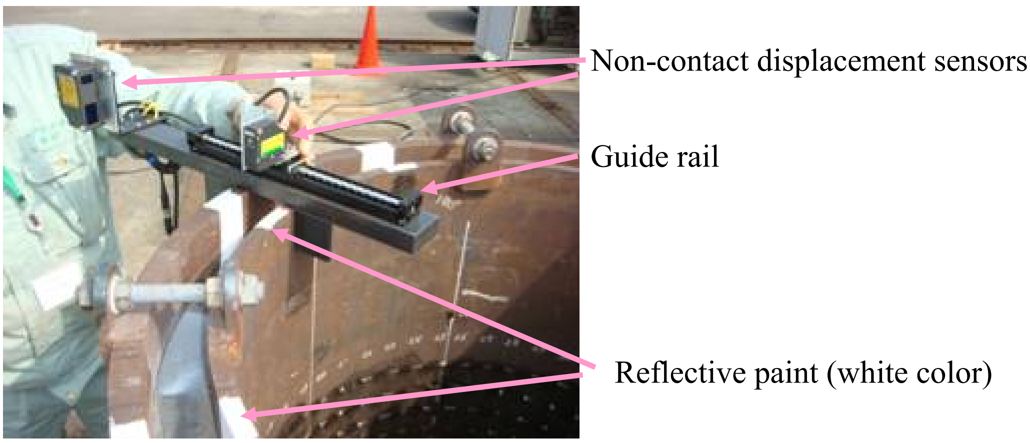
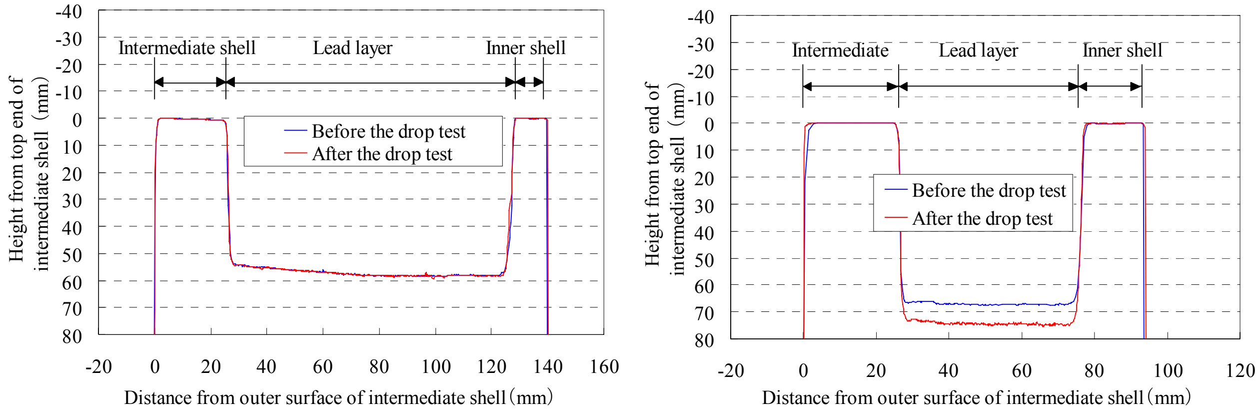


Figure 11 Measurement apparatus for the lead layer top end shape



(a) L-model (b) S-model

Figure 12 Results of the shape measurements

Table 4 Results of the lead slump

Circumferential direction at top end surface of lead layer	L-model			S-model		
	Average of lead layer height from top end of intermediate shell		Amount of lead slump (mm)	Average of lead layer height from top end of intermediate shell		Amount of lead slump (mm)
	Before the drop test (mm)	After the drop test (mm)		Before the drop test (mm)	After the drop test (mm)	
0°	57.51	57.53	0.02	66.68	73.59	6.91
45°	57.34	57.56	0.22	66.58	72.97	6.39
90°	57.17	57.07	-0.09	66.72	72.64	5.93
135°	58.30	58.28	-0.02	66.62	73.38	6.76
180°	58.53	58.45	-0.08	66.31	73.21	6.90
225°	58.43	58.42	-0.02	67.07	74.27	7.21
270°	58.12	58.22	0.10	66.77	73.87	7.10
315°	57.69	57.85	0.16	66.52	73.49	6.96

CONCLUSIONS

The heat transfer ability and the lead slump of the lead-type multi-wall cask were confirmed experimentally using scale model. The conclusions obtained through this study are summarized as follows:

(1) The heat resistance between the lead layer and the steel shells are almost negligible.
(2) The heat transfer ability of actual cask with the lead-soldering treatment, which was calculated with the formula defined after the experimental result, was almost the same as the one where the heat resistance between the lead layer and the steel shells are zero.
(3) No lead slump occurred on the model with the lead-soldering treatment. The test conditions were settled to achieve the same impact acceleration as the assumed one for the actual casks. So, it is confirmed that no lead slump will occur for actual casks.