鉛多層キャスクの伝熱および落下実験

Heat Transfer Test and Drop Test for Lead-type Multilayer Cask

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あ ら ま し

当社は多くの鉛多層型キャスクの設計・製造実績を有している。しかし、鉛多層型キャスクの設計は鉛層界面の伝熱性能および鉛スランプ現象（衝突事故時の鉛層変形）についてデータが十分でないために、安全側の保守的な設計となっている。そこで合理的な設計を行うために、キャスク本体胴の平行部を模擬した円筒形式のスケールモデルを製作し、伝熱実験および落下実験を実施した。実験より、鋼・鉛界面における熱抵抗データを定量化し、さらに、IAEA規則で想定される事故発生時に鉛スランプ現象が発生せず遮蔽性能が保たれることを確認した。

Abstract

We have considerable experience in designing and fabricating lead-type multilayer casks. At present, the lead-type multilayer cask is designed conservatively since data on heat transfer at the interface between the lead layer and steel and on the lead slump phenomenon are insufficient. For realizing a reasonable design, a cylinder-shaped scale model representing the middle part of the cask body is prepared. The heat-transfer test and drop test are then conducted, and the heat-transfer resistance at the interface is quantified by considering the test results. It is confirmed that no lead slump occurs and the capability of the shield is maintained in the case of accidents that are envisioned by the IAEA regulation.

1. INTRODUCTION

We have considerable experience in designing and fabricating casks that are used for the transport and storage of spent nuclear fuel; in fact, the first domestic cask (HZ-75T) was fabricated by us [1][2]. Casks are classified into two types on the basis of the radiation shielding structure: forging type (in which a single-wall cylinder is formed by forging) and lead type (comprising two concentric steel pipes with the intervening space filled with lead).

We have fabricated many lead-type casks, including HZ-75T mentioned above. We have a lead casting facility at Ariake Works and use an established fabrication technique. It appears that few companies have their own facility and fabrication technique for lead casting for large-scale structures. Therefore, our expertise in fabricating the lead-type multilayer cask gives us a competitive advantage.

Figure 1 shows a schematic diagram of the lead-type multilayer cask. The cask consists of the main body, lids (three), a basket that holds spent fuel assemblies, and impact limiters that absorb shock loads in case of an accident. The main body is a three-layered cylinder (with an inner shell, intermediate shell, and outer shell). The space between the inner shell and the intermediate shell is filled with lead, which acts as a shield against γ-rays. The surfaces of the inner shell and intermediate shell that are in contact with the lead are subjected to lead-soldering treatment for facilitating the bonding of the steel shells and the lead layer, which is necessary for improving heat-transfer ability of the steel-lead interface. The space between the

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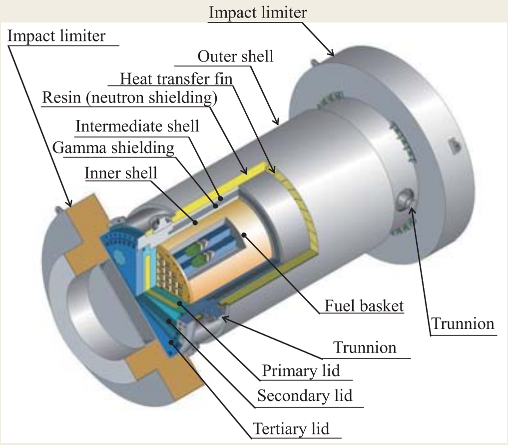


Fig. 1 Schematic of the cask

intermediate shell and the outer shell is filled with resin, which acts as a shield against neutrons.

There have recently been calls to make explicit the basis of the data and concepts used in safety evaluations carried out for cask licensing and, if needed, for verification of them through experimentation. We therefore studied the issues relating to the basic data used in the design and safety evaluation of the lead-type multilayer cask. **Table 1** shows the results. From them, we realized that we had insufficient experimental data of the following kinds:

- ●Data on heat-transfer ability at the interface between the lead and the steel shells
- ●Data on deformation of the lead part in the case of a drop (lead slump phenomenon)

We therefore conducted experiments to obtain these additional data.

2. HEAT TRANSFER TEST

This test was performed to examine the heat transfer at the interfaces between the lead layer and the steel shells.

2．1　Test model　**Figure 2** shows a schematic drawing of the model. The dimensional data are presented in **Table 2**. The thicknesses of the steel

Table 1 Design problems in the case of the lead-type multilayer cask

No.	Item	Matter	Foundation data	Handling
1	Safety design			
(1)	Structural design			
	Strength data for lead	Strength data for lead is obtained from the literature, but is insufficient compared to data available for steel.	Literature data	Literature data would be considered as sufficient because lead is not considered to be a structural material.
	Deformation of lead layer in case of fall	(i) Estimation of the effect of lead deformation force generated by drop impact, on inner and intermediate shells.	By analysis	Deformation of inner and intermediate shells would not occur because the lead deformation force is small. This can be shown by analysis.
		(ii) When there is void in the lead layer, the layer becomes deformed since lead from neighboring regions fills the void (so-called slump phenomenon).	Literature data	There is not sufficient data to know whether slump phenomenon will occur with or without lead bonding and under what force of impact.
(2)	Heat design			
	Heat-transfer coefficient between lead and inner shell/intermediate shell	In the case involving lead-soldering treatment, heat transfer resistance is assumed to be zero. In the case without lead-soldering treatment, finite heat transfer resistance should be assumed.	Result of heat-transfer test at the time the fabrication of the lead-type cask is completed	The test data at left can explain that the heat-transfer resistance used in heat analysis is on the whole correct, but available test data on the lead interface are insufficient.
2	Fabrication Inspection Filling lead Test after filling	Fabrication of product that meets design specifications		Hitachi Zosen Corporation has considerable experience in fabricating casks, and it has collected a significant amount of data.

shells of the model were set so as to make the pressure required for detaching the steel shell from the lead layer equal to that in the case of an actual cask. The model was subjected to lead-soldering treatment (providing a lead layer to the carbon steel shells that would be in contact with the lead part). **Figure 3** shows the external appearance of the test model.

2.2 Conditions The inner surface of the inner shell was heated by an electrical heater mounted on the surface. The temperature of the heater was kept stable at four levels—100° C, 150° C, 200° C, and 250° C—and the temperatures at several points in the cross-section at a height corresponding to that of the center of the model were measured. Thermocouples were used for the measurement. The bonding at the inner and outer interfaces of the body at a height of 400 mm, which is the height of the center of the model, was confirmed by an ultrasonic test (UT). **Figure 4** shows the UT result. The bonding rates at the outer and inner interfaces were 87% and 94%, respectively.

2.3 Test results **Figure 5** shows the temperature distribution measured when the heater temperature was at 200 °C. The solid lines

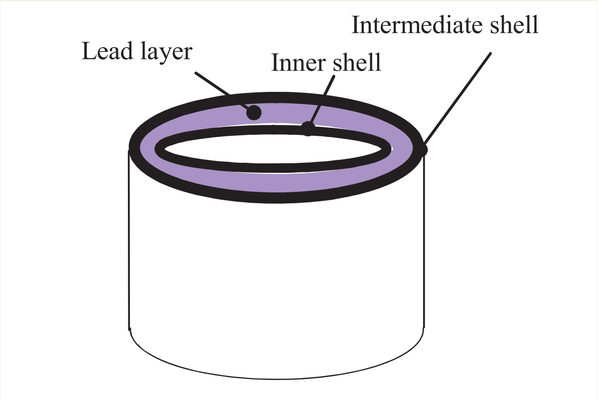


Fig. 2 Schematic drawing of the multilayer cask model

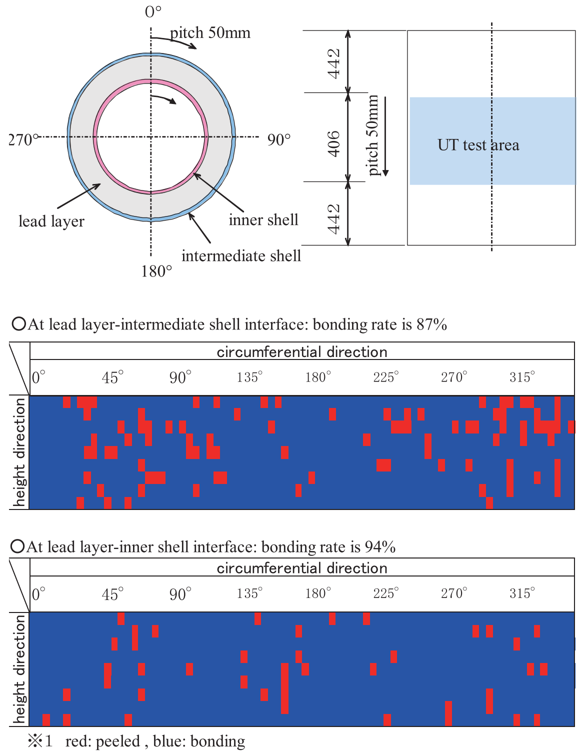
Table 2 Dimensional data for the test model

		Test model	Actual cask*
Mass	(ton)	6.6	135
OD of inner shell	(mm)	990	1592
Thickness of inner shell	(mm)	12	38
Thickness of lead layer	(mm)	105	105
Thickness of intermediate shell	(mm)	25	80
OD of intermediate shell	(mm)	1250	1962
Lengthof test specimen	(mm)	1290	6800
Length of test area	(mm)	406	-
Peeling pressure at inner interface	(MPa)	-0.89	3.11
Peeling pressure at outer interface	(MPa)	14.63	14.6

* : Transport and storage cask containing BWR 54 spent fuel developed by Hitachi Zosen Corporation
OD: Outer diameter

(a) Top view (b) Side view

Fig. 3 External appearance of the test model



○At lead layer-intermediate shell interface: bonding rate is 87%

○At lead layer-inner shell interface: bonding rate is 94%

※1 red: peeled , blue: bonding

Fig. 4 Ultrasonic test result

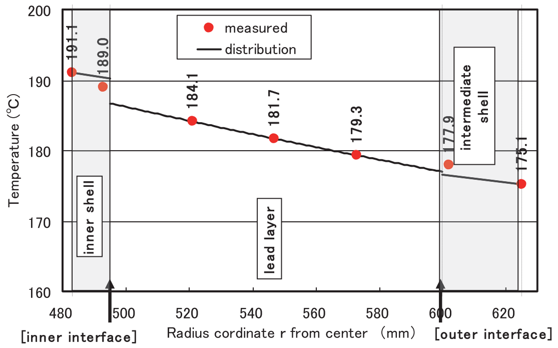


Fig. 5 Temperature distribution

in this figure show the temperature distribution estimated from the radial heat flow, which was calculated by three temperature values in the lead layer. The temperature difference at the inner and the outer interfaces were estimated 3.5 °C and 0.4 °C, respectively. **Table 3** shows the measured temperature at each point, the heat flow, and the sum of heat-transfer resistances at the two interfaces (between the lead layer and steel shells) for the four heater temperatures.

2．4　Heat-transfer resistance at the lead-steel interface

The formulas for the calculation of the heat-transfer resistance at the interface were obtained from the test results. They are assumed to be a function of the heat flow. they are shown in **Figure 6**. In this model (subjected to lead-soldering treatment), the heat-transfer resistance was small. The effect of lead-soldering treatment on the heat-transfer resistances is evident.

2．5　Trial calculation for actual cask

The temperature distribution was calculated with formulas for the interface heat-transfer resistance (given in **Figure 6**) by assuming thermal conditions that exist in the case of actual casks. The heat flux at the inner surface of the inner shell was 1178 W/m2, and the temperature at the outer surface of the intermediate shell was 140 ° C. **Figure 7** shows the results of a trial calculation for the actual cask. The red lines that show the case in which lead-soldering treatment was performed are slightly different from the black solid lines that show the case in which the heat-transfer resistance at the interface was zero. The effect of the lead-soldering treatment on the cask is evident, as expected.

Table 3 Heat resistance at interfaces

Temperture of inner surface of inner shell (°C)	Temperture of outer surface of intermediate shell (°C)	Temperture around model (°C)	Heat flow* per unit height (W/m)	Heat-transfer resistance at interface** (m^2K/W)
95.0	90.7	27.1	3539	3.67E-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 for a pipe and on the basis of 3 values in the lead layer
**Sum of heat-transfer resistances at the inner and outer interfaces

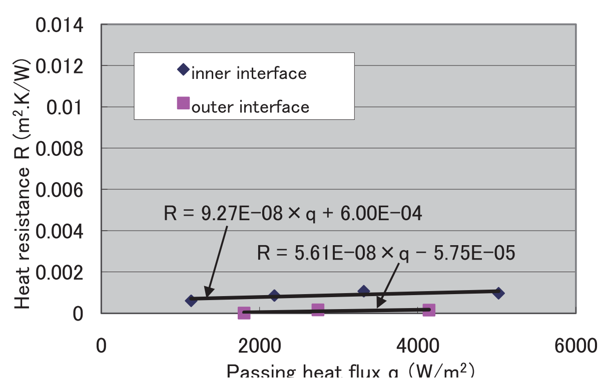


Fig. 6 Heat resistance characteristics

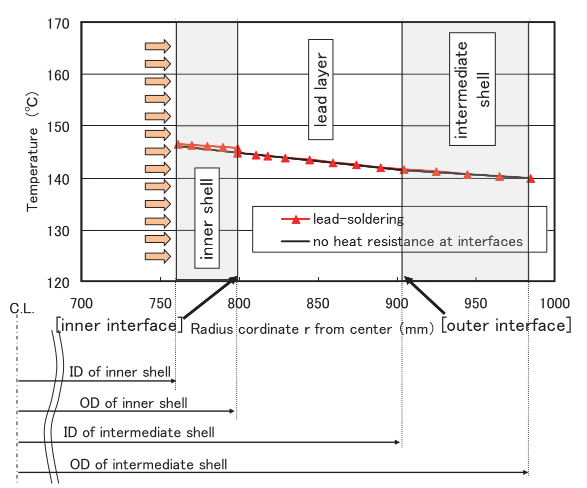


Fig. 7 Result of trial calculation for an actual cask

3.　LEAD SLUMP TEST

Any deformation of the lead layer resulting from a drop impact (so called “lead slump”) would cause a small gap at the top edge of the lead layer. This gap may allow γ-rays to pass through. The drop impact test is performed to check for the lead slump phenomenon and the effect of lead-soldering treatment.

3．1　Test model and conditions

The model used in the heat transfer test was used for the lead slump test. By the FEM analysis results of the drop impact of an actual cask (Hitz-B54 cask equipped with impact limiters, end drop test from 0.3 m height) with LS-DYNA, the acceleration of the central body was estimated to be 451 m/s^2. The drop height and shock absorbing characteristics like the depth and the density of the collision target were set to achieve the same impact acceleration as that for the actual cask. **Table 4** shows the test conditions. **Figure 9** shows photographs taken before and after the drop test. **Figure 10** shows the sensors used for determining the acceleration and the strain.

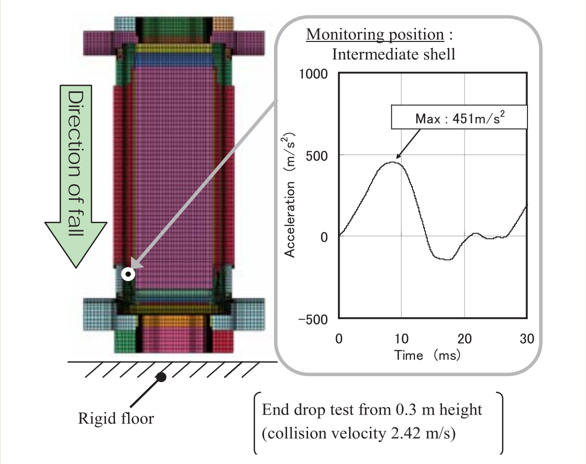
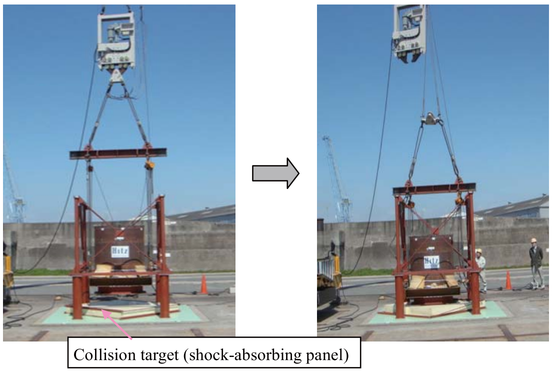


Fig.8 FEM analysis model and the result

Table 4 Conditions of the drop test

Drop height (m)	Target depth (mm)	Target density (ton/m^3)
0.3	200	0.2



(a) Before the drop test (b) After the drop test

Fig. 9 Photographs taken before and after the lead slump test

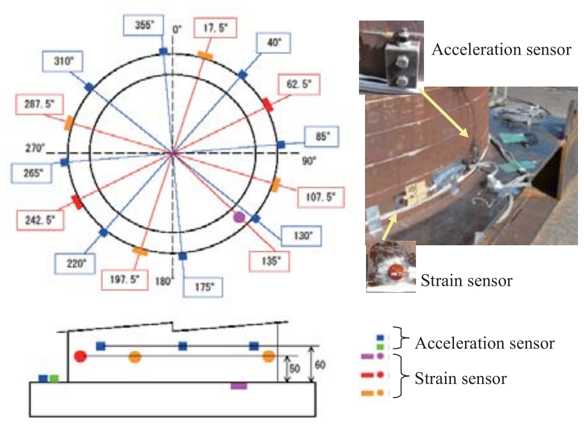
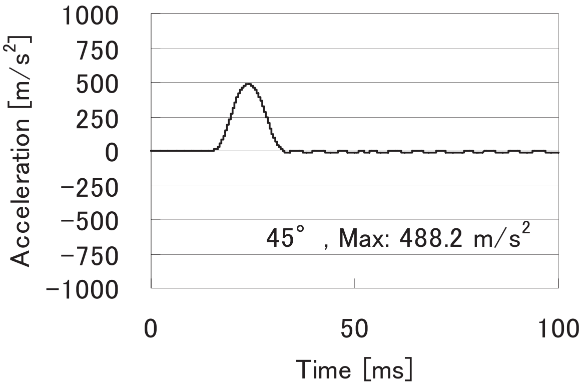


Fig. 10 Sensors used for determining the acceleration and strain

Monitoring position		Maximum acceleration (m/s^2)
Circumferential direction at outer surface of intermediate shell	Height from base plate	
0°	60 mm	478.5
45°		488.2
90°		499.2
135°		476.1
180°		469.3
225°		452.6
270°		449.1
315°		462.5

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

(a) Maximum Acceleration



(b) Acceleration wave

Fig. 11 Acceleration of the Model in the drop test

3.2 Test results

The impact acceleration in the test is shown in **Fig. 11(a)**. The impact accelerations were almost equal to that assumed for the actual cask given in **Figure 8**. Thus, the drop test was performed as intended, and it was confirmed that the setting of condition was reasonable. **Figure 11(b)** shows a sample shape of an impact acceleration wave. It is smooth and shows that the collision was realized as expected.

The shapes of the top edge of the lead layer of the models were determined before and after the drop test by using a non-contact displacement sensor.

Figure 12 shows the apparatus used for the shape determination. **Figure 13** shows samples of the determined results. The blue line shows the shape before the drop test, while the red line shows the shape after the drop test. The difference between the average lead layer heights before and after the drop test for different circumferential directions are shown in **Table 5**. The differences are very small, and therefore, it can be said that no lead slump occurred.

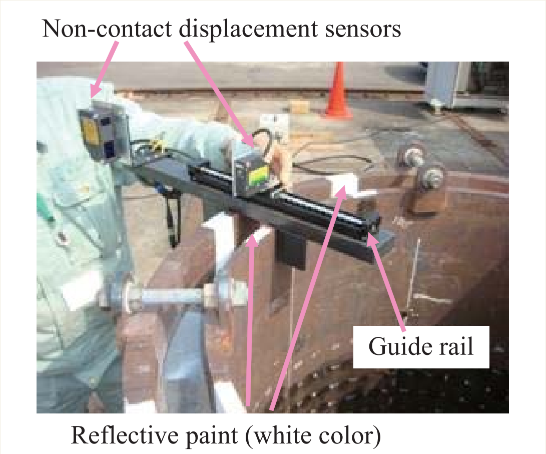


Fig. 12 Apparatus for determining the lead layer shape

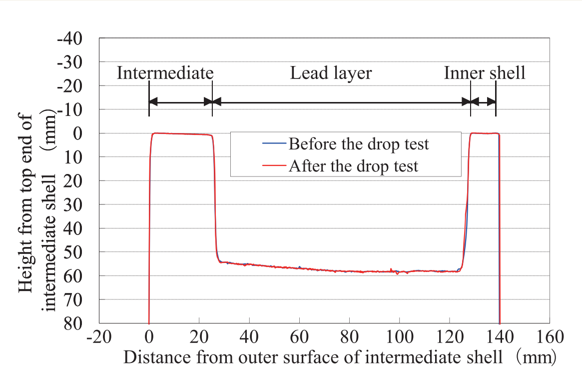


Fig. 13 Results of shape determination

4. CONCLUSION

The heat-transfer ability of interfaces and the lead slump phenomenon in the lead-type multilayer cask were examined experimentally by using a scale model. The main features of the study and the conclusions can be summarized as follows:

(1) The calculation formulas for the heat-transfer resistance at the lead layer-steel shell interface were obtained as a function of the heat flow.

(2) The heat-transfer ability of an actual cask that has been subjected to lead-soldering treatment can be calculated with the formula obtained from the experimental result, and it is almost identical to that in the case where the heat-transfer resistance between the lead layer and steel shells is zero. The effect of the lead-soldering treatment on the cask is evident, as expected.

Table 5 Results of the lead slump test

Circumferential direction at top end of lead layer	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)	
0°	57.51	57.53	0.02
45°	57.34	57.56	0.22
90°	57.17	57.07	-0.09
135°	58.30	58.28	-0.02
180°	58.53	58.45	-0.08
225°	58.43	58.42	-0.02
270°	58.12	58.22	0.10
315°	57.69	57.85	0.16

(3) No lead slump occurred in the model subjected to lead-soldering treatment. The test conditions were set so as to achieve the same impact acceleration as that for an actual cask. It is confirmed that no lead slump will occur in the case of actual casks.

From these tests, we acquired valuable data on the heat transfer and the slump phenomenon. We intend using these data for the safety evaluation in the licensing procedure. We shall also continue work on the design and fabrication of safe lead-type casks.

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