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Test program of the drop tests with full scale and 1/2.5 scale models of spent nuclear fuel transport and storage cask

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1. Introduction

MHI have been developing 5 types of spent nuclear fuel transport and storage cask (MSF cask fleet) as a cask line-up. In order to demonstrate their safety, a representative cask model for the cask fleet have been designed for drop test regulated in IAEA TS-R-1. The drop test with a full and a 1/2.5 scale models are to be performed. It describes the test program of the drop test and manufacturing process of the scale models used for the tests.

2. Outline of the MSF Cask Fleet

Cask fleet means total 5 casks MSF-21P, -24P which accommodate 21 and 24 PWR fuels, and MSF-57B, -60B, -69B which accommodate 57, 60 and 69 BWR fuels, respectively. Specifications are shown in **Table 1**. The feature of the cask fleet is described as below.

(1) Body

Low alloy steel is applied. Shape is optimized and its weight is saved. Heat dissipation capacity is improved by a reduction of unnecessary gap between inner body and basket. It is possible to apply monolithic forging process which is the forging technique provides vessel shape forging without weld joint between body shell and base. As a neutron shield, self-developed neutron shield material is applied.

(2) Containing System

Seal part consists of primary lid and secondary lid. The both lids are sealed with double seal type metallic gaskets and fastened by bolts. Some secondary lid bolts are used for fixing of shock absorber during transport.

(3) Basket

Boron containing aluminum alloy developed in-house is applied, weight saving and heat dissipation capacity is improved. For BWR version cask, same numbers of Individual square tubes for spent fuels to be contained are installed in cask cavity. And for PWR version cask, hollow plates are piled up as egg crate structure.

(4) Shock Absorber

Considering the train transportation in EU, maximum dimension is limited within about 3100mm. Three species of timber wood balsa, red cedar and oak are arranged in stainless steel cover plates and its structure is optimized for impact absorbing of drop test.

Table 1 Specification for MSF CASK FLEET

	MSF-				
	21P	24P	57B	60B	69B
Payload	21PWR	24PWR	57BWR	60BWR	69BWR
Burn up (average)	60GWd/MTU	52GWd/MTU	63GWd/MTU	63GWd/MTU	45GWd/MTU
Initial enrichment	4.45%	4.05%	5%	5%	3.7%
Cooling time	6 years	7 years	5 years	8 years	9 years
Thermal Power	41kW	35kW	49kW	39kW	22kW
Dimensions*	φ 2.5×5.7m	φ 2.5×5.7m	φ 2.5×5.3m	φ 2.4×5.3m	φ 2.5×5.3m
Weight**	121 tons	127 tons	125 tons	129 tons	126 tons

Notes: *:Cask body and lids, **: Transport package

3. Drop Test Program with Full and 1/2.5 Scale Models

The test program has been investigating with review/comments raised by the German authority (Federal Institute for Material Research and Testing: BAM)

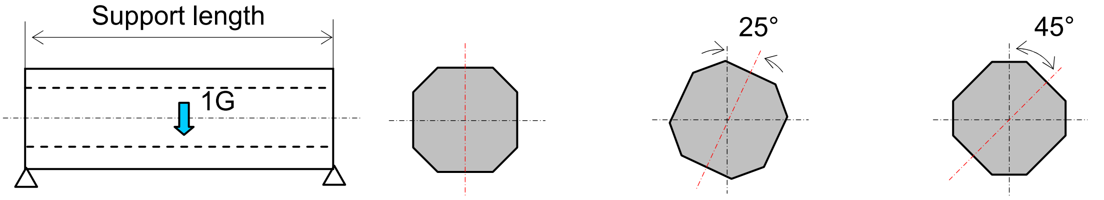
3.1 Outline of the Test Models used for the Drop Tests

Dimensions of main components and its stress to be occurred in the test were evaluated for the selection of drop test model, because test results have to be applied to all cask fleet. As a result of evaluation, a drop test model which can cover cask fleet structure to be safe side is designed based on MSF-69B. The comparative evaluation results of stress on body and basket are shown as follows;

(1) Evaluation of the Stiffness of Body Shell

FEM analysis was carried out to estimate bending strength of the body shell when it is subjected to a horizontal drop accident. As shown in **Fig. 1,** the body shell is assumed as a longitudinal solid model having the same cross section over the whole length. The body shell is supported at each end. Because the purpose of this analysis is to make comparison of the strength of body shell among five casks, three rotations (0, 25 and 45 degrees) were considered for each cask applying only a dead load (1G) of the body shell.

Maximum Von Mises stresses are shown in **Table 2**. It is found that the maximal stresses generated to the 1/1 scale model (based on MSF-69B) are kept to be higher level in the three angles than the other. In the test model, the body shell based on MSF-69B is adopted and 25 degrees of rotation is selected as drop orientation.



(a)case 1
(0°rotation model)

(b)case 2
(25°rotation model)

(c)case 3
(45°rotation model)

Fig. 1 Evaluation mode

Table 2 Results of evaluation

	Maximum stress(von Mises stress)[MPa]			Support length(mm)
	0°	25°	45°	
MSF-21P	1.01	1.32	1.28	5000
MSF-24P	1.02	1.47	1.42	5000
MSF-57B	1.06	1.43	1.31	4520
MSF-60B	0.74	1.40	1.46	4520
MSF-69B	1.08	1.45	1.41	4520

(2) Basket Compression / Bending Strength

The structures of the PWR baskets and the BWR baskets are different as follows.

- The PWR basket consists of rectangular tubes assembled into lattices.
- The BWR basket consists of individual square tubes.

To determine the basket design with the decreased strength, which has to be used for the tests, calculations have to be performed.

Fig. 2 shows the results of stress calculations for the 9 m drop test. A deceleration of 120G is used for these calculation according to the deceleration estimated for impact analysis as shown in 3.2(4) taking into account the scatter of the wood properties.

The stress in the case of MSF-69B is larger than the others' because the thickness of the basket as for the 1/1 scale model (based on MSF-69B) is the smallest one.

Furthermore, the maximum stress is generated at a rotation angle of 25 degree.

Detailed calculations for structural basket strength are described as follows.

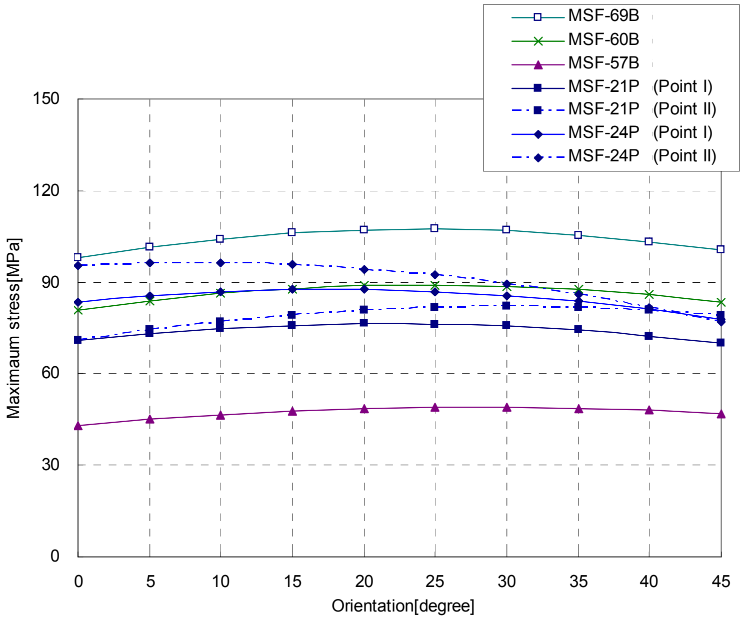


Fig. 2 Maximum stress of the basket

3.2 Drop Test Conditions

(1) Purpose and sequence of the drop tests

In order to evaluate the safety of cask fleet, the drop test is planed to be performed with two models (1/1 scale model and 1/2.5 scale model).

Generally, drop test is performed with scale model. However, it seems to be difficult to evaluate the integrity of containment system, especially around the lid and metallic gasket, from the following points of view;

- It is difficult to scale down the gasket
- Leakage is affected by lots of factors such as opening and sliding of lids and deformation of gaskets, etc.

Main purposes of drop tests with 1/1 and 1/2.5 scale models, and the sequence of drop test are shown in **Table 3** and **Table 4**, respectively.

Table 3 Main purposes of drop test with 1/1 and 1/2.5 scale model

Model	Main purposes of drop test
1/2.5 scale model	- Definition of the drop position, which gives the maximal damage to the closure system----the drop position which gives the largest degradation of the leak test result between before and after the drop tests - Demonstration of structural integrity of the basket and the deformation of the shock absorber to induce the justification of the assumption for criticality safety and radiation dose calculation respectively
1/1 scale model	- Demonstration of the package's integrity focuses on the containment integrity under the severest condition for the closure system based on the results of drop tests with 1/2.5 scale model.

Table 4 Sequence of drop test program

(a) Drop Test Conditions (1/2.5 scale model)

Test Conditions		Sequence	Orientation angle facing downward
Vertical	(a) Sequence No.1	1. Drop from a height of 0.3m 2. Drop from a height of 9.0m 3. 1m penetration	–
Horizontal	(b) Sequence No.2	1. Drop from a height of 9.3m	155°
Oblique	(c) Sequence No.3	1. Drop from a height of 0.3m 2. Drop from a height of 9.0m 3. 1m penetration	180°
Slap-down	(d) Sequence No.4 (First impact :Bottom)	1. Drop from a height of 0.3m 2. Drop from a height of 9.0m 3. 1m penetration	270° (trunnion side)
	(e) Sequence No.5 (First impact :Bottom)	1. Drop from a height of 9.3m 2. 1m penetration	155°
	(f) Sequence No.6 (First impact :Lid end)	1. Drop from a height of 0.3m 2. Drop from a height of 9.0m 3. 1m penetration	270° (trunnion side)
	(g) Sequence No.7 (First impact :Bottom)	1. Drop from a height of 9.3m	180°

(b) Drop Test Conditions (1/1 scale model)

Test Conditions		Drop Tests with the 1/2.5 Scale Model	Orientation angle facing downward
Slap-down	(a) Sequence No.1* (First impact: Bottom)	Drop from a height of 9.3m	180°
Horizontal	(b) Sequence No.2*	1m penetration	180° **
Vertical	(c) Sequence No.3	Drop from a height of 9.0m	–

* In accordance with the requirement in TS-R-1 the tests shall be performed continuously

** Same orientation as sequence No.1

(2) Slap-down Angle

An inclined angle of test model in slap-down test is determined by the following. Computation is evaluated by applying the procedures shown in the BAM report [1] to all casks of the MSF cask fleet. The calculation was evaluated by taking into account the moment of inertia by considering the cask shell as a rigid bar (see **Fig. 3**).

The final angular velocity ω_2 can be showed with equation (4) from equations (1), (2), and (3). And, according to the BAM report, the angular velocity during secondary impact ω_x, the tangential velocity at secondary impact part $\dot{x}_{R*}$, the normal velocity $\dot{z}_{R*}$, etc. may be showed as the functions of the final angular velocity ω_2; thus, calculation was realized by substituting the final angular velocity ω_2. Finally, the final kinetic energy at the mass center was computed from the angular velocity ω_x, the tangential velocity $\dot{x}_{S*}$, and the normal velocity $\dot{z}_{S*}$ during the secondary impact, and the maximum ratio of final to initial kinetic energy was computed [See equation (5)].

The maximum ratio of final to initial kinetic energy was computed by using the impact angle φ_o as the parameter for each cask. The tilt angle of 10 degrees, that showed the largest difference from the initial position energy during the secondary impact under 9 m drop with the rough impact, was employed. The results of calculation at smooth impact and rough impact are shown in **Fig. 4**. The reason why we decided to use the rough impact for the slap-down behavior is as shown below.

- For the slap-down test with the 1/2.35 test model of MSF-69B tested by MHI, the container's rotary behavior was confirmed after the primary impact.
- As described in the BAM report, the slap-down behavior of the Castor V-HAW cask optimally matches if

simulated with the rough impact.

$$I_x = m(\dot{x}_{S_2} - \dot{x}_{S_0}) \text{ ....(1)}$$

$$I_z = m(\dot{z}_{S_2} - \dot{z}_{S_0}) \text{ ....(2)}$$

$$\theta_S(\omega_2 - \omega_0) = I_z x_S - I_x z_S$$

$$= I_z \frac{\ell}{2}\cos\varphi_0 - I_x \frac{\ell}{2}\sin\varphi_0 \text{ ....(3)}$$

$$\omega_2 = \frac{m(k+1)v_0}{\theta_s + m\frac{\ell^2}{4}} \frac{\ell}{2}\cos\varphi_0 \text{ ....(4)}$$

$$R_K = K_{S*}/K_0 \text{ ....(5)}$$

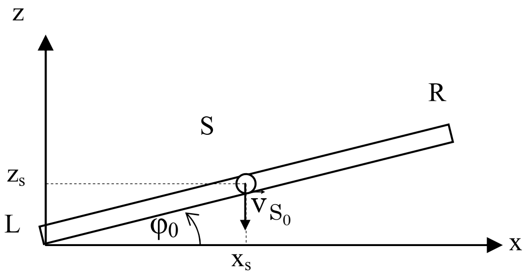


Fig. 3 Impact of a rigid bar

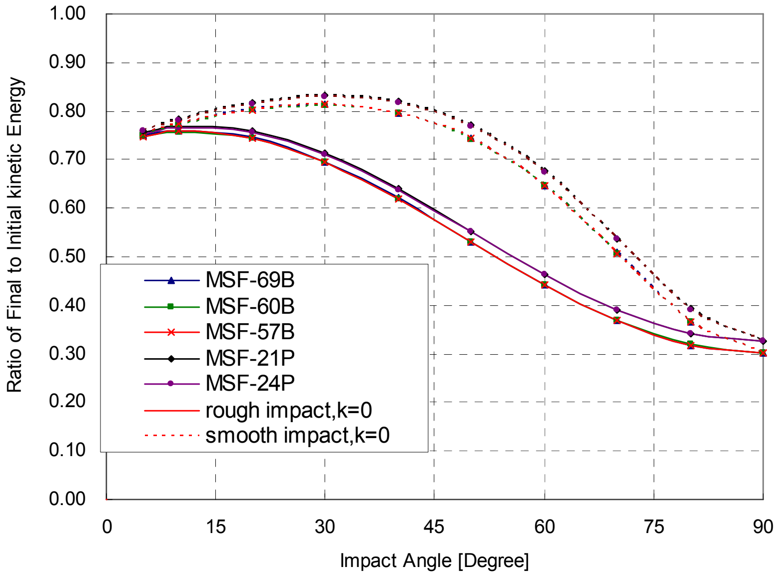


Fig. 4 Effect of secondary impact under slap down

(3) Cask Rotation Angle

The cask rotation angle of 25 degrees to be inclined is selected based on the maximum stress occurred to the body shell and basket as described in 3.1. Therefore the rotation angle is applied to some test conditions (horizontal and slap-down) for 1/2.5 scale model.

(4) Evaluation of Deceleration during Drop Test

Deceleration of each drop test sequence is evaluated by in-house code “CASH-II” [2] which is used to estimate the deformation of the shock absorbers and the deceleration testing the event of drop test. **Fig. 5 to 7** show the input data of the compression properties of the oak, red cedar and balsa woods for CASH-II. Results of the deceleration estimated are shown in **Table 5.**

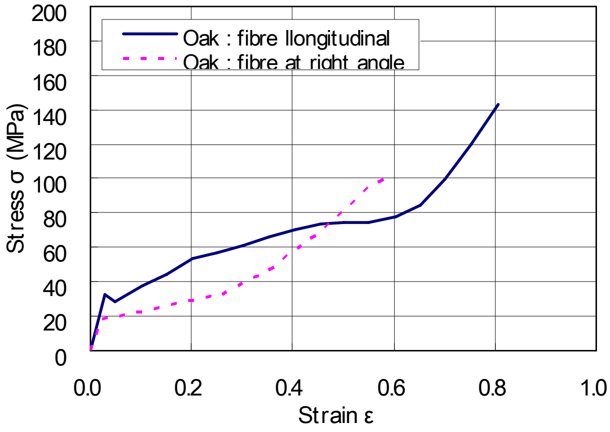


Fig. 5 Compression properties of oak wood

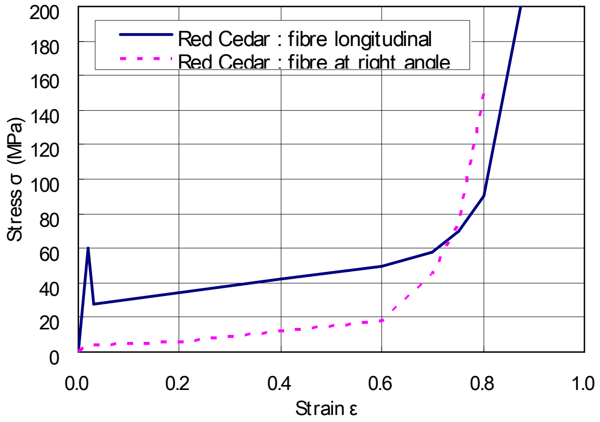


Fig. 6 Compression properties of red cedar wood

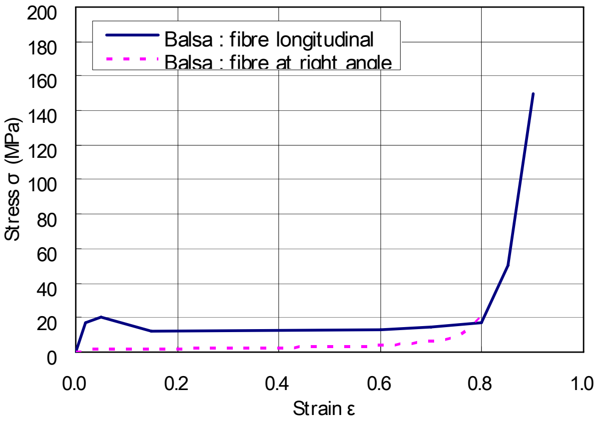


Fig. 7 Compression properties of balsa wood

Table 5 Results of decerelation estimation

Test conditions		Deceleration
Vertical		49G
Horizontal	0 degree(*)	80G
	45 degree(*)	75G
Oblique		37G
Slap-down	0 degree(*)	98G
	45 degree(*)	94G

(*) The cask rotation angle to be inclined

3.3 Instrumentation Plan

We evaluate sealing integrity and structure integrity of cask in drop test. By measuring dynamic structure response by using strain gauge, we clarify the fall behavior of cask. Therefore, we did the preliminary analysis on the drop test of the 1/1 scale model of the MSF cask by using FEM analysis to plan the instrumentation of MSF-Cask drop test. We calculated the structure responses by 9m drop and Impuncture analysis of whole cask model using LS-DYNA code to evaluate the portion that the maximum stress occur for fixing the measurement portion. We select the measurement portion taking into account the point that the maximum stress occur. Axis direction of strain gauge made maximum principal stress vector, minimum principal stress vector direction.

As the example of the analysis result, Von Misses stress distributions when the kinetic energy is minimum are shown in **Fig. 8.** and **Fig. 9** shows time history of kinetic energy. Flange of 180 degree positions that is impact surface at the time of the secondary impact is bent inside and is occurred ovaling behavior at whole flange. Therefore, high stress is occurred with the root of flange by bending and with the top of flange by ovaling. Attaching strain gauge in that position, we measure structure stress.

We use accelerometer in order that we estimate load input to the cask body of fall impact. Therefore, we attach more than two accelerometers to impact surface.

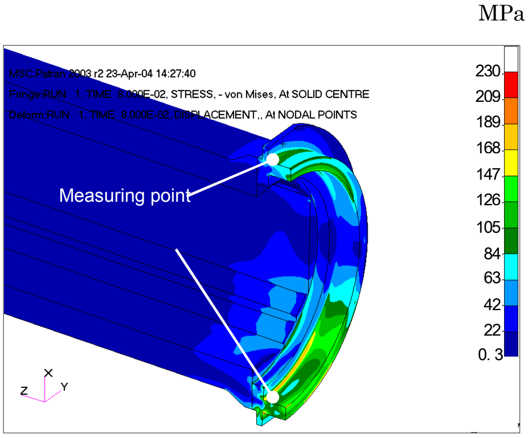


Fig. 8 Stress of the flange (1/2.35 scale model)

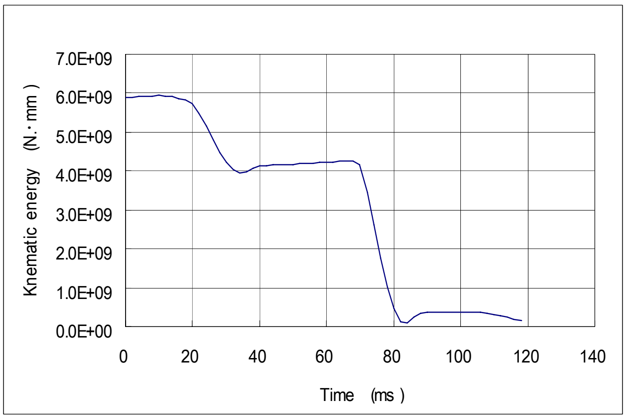


Fig. 39 Time history of kinetic energy

3.4 Results of in-house Drop Test

As in-house test, we executed drop test using 1/2.35 scale model. We attached strain gauges at flange and lid to evaluate structure integrity of cask like 1/1 scale model drop test. And tightness leakage test was carried out to evaluate sealing integrity. Cask drop positions are 9m slap-down, 9m vertical drop, 9m oblique drop and 1m puncture test.

The time histories of the flange stress that was measured in 9m slap-down are shown in **Fig. 10**. Flange of 180 degree positions that is impact surface at the time of the secondary impact is bent inside and is occurred ovaling behavior at whole flange. The leakage test result in this time is shown in **Table 6**. In all test cases, sealing integrity was able to be secured.

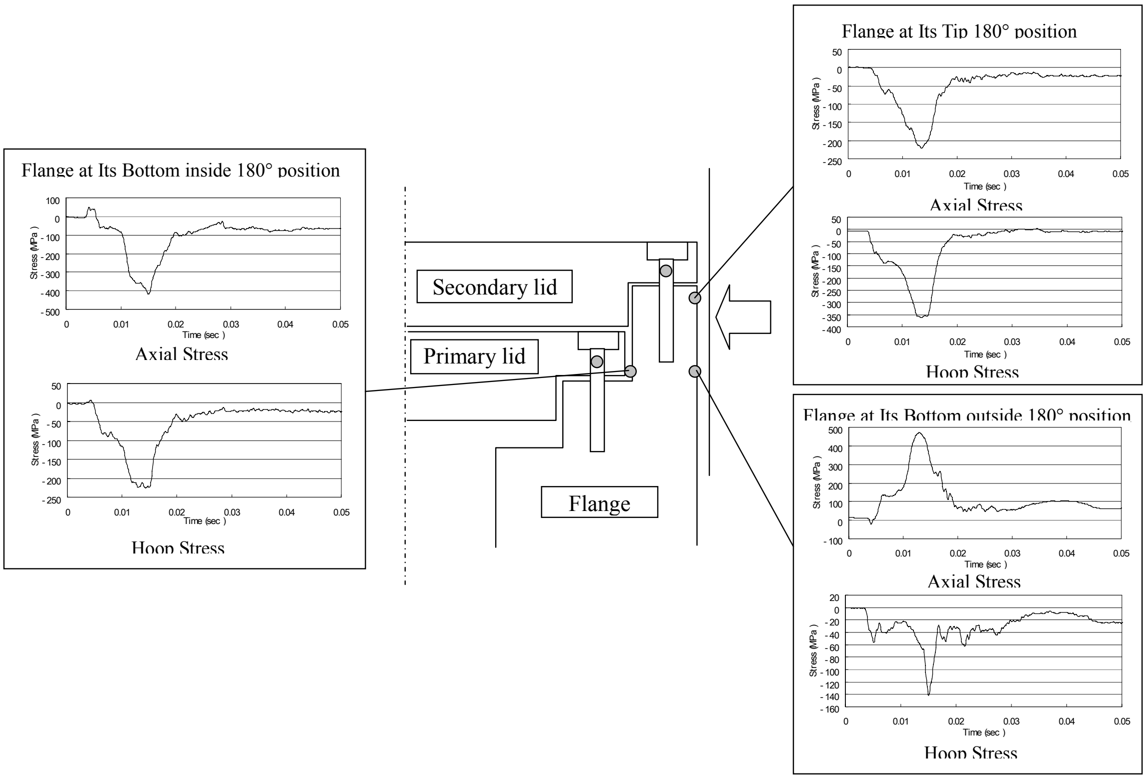


Fig. 10 Time histories of flange stress

Table 6 Leakage rate measured after the drop test

Dropping attitude	Leakage rate(Pa· m^3/s)	
	Primary lid	Secondary lid
9m Slap Down	5.0×10^{-9}	4.4×10^{-9}
1m Vertical Puncture	1.0×10^{-11}	1.0×10^{-11}
9m Vertical drop	1.0×10^{-11}	2.0×10^{-11}
9m Oblique	6.0×10^{-11}	1.0×10^{-11}
1m Horizontal Puncture	8.0×10^{-11}	8.6×10^{-9}

4. Manufacturing of the Drop Test Models

The manufacturing period of 1/1 and 1/2.5 scale models are 8 and 4 months without material procurement term, respectively, **Fig. 11.**

Fig. 11 1/1 Scale Model

The two drop test models are strictly simulated with the structure of the body, the sealing area and the flange structure in order to simulate all the elemental structures of the cask to be considered for structural evaluation as a representative of cask fleet. Neutron shield and its covers were also composed and manufactured to simulate the actual cask.

As a substitution of spent nuclear fuel, dummy fuel weights made of carbon steel were installed. Total mass of 1/1 scale model including dummy fuel weights and shock absorbers is 127 ton.
Concerning of the basket structure which assures the sub-criticality system structurally, a substituting aluminum material is applied to simulate the strength of boron containing aluminum alloy at elevated temperature during transport and storage of the cask.

The manufacturing and quality control of the drop test models has been proceeded in accordance with the requirement of guidance concerning about cask manufacture and maintenance in German (TRV006) under the instruction of German authority (BAM) and the certified third party, TÜV, entrusted by BAM. The justification of the manufacturing control of models is confirmed mainly by TÜV with respect to the manufacturing process such as welding and machining for the flange part.

The application of acceleration sensor and strain gages has been also performed under the BAM instruction and TÜV witness in the same manner of the cask manufacture.

And some qualification of the manufacturing and inspection procedures for the actual cask such as welding procedures are performed thorough these manufacturing and drop test.

5. Summary

With respect to the planning of the drop test program, the representative drop test model which covers the all cask fleet with safe side is selected. Further the 1/1 and 1/2.5 scale models are prepared concerning the objectives of the drop test and the drop test conditions are decided. In the sequence of the drop test, the integrity of the structure and the containment system as for the cask fleet developed by MHI will be verified. Then the drop test of slap-down with 1/1 scale model will be carried out during the PATRAM'04 in public.

Reference

[1] T. Quercetti, V. Ballheimer, G. Wieser ; Analytical, Numerical and Experimental Investigations on the Impact Behaviour of Packagings for the Transport of Radioactive Material under Slap Down, 12200 Berlin, Germany.
[2] Asada, K. et al, Development of simplified analysis codes for 9m drop and 1m puncture test for a radioactive material cask, Proc. Waste Management 88, (Tuscon), 1988