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CONFINEMENT ANALYSIS OF DUAL PURPOSE METAL CASK SUBJECTED TO IMPULSIVE LOADS DURING HANDLING ACCIDENTS

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ABSTRACT
Necessity of the interim dry storage of nuclear spent fuel using metal casks has risen year by year. The metal gaskets are used to keep the leak-tightness of the metal cask for long-term storage. The metal cask storage system should be designed to withstand man-made events such as handling accidents, and external natural events, such as earthquakes, tornadoes, floods, etc. without impairing its capability to perform its intended design functions. The purpose of the investigation in this paper is to assess the structural and confinement integrity of the transport and storage metal cask for spent fuel without impact limiters in case of severe impact loads and to estimate a conservative leakage rate for calculating the amount of radioactive release. Behavior of the structural integrity of the metal cask was examined using a finite-element method of analysis in a computer program, LS-DYNA. A detailed 3-D finite element model of the floor structure and the metal cask was developed for the explicit method of dynamic analysis, and confirmed by comparing with the impact test results with a full-scale metal cask (horizontal drop and rotational impact onto concrete floor from 1m height). The analyses of the several non-mechanistic tip-over (on the concrete floor and transport rack) and drop events from 1m height in the storage building have been executed. The leakage rates were calculated in connection with the determination of the accumulated relative displacements between the metallic gaskets and the flange. After the lid behaviors in each case have been evaluated, it is found that the leakage rate from the primary lid might be less than 1.0×10^{-5} Pa・m^3/s and the loss of the inner pressure in the cask might be excluded in the accidental events considered in the storage building.

INTRODUCTION
In Japan, the first ISF outside of NPP site in use of dual-purpose metal cask as shown in Fig.1 is being planned to start its commercial operation in around 2010 in Mutsu city, Aomori prefecture. On safety technical requirements for spent fuel interim storage facility using dry cask, NISA/METI (Nuclear and Industrial Safety Agency, Ministry of Economy and Trade Industry) issued the technical requirements on interim spent fuel storage facility (ISF) using dry metal cask and concrete cask on April 2006 [1][2]. In parallel with those regulatory and promoting activities on ISF, CRIEPI has been performed supportive research studies for the regulation and early realization of ISF to reflect in the technical requirements issued by NISA.

In the ISF of spent fuel, the metal casks will be handled without impact limiters, so there are still uncertainties for their impact behaviors under severe impact loads, such as drop or tipping-over events. Therefore, CRIEPI has executed two impact tests (horizontal drop and rotational impact onto concrete floor) with the full-size metal cask and the relationships between gasket movements and leak rate of inert gas have been clarified. Moreover, according to the drop analysis using dynamic analysis code LS-DYNA and the comparison with the experimental results, CRIEPI has clarified that the dynamic behavior of the metallic gaskets subjected to sliding and opening movements of the lid structures during impact loads could be simulated accurately and directly. The purpose of the investigations in this paper is to investigate the structural and confinement integrity of the transport and storage metal cask for spent fuel without impact limiters in case of severe impact loads and to estimate a conservative leakage rate for calculating the amount of radioactive release.

Figure 1. First Interim Storage Facility Outside of NPP Site in Japan (3,000tU)

IMPACT ANALYSIS WITH THE METAL CASK ONTO CONCRETE FLOOR

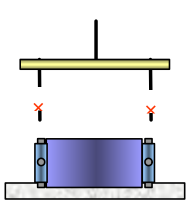
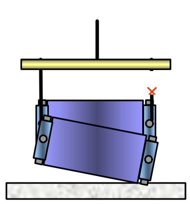
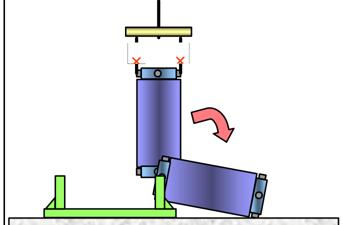
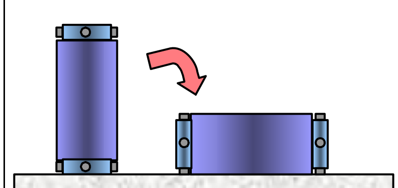
Non-Mechanistic Events

With the object of clarifying the movements of the lid structure of metal cask during the impact load, five impact non-mechanistic events of the metal cask without impact limiters were considered as shown in Table 1. The non-mechanistic events include the horizontal drop and the rotational impact onto concrete floor from 1m height, the rotational impact on the transport rack and the tip-over onto the concrete floor and onto the trunnion in the storage building. To evaluate the lid structure behavior during impact loads, the impact analyses for these events have been executed with dynamic Finite Element Method analysis code LS-DYNA.

Target storage cask Description

Fig.2 shows overview of the full-size metal cask model for impact analysis, and Table 2 shows main specifications of this model [3]. This model has been designed as metal cask for dry storage and transportation including 21 PWR-type fuel assemblies.

Table 1. Considered Non-Mechanistic Events for Structural and Confinement Analysis

Drop impact	Rotational impact		Tipping-over	
from 1m height	from 1m height	on the transport rack	onto trunnion	onto floor
Case H	Case R1	Case R2	Case T1	Case T2
V = 4430 mm/s	ω = 1.09 rad/s	ω= 2.57 rad/s	ω= 1.68 rad/s	
				

This cask has double lid structure, and lid gaskets are double type metal gasket made of aluminum coating material. For primary and secondary lids, a section diameter of the gasket is 5.6 mm and 10 mm, respectively. And this cask has a gap between lid side and body. At initial condition, primary and secondary lid are set carefully to make the gap equal. Nominal gap of primary and secondary lids at one side is 1mm 0.5 mm, respectively.

Figure 2. Overview of Full-Size Metal Cask Model

Table 2. Specification of Metal Cask Model

Part	Material	Size (mm)	Weight (ton)
Body	Carbon steel (ASTM A350LF5)	Inner Dia. : 1672 Thickness : 250	84.6
Neutron shielding	Lightweight concrete equivalent to resin	Thickness : 164	
Outer sell	Carbon steel	Outer Dia. : 2524 Thickness : 12	
Trunnion	Stainless steel (SUS F630)	Diameter : 190	
Primary ld	Carbon steel (ASTM A350LF5)	Outer Dia. : 1946 Thickness : 198	4.2
Secondary ld	Carbon steel (ASTM A350LF5)	Outer Dia.: 2236 Thickness : 235.5	5.5
Contents	Equivalent weight		3.5+21.2
Total Weight			119

Drop test without impact limiters under accident

To clarify the impact response of the lid system of the metal cask without impact limiters considering drop accidents during handling in a storage facility, CRIEPI executed a series of impact tests (a horizontal drop test from a 1m height and a rotational impact test around an axis of a lower trunnion of the cask from the horizontal orientation at a 1m height) using a full-scale metal cask as shown in Fig.2 [3]. Fig.3 shows drop test conditions.

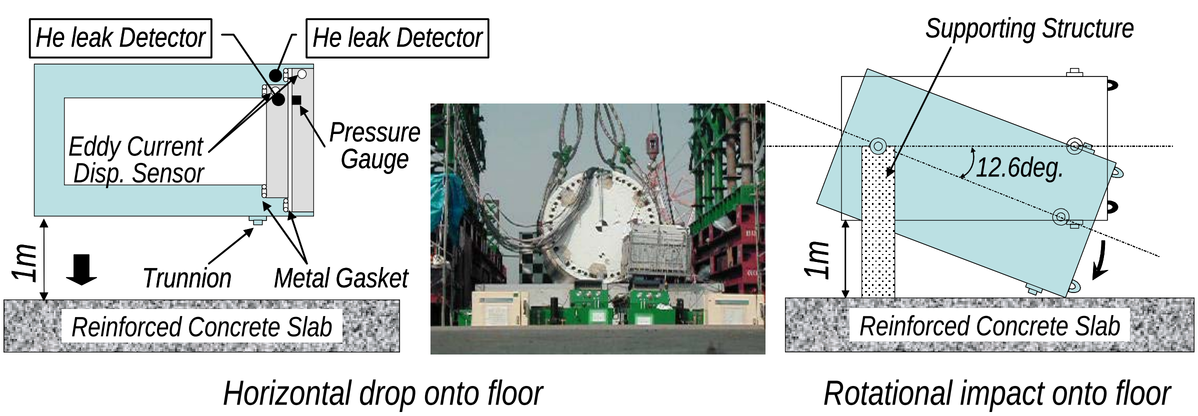


Figure 3. Drop Test Conditions with Full-Scale Metal Cask

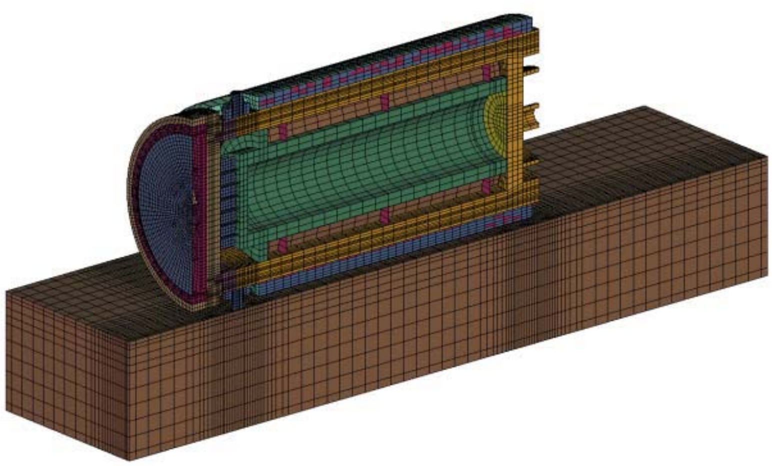
According to the test results, it seems that the relationship between the maximum sliding displacement of the lids and the maximum leak rate of the full-scale metal cask subjected to the impulsive loads showed a good agreement with the leak-rate and sliding displacement curve obtained by the scale model gasket structure.

Analysis Model Description

Analysis code is LS-DYNA Ver.970 with user subroutine of material model for concrete originally developed by CRIEPI [4]. Fig.4 shows analysis model of horizontal drop test and a number of elements and nodes of this model. This model is made as a 1/2 symmetric model considering the cask structure and the drop orientation. The accuracy of this analysis model was benchmarked by comparing the impact test results to simulate the impact behavior of the complicated gasketed joints [5].

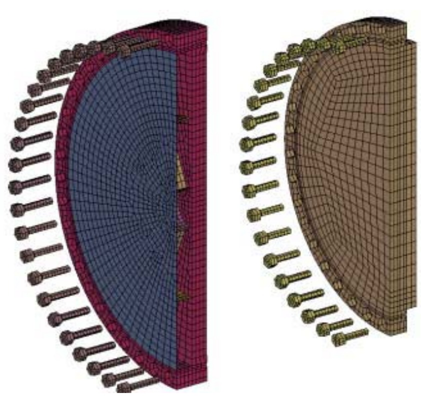
Material properties

Metallic materials are used for body, lid, lid bolts, outer shell, trunnion, contents and reinforce bar of concrete floor. These materials are simulated as isotopic elastic plastic material. Table 3 shows material properties applied to the calculation. Concrete materials are also used for concrete floor and lightweight concrete filled between main body and outer shell. Table 4 shows material properties of these concrete materials. These properties have been determined from the results of material tests. Test Samples are prepared from actual test model's concrete by core boring method, and these values are used for input data of user subroutine of concrete material.

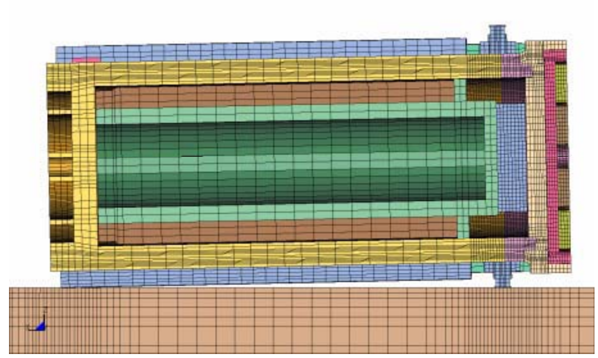


Part	Elements	Nodes
Main body	91210	80221
Two lids	22146	15164
Contents	3776	3104
Concrete floor	28800	29658
Total	145932	128147

(Bird View of the Model for Horizontal Drop Event or Tipping-over Event)



(Lids and Bolts)



(Cross-Section of the Model)

Figure 4. Analysis Model for Horizontal drop and Tip-over on to the Floor Event

Analytical condition

As to the contact condition, on every contact surface between parts of this analysis model, a slide surface condition with voids is applied. Friction coefficient of the slide surface is set to 0.14., however, only for flange surface of primary and secondary lids, these coefficient values are set to experimental value (0.6) obtained from the sliding test result with a scaled lid model [5]. The initial tightening force of the lid bolts, equivalent to tightening torque of 2400 N-m, is set by the method of relaxation of initial penetration.

Initial condition

For horizontal drop event (Case H), initial velocity 4430 mm/s equivalent to the free drop velocity form 1-meter height is set to the cask model. For rotational impact events from 1 m height (Case R1) and onto the transport rack (Case R2), initial rotational velocity is 1.09 rad/s equivalent to the velocity form 1-meter height rotation and 2.57 rad/s equivalent to the velocity form standing upright position on the support structure of the transport rack, respectively. The rotational center is set to a center axis of bottom side trunnions. For tipping over event (Case T1, T2), initial rotational velocity is 1.68 rad/s equivalent to the velocity form standing upright position onto the trunnion or concrete floor.

Table 3. Material Properties of Metallic Materials

Part	Density (kg/m^3)	Young's modulus (MPa)	Poison's ratio	Yield stress (MPa)	Hardening modulus	Strain rate parameter*	
						P	C
Body and lid	$7.85x10^3$	203460	0.3	205	2034	200	5
Lid bolts	$7.85x10^3$	202000	0.3	890	2020	200	5
Outer shell	$7.86x10^3$	203000	0.285	215	2030		
Trunnion	$7.86x10^3$	195000	0.3	725	1950	200	5
Contents	$7.86x10^3$	203000	0.3	215	2030		
Reinforced bar	$7.86x10^3$	206000	0.3	295	2060		

*Note: Yield stress coefficient at strain rate $\dot{\varepsilon} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P}$

Table 4. Material Properties of Concrete

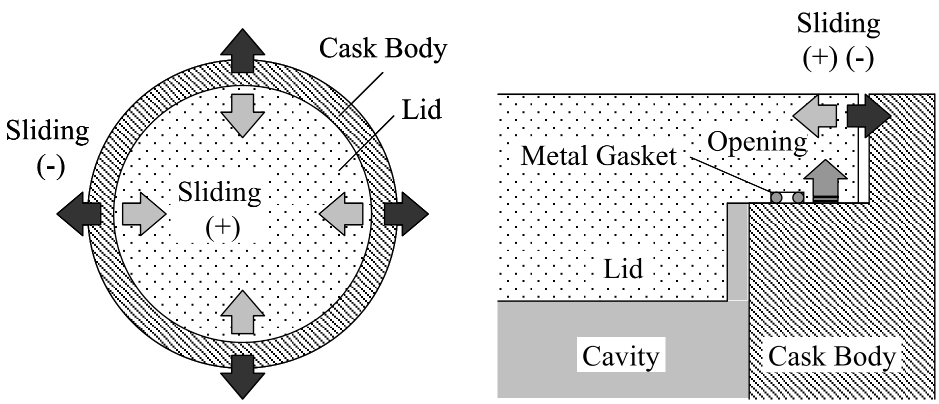
Part	Density (kg/m^3)	Shear modulus (MPa)	Bulk modulus (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
Concrete floor for horizontal drop	$2.286x10^3$	11939	16177	36.92	3.30
Concrete floor for rotational impact	$2.281x10^3$	11919	15706	35.93	2.39
Lightweight concrete	$1.543x10^3$	5876	8805	22.68	3.30

CONTAINMENT EVALUATION CRITERIA

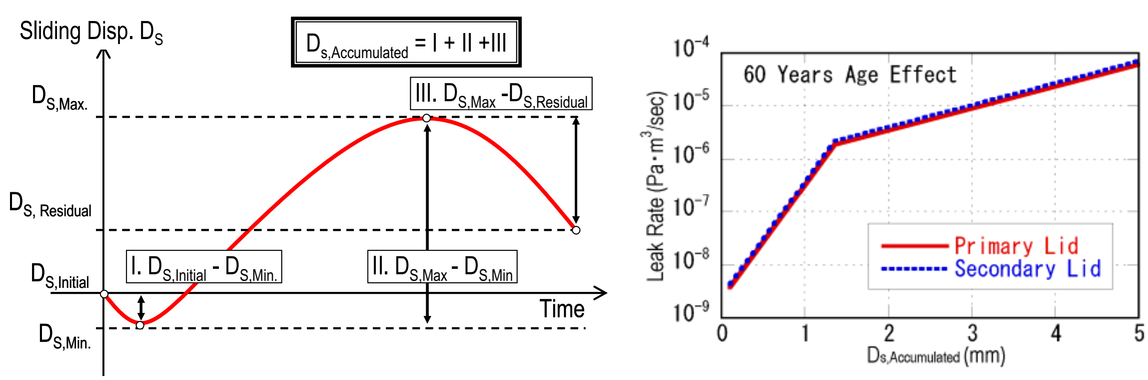
Containment evaluation criteria was proposed by Japan Nuclear Energy Safety Organization (JNES), according to a series of leakage tests using scale models with double type aged metal gasket made of aluminum coating material of which section diameter was 10mm [4]. Fig.5 shows the outline of the containment evaluation criteria for the metal gasket seal. Sliding or opening of the lid is defined by the relative displacement of the metallic gaskets parallel or normal to the flange, respectively. The accumulated relative displacement $D_{S,Accumulated}$ is defined by subtracting the difference between the values of initial and residual, $D_{S,Resiual}$ -$D_{S,Initial}$ from twice the difference between maximum and minimum, 2*($D_{S,Max.}$ -$D_{S,Min.}$).

The instantaneous leak rate for 60 years aged metal gasket seal subjected to the impulsive loads can be evaluated by the relationship between the leak rate and $D_{S,Accumulated}$ if the lid system would satisfy the following conditions.

* There is no plastic deformation in the lid system
* There is no considerable opening of the lids
* There is no considerable loss of the torque of the lid bolts



(Definition of the Sliding or Opening of the Lids)



(Relationship between the leak rate and the accumulated relative displacement)

Figure 5. Outline of the Containment Evaluation Criteria for the Metal Gasket Seal

IMPACT ANALYSIS RESULTS

Plastic Deformation

Fig.6. shows the occurrence of the plastic deformation in each event In each case of the rotational impacts (Case R1, R2), the plastic deformation was occurred in the second lid flange, therefore the leak-tightness of the secondary lid system might be lost during impact loads according to the leakage criteria described above.

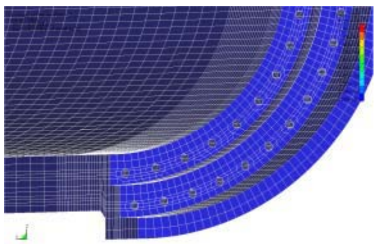
Lid Movements

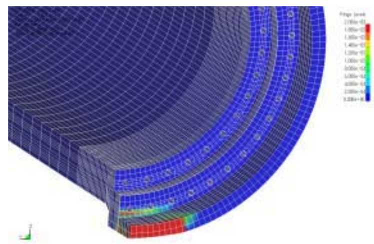
Fig.7. shows the example of the time history of the lid movements during the rotational impact on the transport rack (Case R2). A considerable lid opening displacement was occurred in the

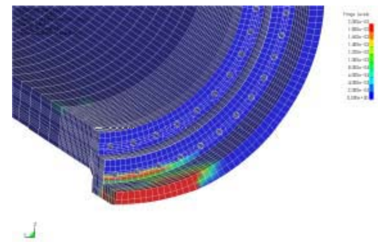
vicinity of the impacted area between the top of the cask edge and the concrete floor surface, and the plastic deformation was also occurred in the lid bolts accordingly.

Evaluation of Leak-tightness

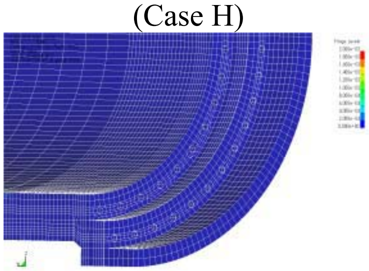
Table 5 shows the summary of the impact analysis results. According to the leakage criteria described above, it can be concluded that the leakage rate from the primary lid might be considerably low (less than 1.0×10^{-5} Pa･m^3/s) and the loss of the inner pressure in the cask might be excluded in the accidental events considered in the storage building.

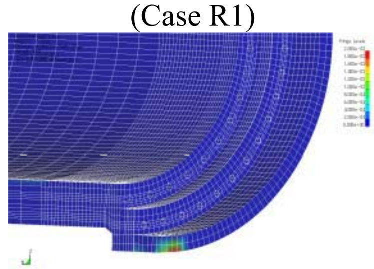


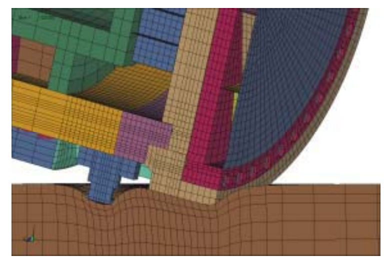




(Case H) (Case R1)

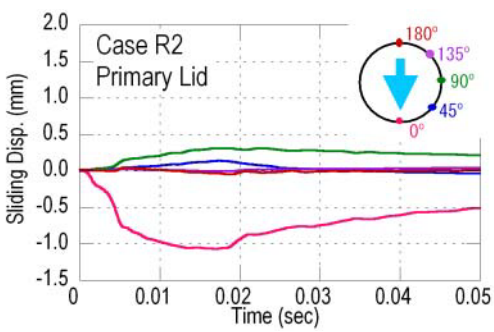


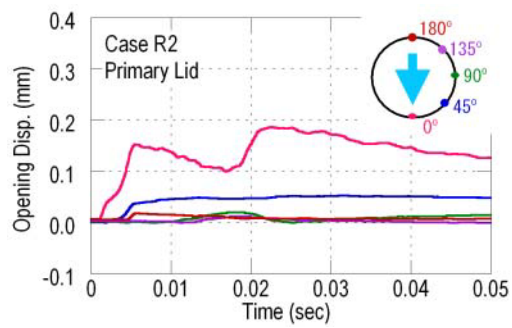




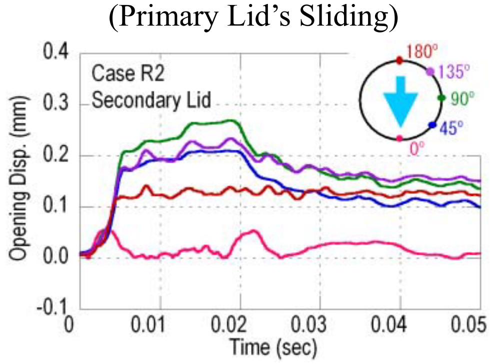
(Case T1) (Case T2) (Case R2)

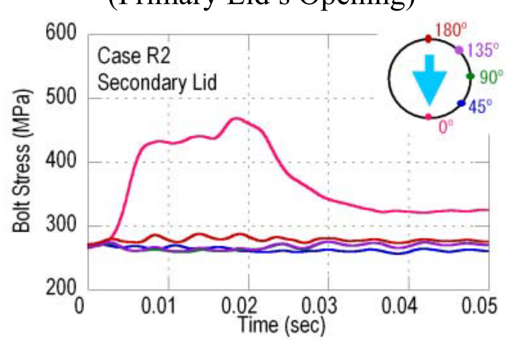
Figure 6 Occurrence of Plastic Deformation in Each Event





(Primary Lid's Sliding) (Primary Lid's Opening)





(Secondary Lid Bolt Stress) (Secondary Lid's Opening)

Figure 7 Time History of the Movements of the Lids in Case R2

Table 5. Summary of the Impact Analysis

Part \ Event		Drop impact 1m height	Rotational impact 1m height	Rotational impact onto the transport rack	Tipping-over onto the trunnion	Tipping-over onto the floor
		Case H	Case R1	Case R2	Case T1	Case T2
Acceleration	Primary lid	$135 m/s^2$	$264 m/s^2$	$619 m/s^2$	$323 m/s^2$	$630 m/s^2$
Primary lid	Sliding*	0.63mm	1.10mm	1.63mm	1.59mm	1.47mm
	Opening	---**	0.01mm	0.19mm	---	---
	Status**	None	None	None	None	None
Secondary lid	Sliding*	0.29mm	1.64mm	1.65mm	0.57mm	0.84 mm
	Opening	0.02mm	0.05mm	0.27mm	0.04mm	0.05mm
	Status***	None	Plastic	Plastic	None	None
Estimated Leak Rate ($Pa \cdot m^3/s$)	Primary lid	$<1.0x10^{-7}$	$5.3x10^{-7}$	$2.4x10^{-6}$	$2.3x10^{-6}$	$2.1x10^{-6}$
	Secondary lid	$<1.0x10^{-7}$	Loss	Loss	$<1.0x10^{-7}$	$1.7x10^{-7}$

* Accumulated Sliding Displacement ** No significant change
*** Occurrence of the plastic deformation in the lid system

CONCLUSIONS

The analyses of the several non-mechanistic tip-over (on the concrete floor and transport rack) and drop events from 1m height in the storage building have been executed. The leakage rates were calculated in connection with the determination of the accumulated relative displacements between the metallic gaskets and the flange. After the lid behaviors in each case have been evaluated, it is found that the leakage rate from the primary lid might be considerably low and the loss of the inner pressure in the cask might be excluded in the accidental events considered in the storage building.

ACKNOWLEDGMENTS

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