Safety Evaluation of the Sealing Performance of a Metal Cask subjected to Vertical and Horizontal Impact Load due to Aircraft Engine Crash

CRIEPI

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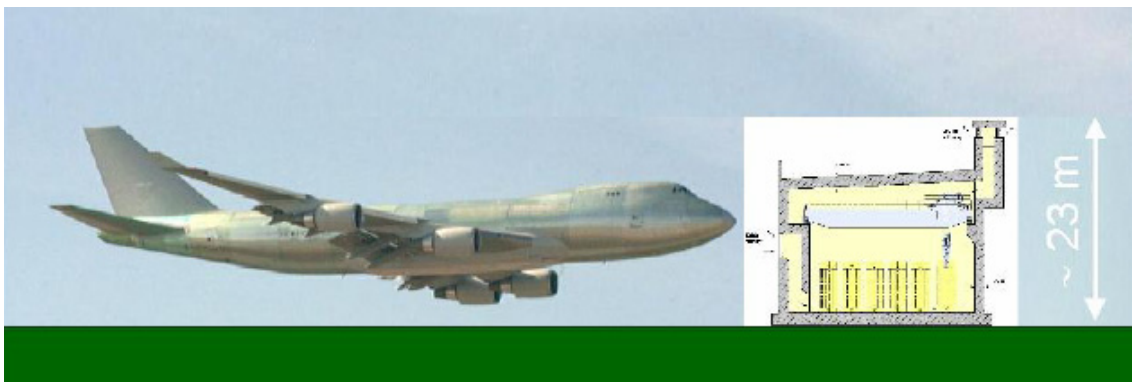
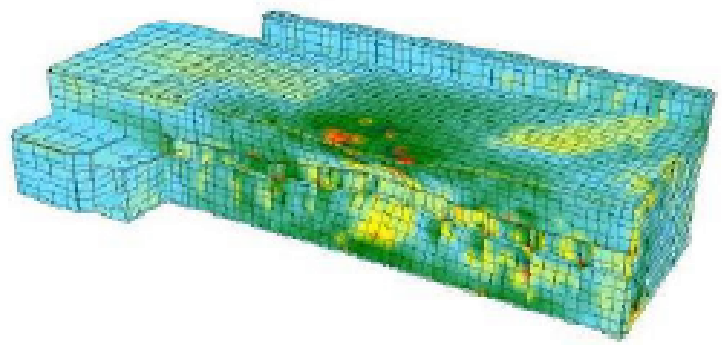
These works have been carried out under the contract from NISA/METI.

Background

- *After the terrorist attacks from 11th September 2001*
- *Accident scenarios exceeding the design requirements, e.g. Forced aircraft crash*
- *Corresponding analysis have been executed with regard to the assessment of the inherent safety in an interim NSF storage facility*



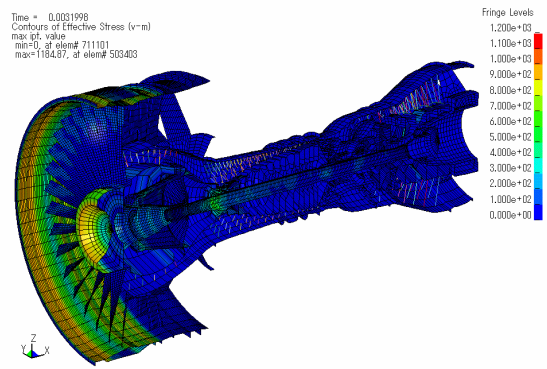


Example by BAM, Germany

- *It is important to ascertain whether a forced aircraft crash event could lead to a significant release of radioactive substances into the environment.*

Aircraft Crash Analysis and Test

- To evaluate integrity of a metal cask under a hypothetical airplane crash accident.
- Dynamic mechanical behavior of the metal cask lid closure system under extreme impact loads
- Key issue "Leak tightness of the metallic gasket is very sensitive to lid movements"
- Study Flow
  - Assume a big passenger aircraft engine crash into a cask storage facility, its engine penetrates the facility and hit the cask.
  - Estimate the reduced velocity of the penetrating engine.



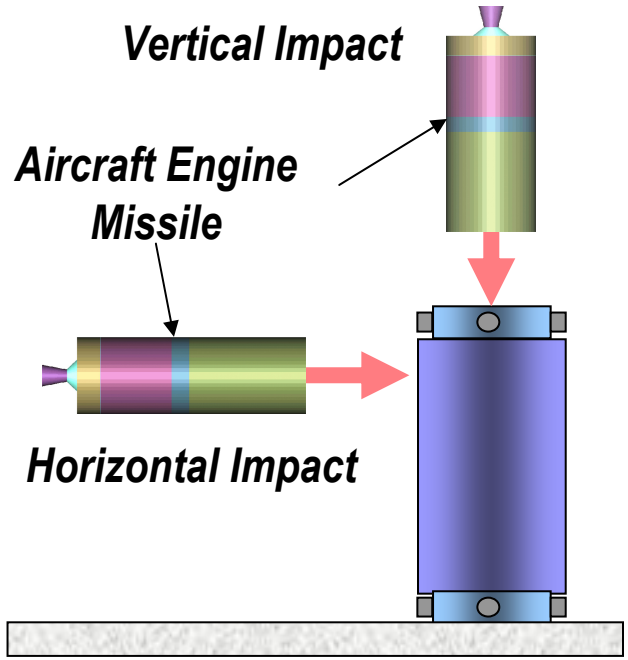
  - Determine the impact load vs. time function of the engine crash on cask.
  - Choose the most critical scenarios for the metal cask.
  - Execute the Impact Analysis by LS-DYNA
  - Execute the Missile Test
  - Estimate the maximum leakage rate from the metal gasket of the cask lid.

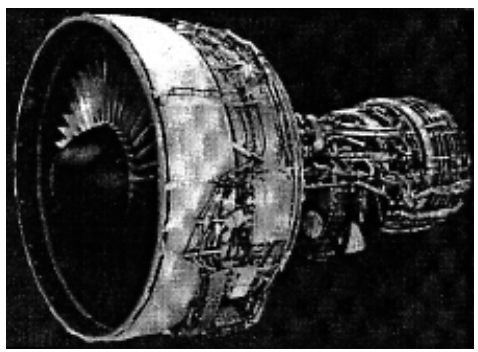
- ***Safety Evaluation of the Sealing Performance of a Metal cask subjected to Vertical and Horizontal Impact Load due to Aircraft Engine Crash by Numerical Method (LS-DYNA)***

- ***Sealing Performance Tests of a Metal Cask with the missile and the lid structure model***

Impact Analysis Condition

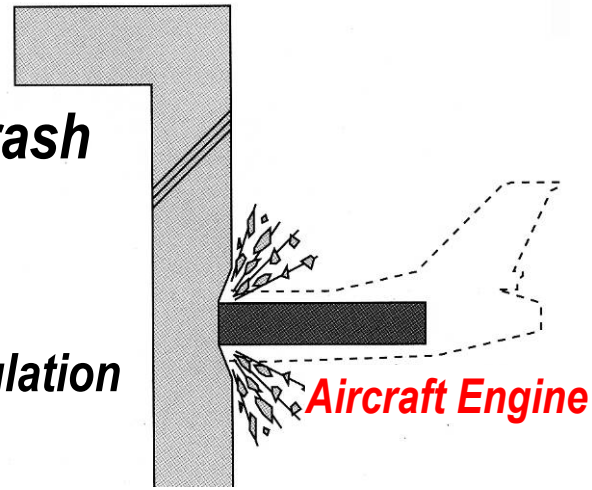
- **Impact scenarios for aircraft engine crash onto the metal cask without impact limiters**
  - Vertical impact onto the lid structure
  - Horizontal impact hitting the cask.
- **Impact Analysis Method**
  - Finite Element Method analysis code
  - LS-DYNA Ver.970.
- **Relevant aircraft engine**
  - Turbo-fan engine (Type GE/CF6-80C2)
    e.g. Boeing747 and Air-Bus 300
  - Length 2.7m, Outer diameter 4.3m, Weight 4.4ton





Impact Velocity

- **Local penetration damage of the interim storage facility building against a relevant aircraft engine crash**
  - **Impact Velocity 90m/sec**
    - **Taking-off, landing speed of the passenger aircraft**
    - **Type C package test conditions in the IAEA Transport Regulation**

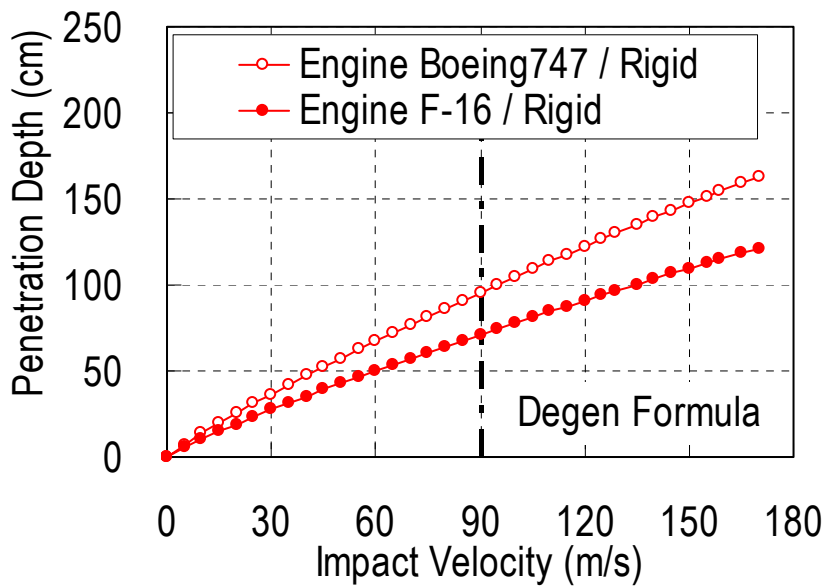


- **Penetration depth**
  - **Degen formula with rigid missile**
    - **In case of the impact velocity 90m/s**
    - **Over 96cm**

- **Reduced velocity of the engine missile**
  - **Design concept of the storage building**
  - **Wall thickness from 0.7m to 1.2m**

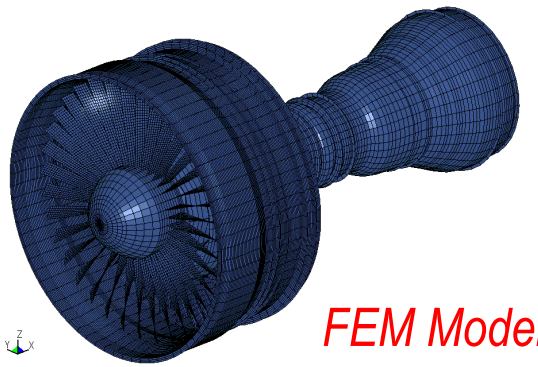
    e.g. after 70cm wall thickness penetration

    Reduced velocity about 60m/s

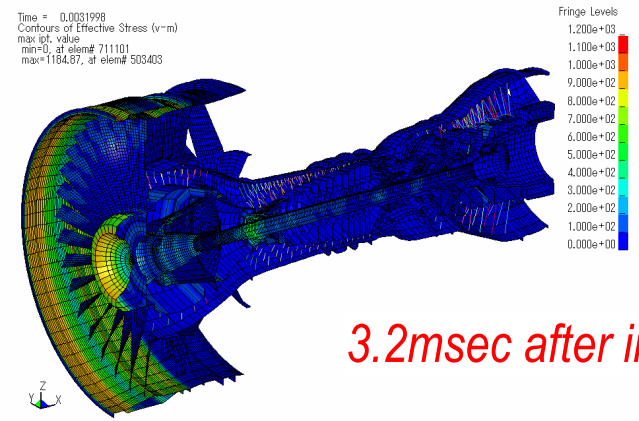


Impact Loading

- **Load vs. time function for the relevant aircraft engine**
  - with reduced velocity 60m/s
  - Impact analysis using LS-DYNA
  - Direct full scale engine model onto hypothetical rigid target

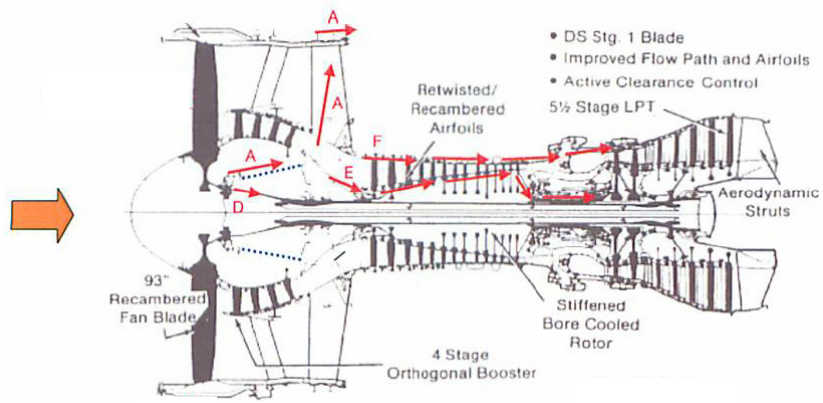


FEM Model



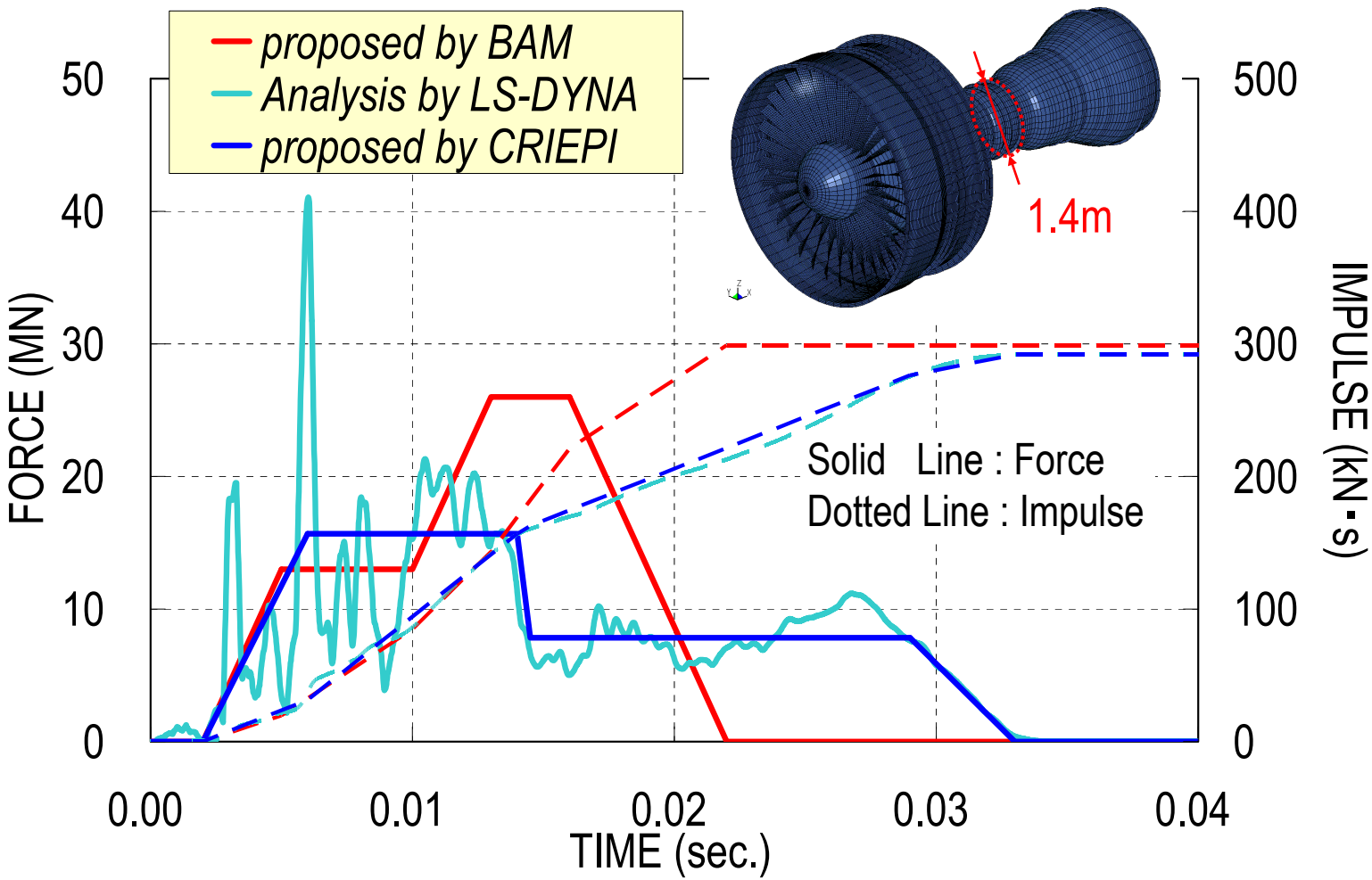
3.2msec after impact

- **Impact loads affected by**
  - Buckling of the nose corn
  - Interactive force between high and low pressure turbines
  - Plastic deformation of the rotor spaced in the center of the engine



Loading Function

- ***Representative diameter of the impact load contact circular area was set to 1.4m considering the stiffness distribution of the relevant aircraft engine***



Target Storage Cask

- **Metal Cask including 21 PWR fuel assembly**

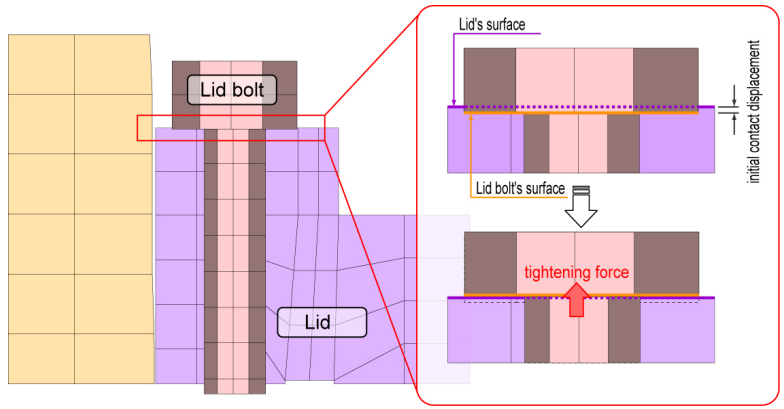
Item	Dimension
Height	5.4 m
Outer Diameter	2.5 m
Weight	119 ton

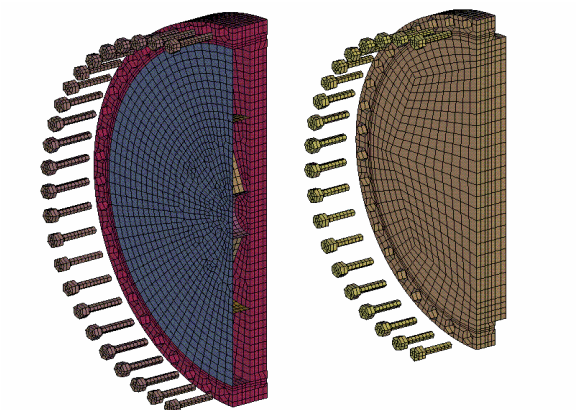
- **Double lid structure with double type metal gasket made of aluminum coating material**

Lid	Section diameter of the gasket	Nominal gap at one side
Primary	5.6 mm	1 mm
Secondary	10 mm	0.5 mm

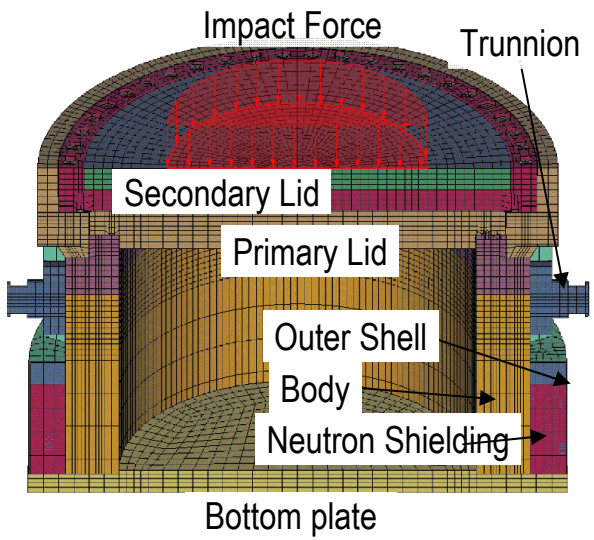
Analysis model

- **Analytical condition**
  - Friction coefficient
  - Initial tightening lid bolt force
    - Equivalent to tightening torque of 2400 N-m
    - Set by the forced initial contact displacement between the lid bolt and lid flange before loading
  - Gasket reaction force
  - Inner pressure

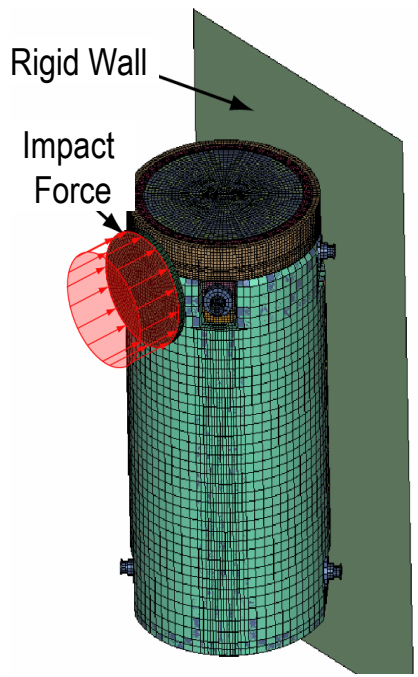




Lid Bolt



Vertical Impact

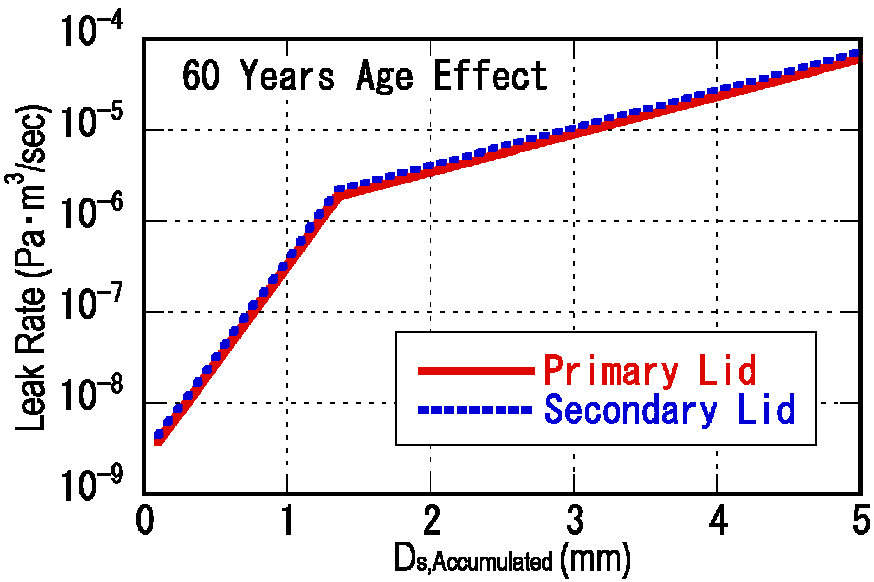


Horizontal Impact

Containment Evaluation Criteria (1)

- **Proposed by Japan Nuclear Energy Safety Organization (JNES)**
  - A series of leakage tests using scale models
  - Double type aged aluminum coating metal gasket (Section Dia. 10mm)
  - 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 DS,Accumulated if the lid system would satisfy the following conditions.
    - No plastic deformation in the lid system
    - No considerable lid opening
    - No considerable loss of the lid bolt's torque

[Relationship between the leak rate and the accumulated relative displacement]

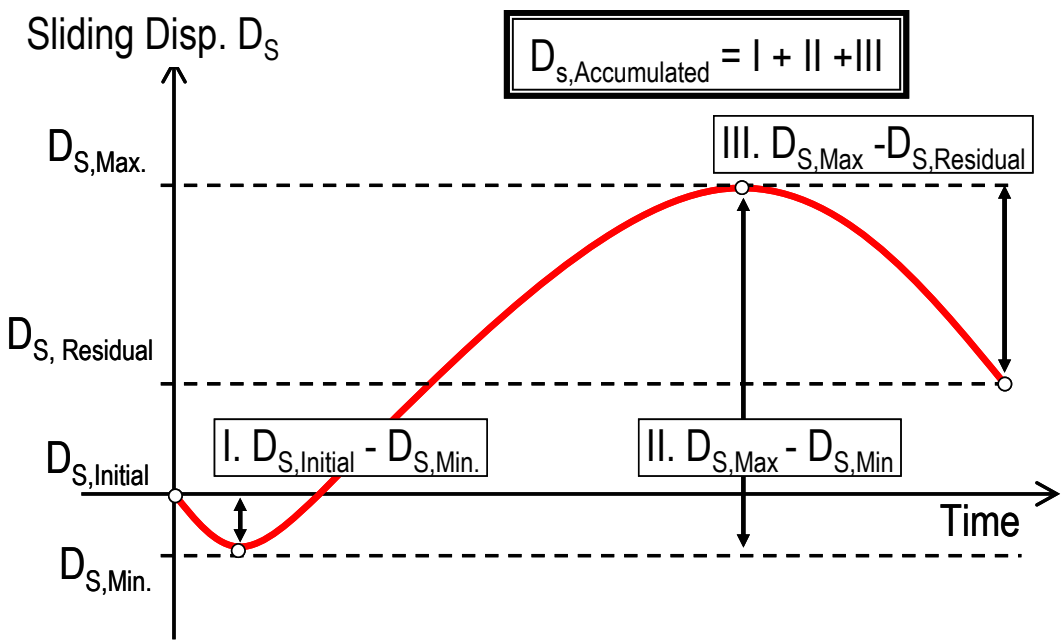


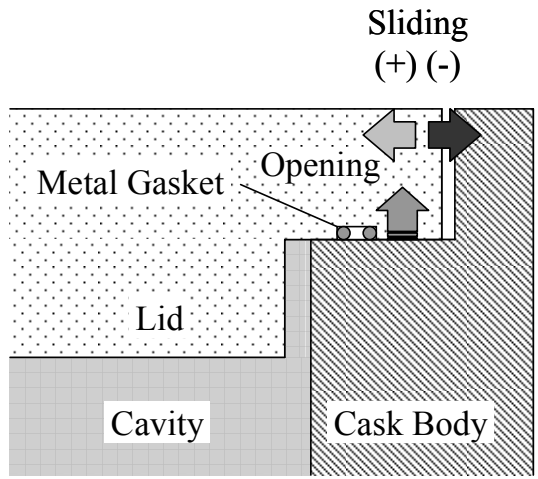
Containment Evaluation Criteria (2)

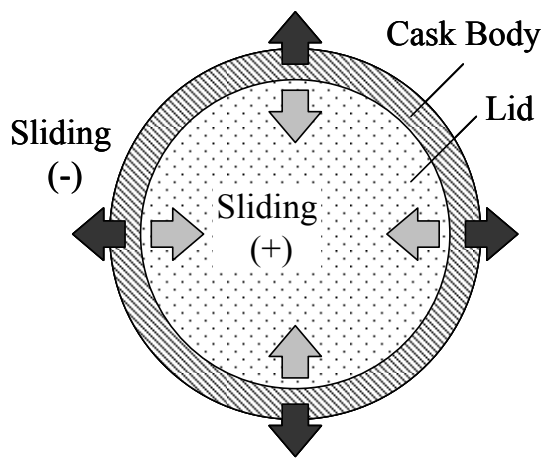
Definition of Sliding or Opening of the Lids

- Relative displacement of the metallic gaskets parallel or normal to the flange
- Accumulated relative displacement

$$D_{S,Accumulated} = 2 \cdot (D_{S,Max} - D_{S,Min}) - (D_{S,Residual} - D_{S,Initial})$$





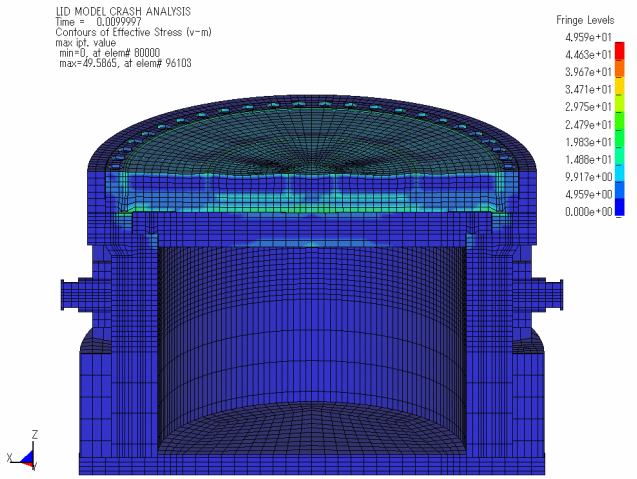


Vertical Impact Analysis (1)

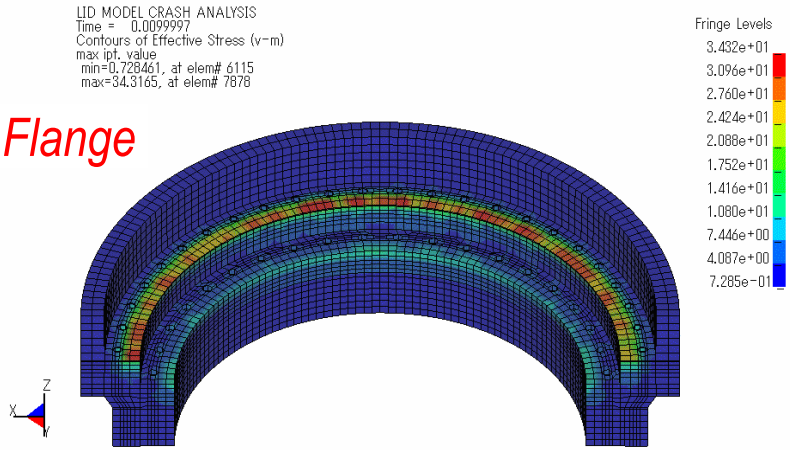
Mises Stress Distribution

Plastic deformation was generated in the 2nd lid flange

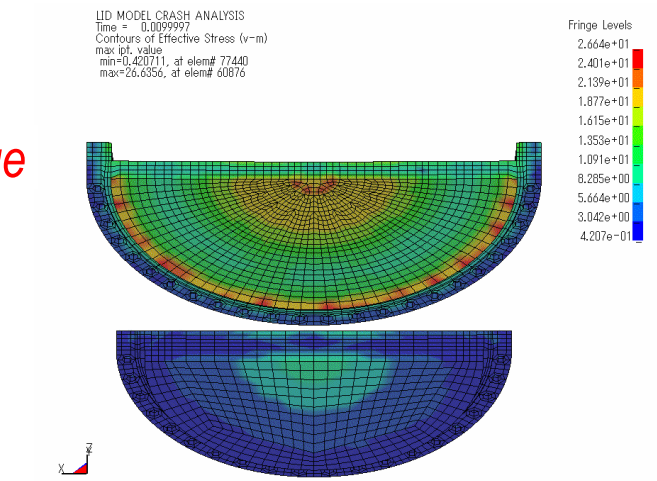
Birdview



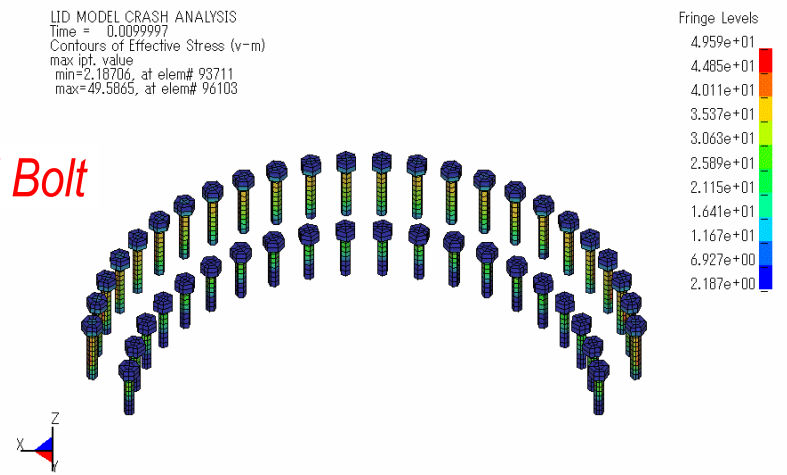
Body Flange



Lid Flange



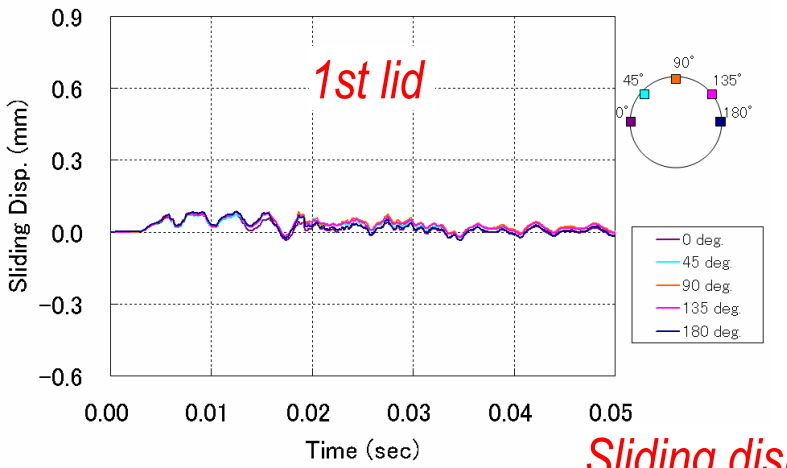
Lid Bolt

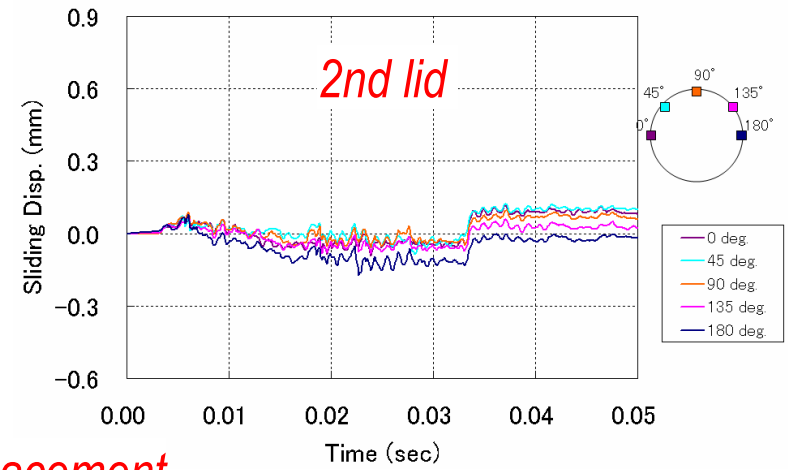


Vertical Impact Analysis (2)

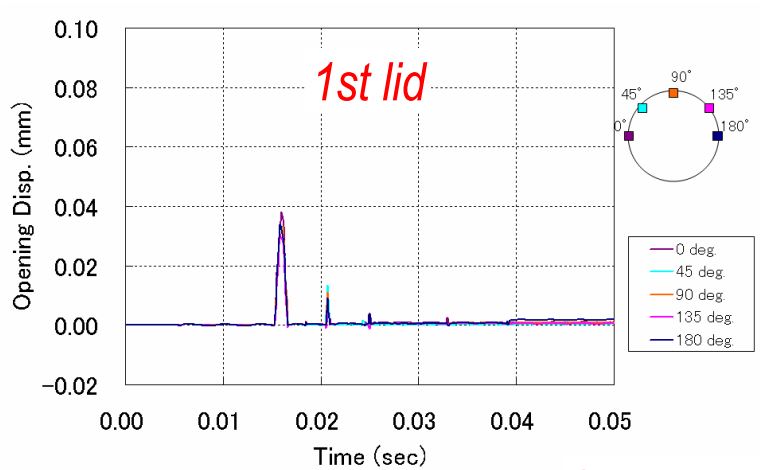
Lid Movement

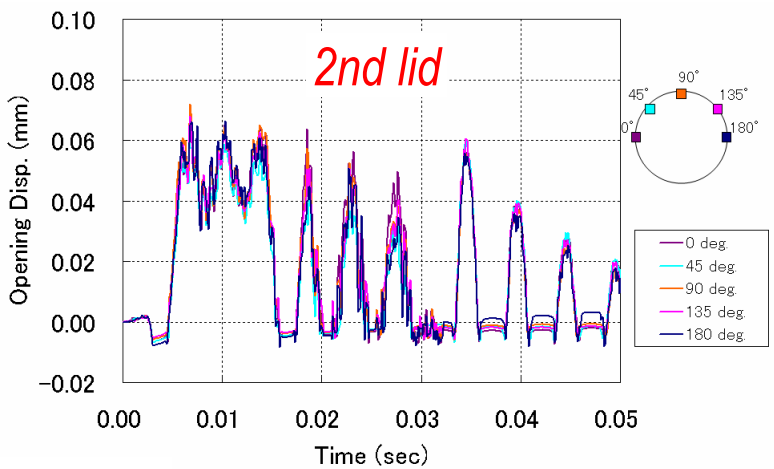
Considerable lid opening displacement was generated in 2nd lid





Sliding displacement





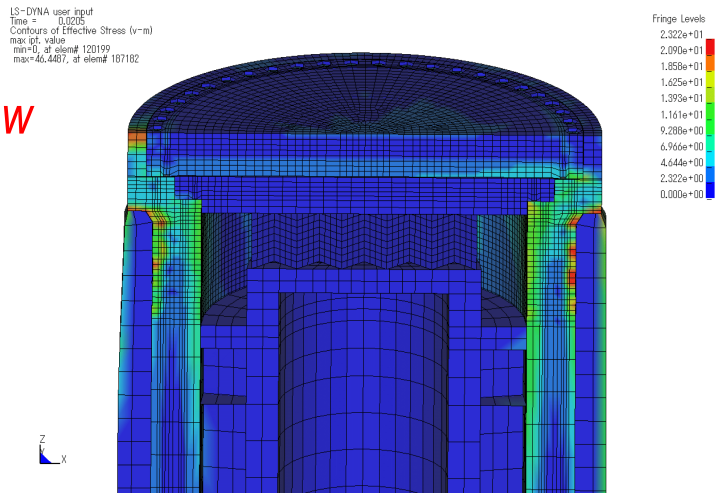
Opening displacement

Horizontal Impact Analysis (1)

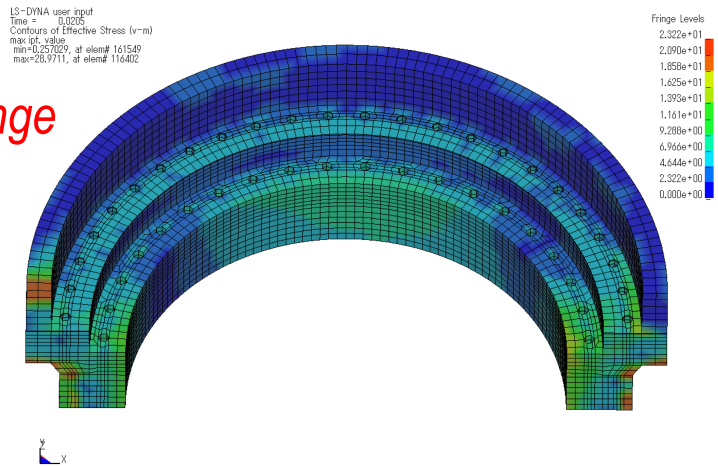
Mises Stress Distribution

- There is no plastic deformation

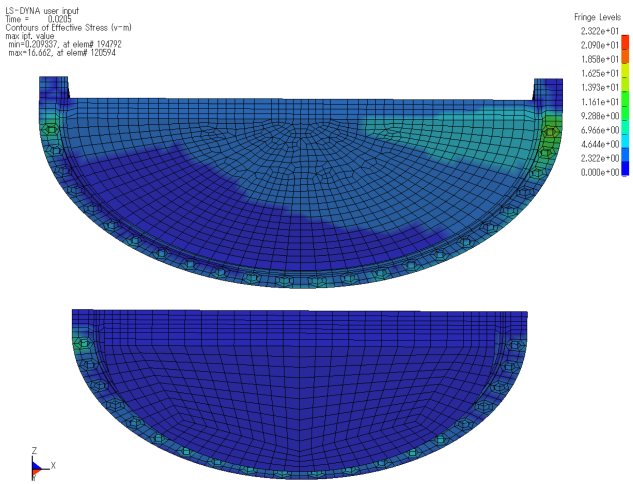
Birdview



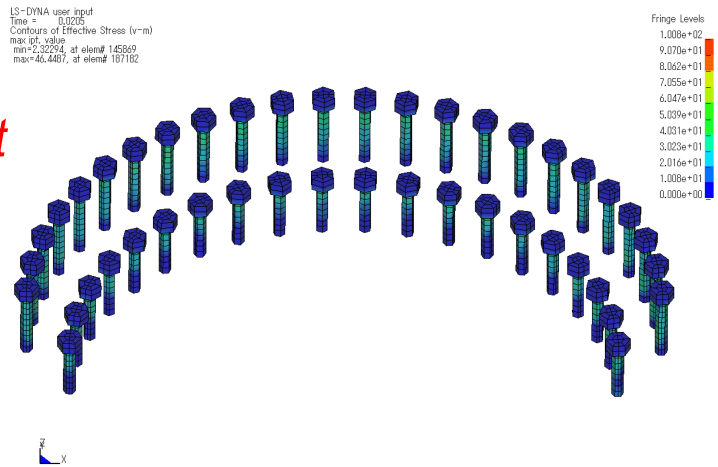
Body Flange



Lid Flange



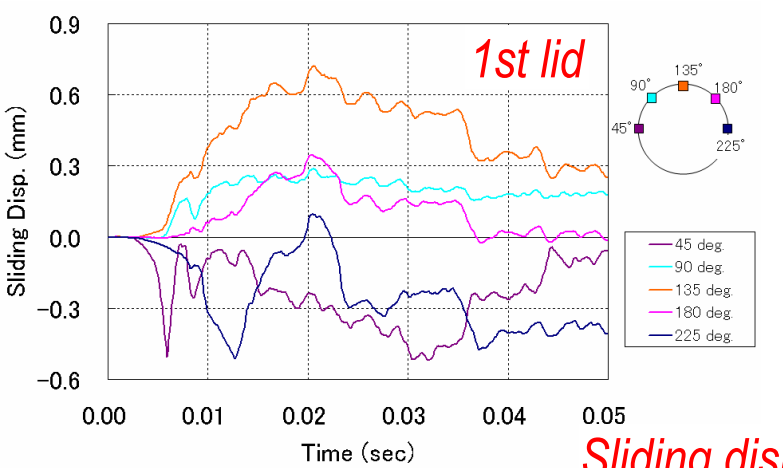
Lid Bolt

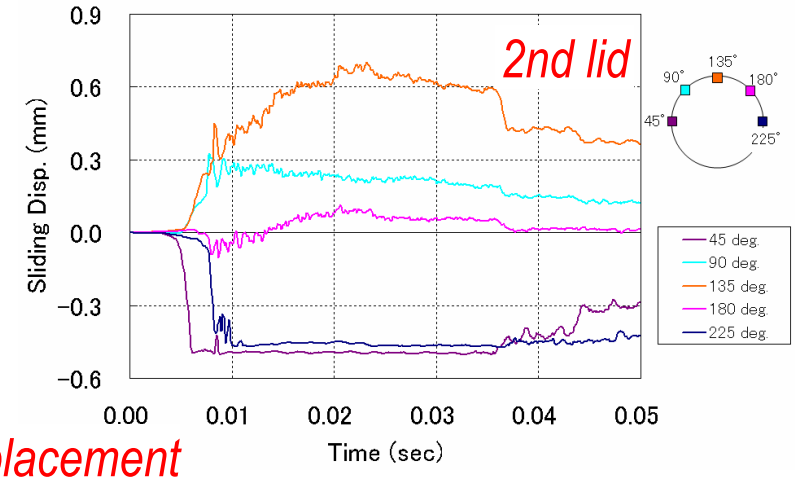


Horizontal Impact Analysis (2)

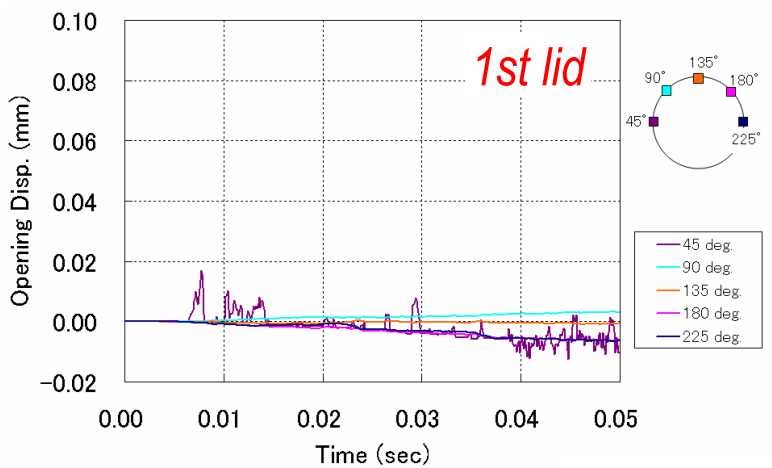
Lid Movement

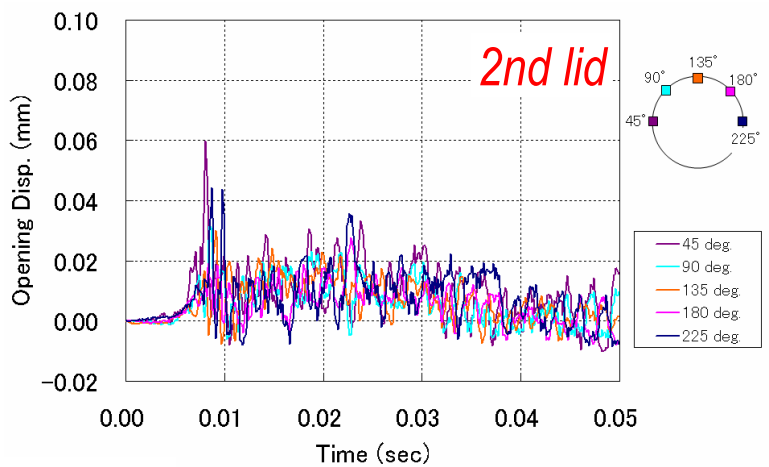
Large sliding deformations of the 1st and 2nd lids were generated





Sliding displacement





Opening displacement

Evaluation of Leak-tightness

- **Leakage rate from the primary lid might be considerably low**

  (less than 1.0×10^{-5} Pa·m^3/s)

- **Loss of the inner pressure in the cask might be avoided**

Part \ Event		Vertical impact	Horizontal impact
Primary lid	Sliding*	0.23mm	1.70mm
	Opening	0.04mm	0.02mm
	Status**	None	None
Secondary lid	Sliding*	0.52mm	1.77mm
	Opening	0.07mm	0.06mm
	Status**	No plastic	No plastic
Estimated Leak Rate (Pa·m^3/s)	Primary lid	<1.0×10^{-5}	<1.0×10^{-5}
	Secondary lid	Loss	<1.0×10^{-5}

* Accumulated Sliding Displacement

** Generation of the plastic deformation in the lid system

Summary

- ***Analyses of two impact scenarios for aircraft engine crash onto the metal cask without impact limiters, a vertical impact onto the lid structure and a horizontal impact hitting the cask, have been executed to clarify the extent of reducing the cask integrity and the leakage increase.***

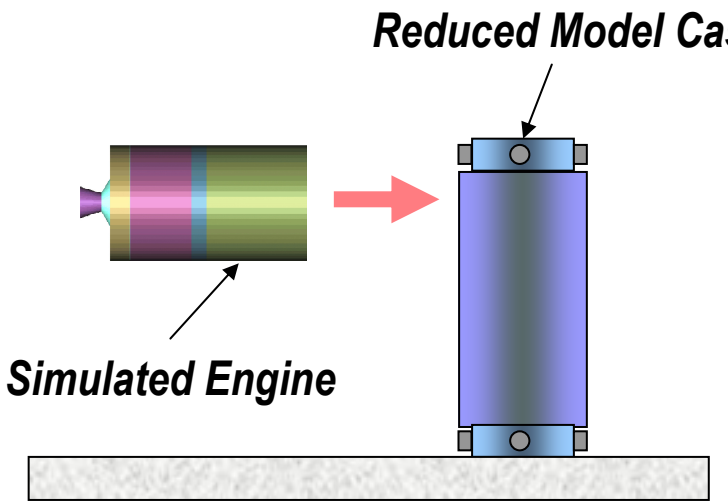
- ***Leakage rates were evaluated in connection with the determination of the accumulated relative displacements between the metallic gaskets and the flange.***

- ***After the lid behaviors in each scenario have been evaluated, it was found that although the secondary lid might lose the leak-tightness in case of the vertical impact, the leakage rate from the primary lid might be low and the loss of the inner pressure inside the cask might be avoided in the extreme impact loading conditions.***

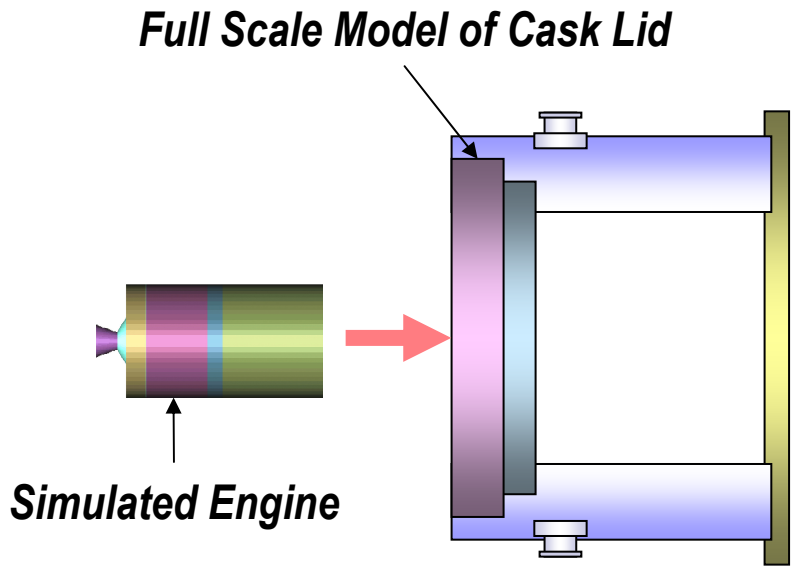
- ***Safety Evaluation of the Sealing Performance of a Metal cask subjected to Vertical and Horizontal Impact Load due to Aircraft Engine Crash by Numerical Method (LS-DYNA)***

- ***Sealing Performance Tests of a Metal Cask with the missile and the lid structure model***

Test Plan for Airplane Crash Tests



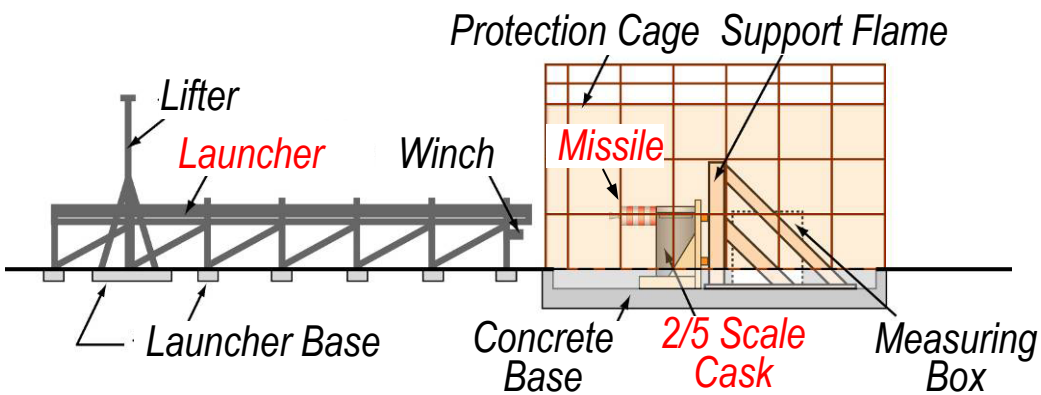
Horizontal impact test of 2/5 reduced cask model crashed by a simulated engine (Jan. 2008)



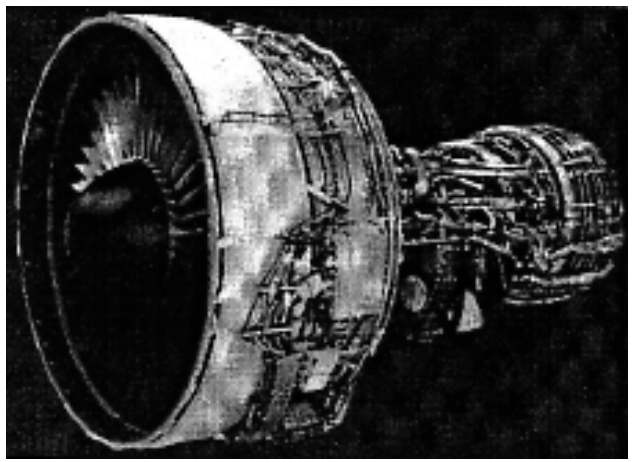
Vertical impact test of full scale model cask lid crashed by a simulated engine (Nov. 2008)

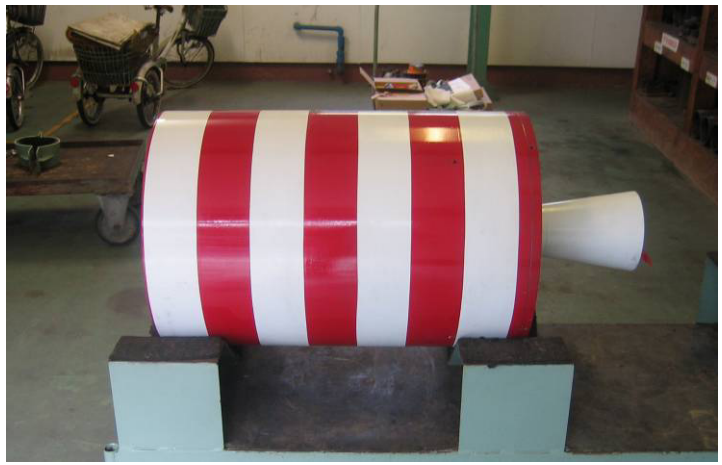
Horizontal Impact Test

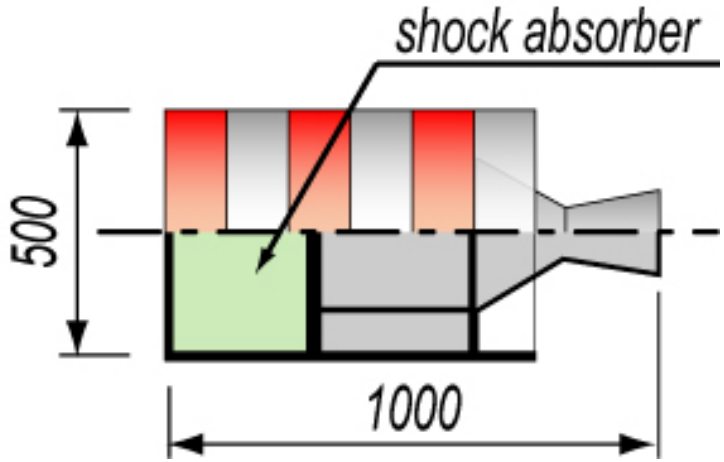
- **Objective**
  - Verification of simulation code to estimate the behavior of a cask under extreme impact load
- **Test Apparatus**
  - 2/5 scale metal cask for horizontal impact test
  - Full-scale metal cask lid structure
  - Deformable missile
  - Test apparatus in the open air



Missile



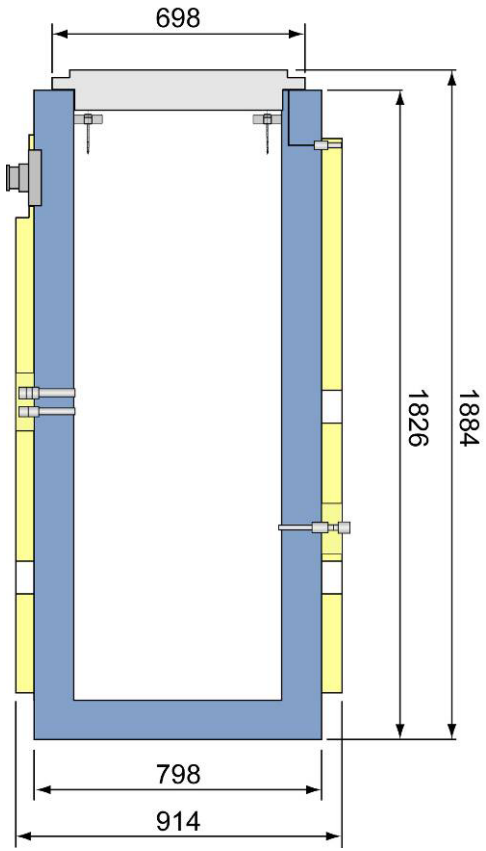




- Weight
  - 4400kg
- Velocity
  - 60m/s

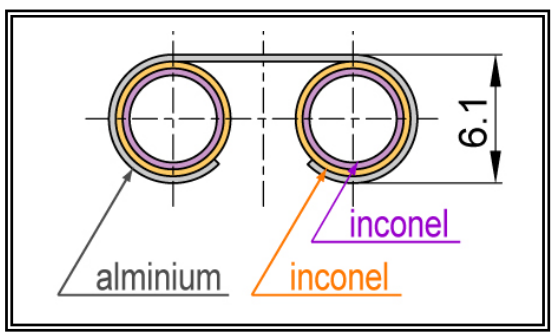
- Weight
  - 316kg
- Velocity (measured Value)
  - 57.3 m/s

2/5 scale cask



Body

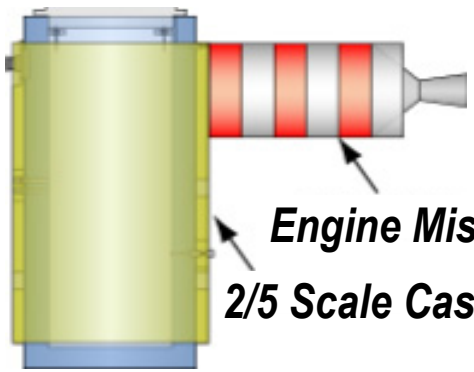
Lid

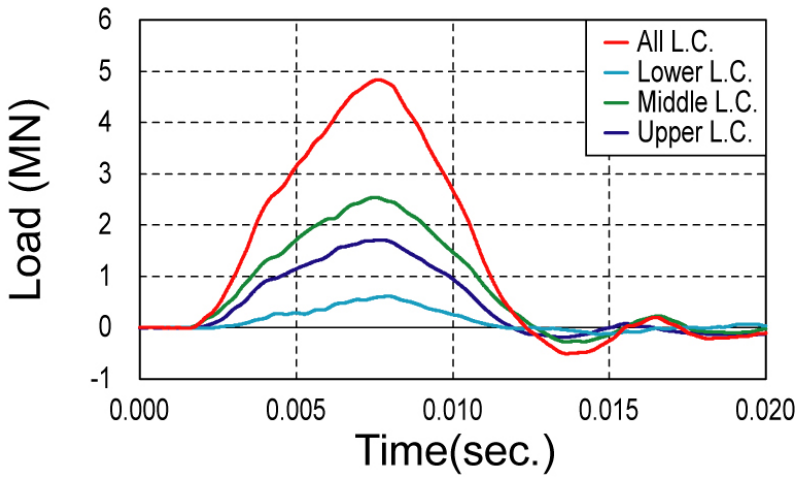


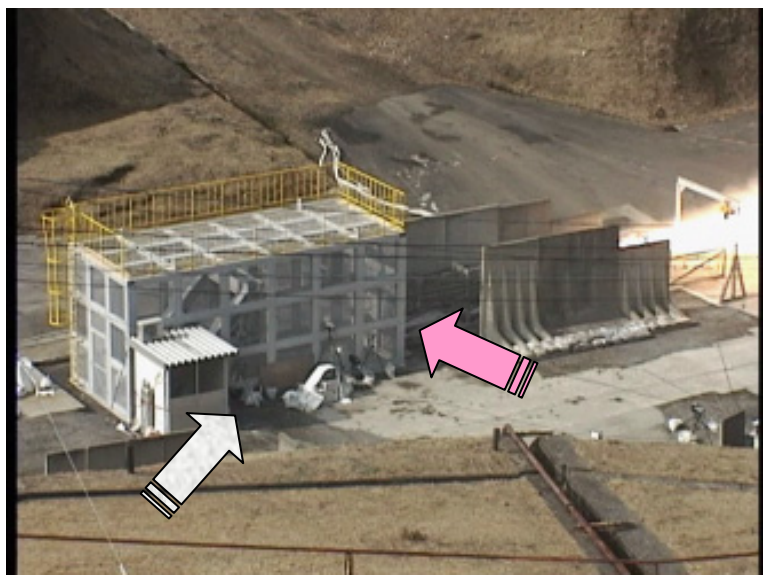
- **Structure**
  - 2/5 scale metal cask
  - Single lid
- **Weight**
  - Body : 4.17 ton
  - Lid : 0.29 ton
- **Gasket**
  - Double Aluminum Metal Gasket (C.S.Dia. 6.1mm)
  - Aging effect (over 30hours under 175°C

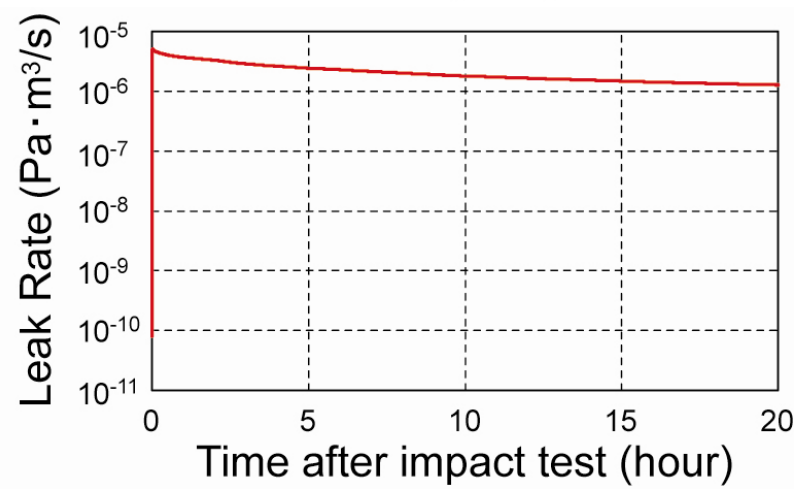
Impact Test Results (1)

- The peak value of total reaction forces was 485kN
- Measured leak rate was under 1.0×10^{-5} Pa·m³/s within the permissible value for a transport cask.



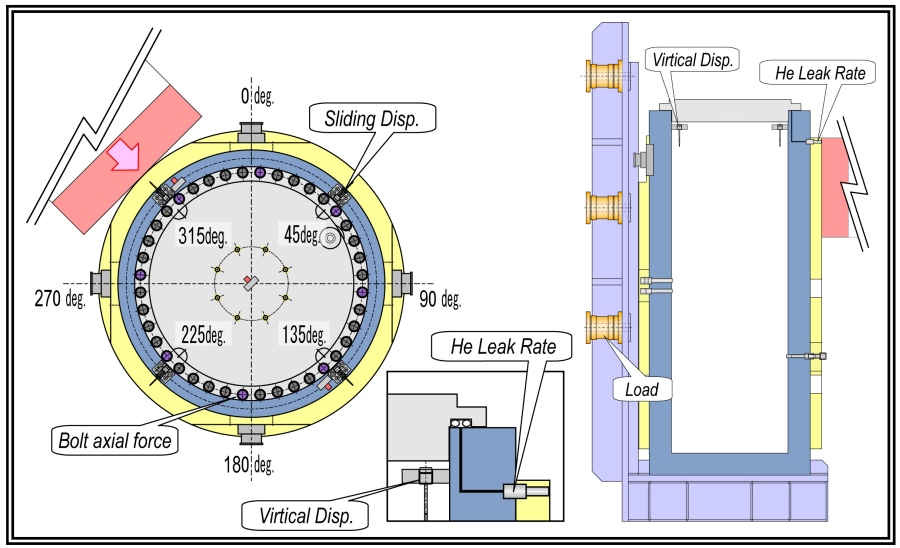




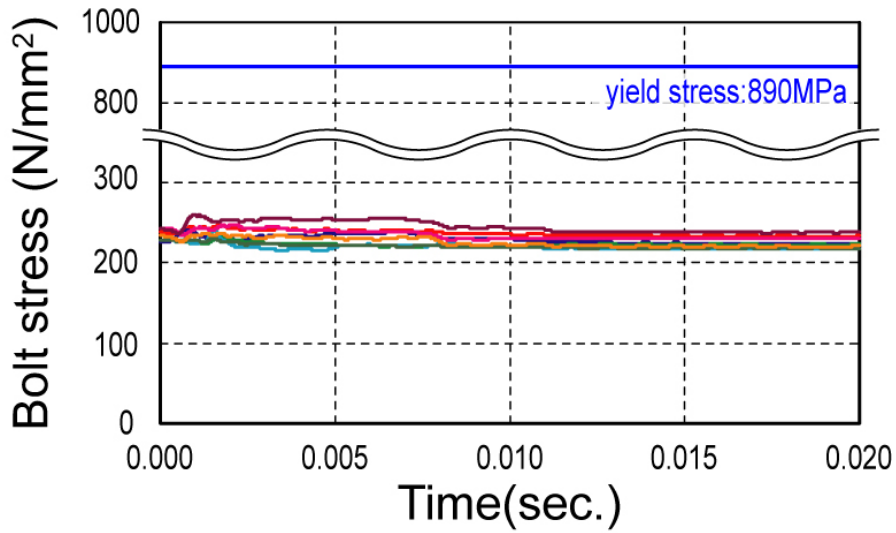


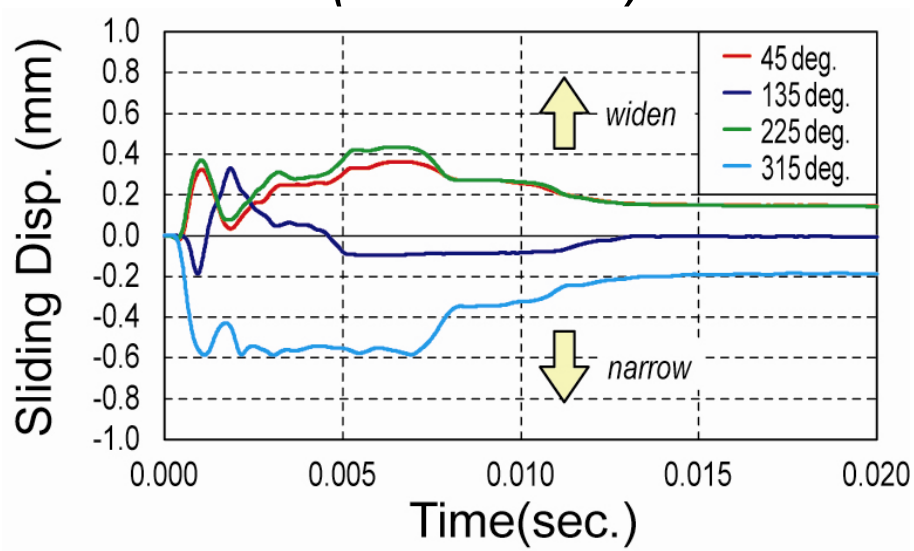
Video High Speed Camera

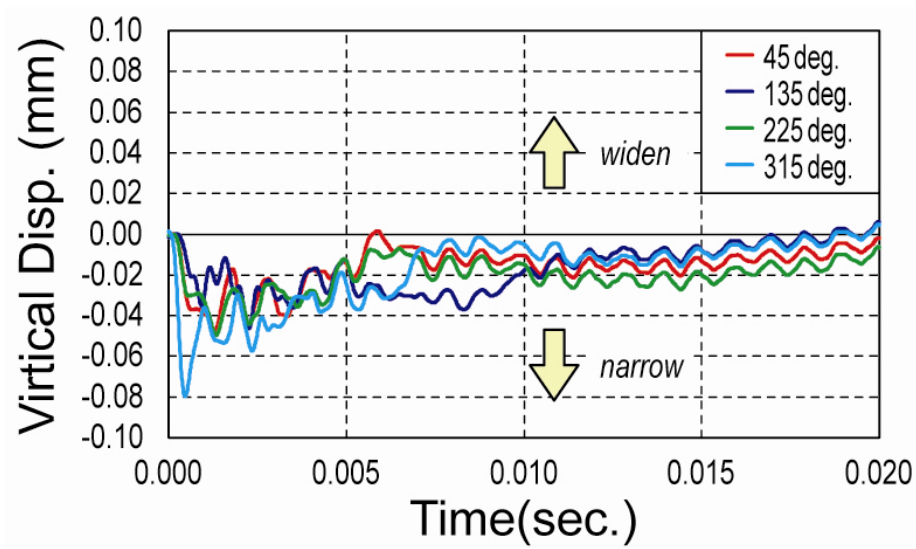
Impact Test Result (2)



(Measurement)



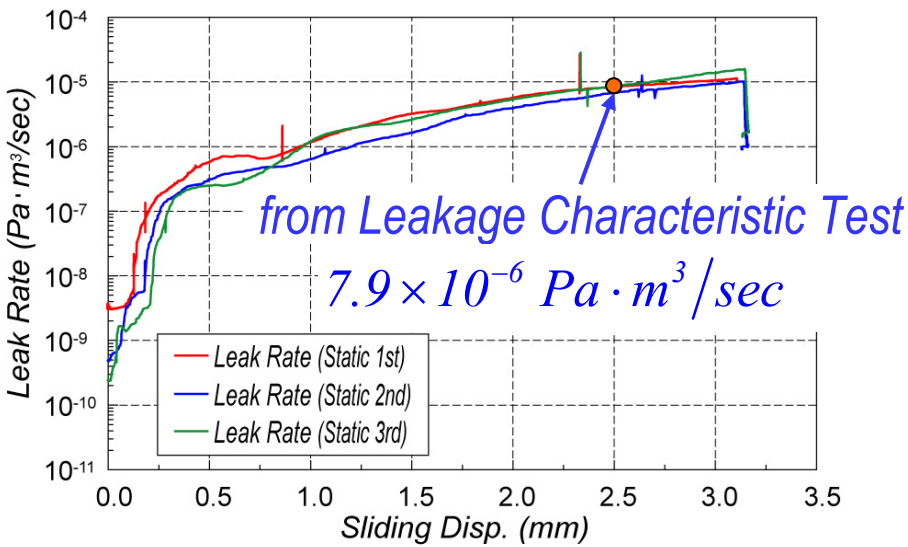




Similarity Law Employed in the Scale Model Test

Parameter	Dimension	Ratio	Typical quantities
Length	L	$L_m/L_p = 1/s$	Missile/Cask dimension
Mass	M	$m_m/m_p = 1/s^3$	Missile/Cask mass
Time	T	$T_m/T_p = 1/s$	Impact Duration Time
Velocity	LT^{-1}	$v_m/v_p = 1$	Missile velocity
Force	MLT^{-2}	$F_m/F_p = 1/s^2$	Impact force Reaction force
Sealability	ML^2T^{-3}	$Q_m/Q_p = 1/s^2$	He Leak Rate

s: geometrical scale factor, p: prototype, m: scale model



Estimated Leak rate of Prototype Cask

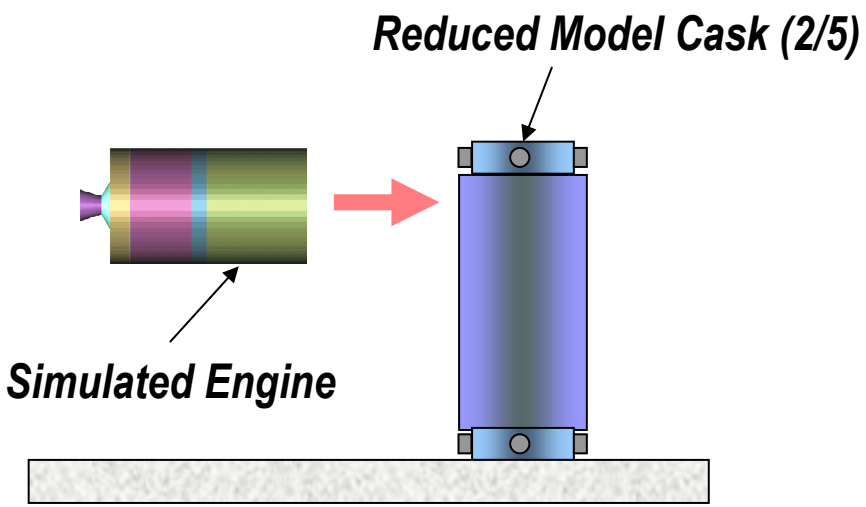
From Similarity Law

$$Q_p = \frac{Q_m}{(1/s^2)} = \frac{4\times10^{-6}}{(2/5)^2}$$

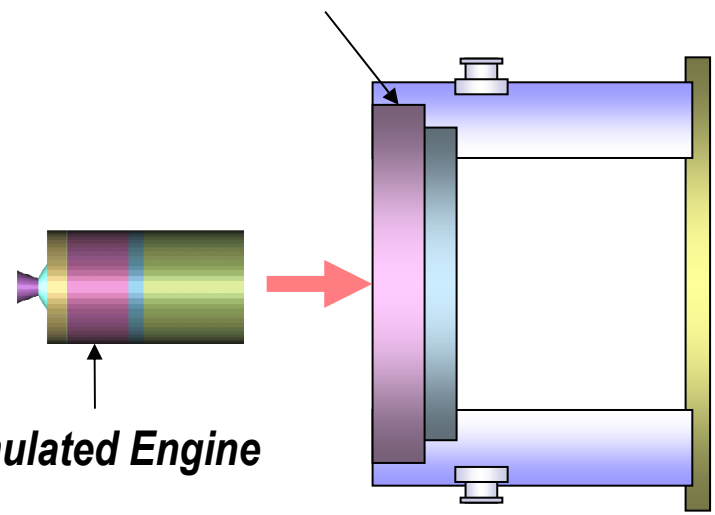
$$= 2.5\times10^{-5}\ Pa\cdot m^3/sec$$

The applicability of the similarity law was confirmed through this test.

Test Plan for Airplane Crash Tests



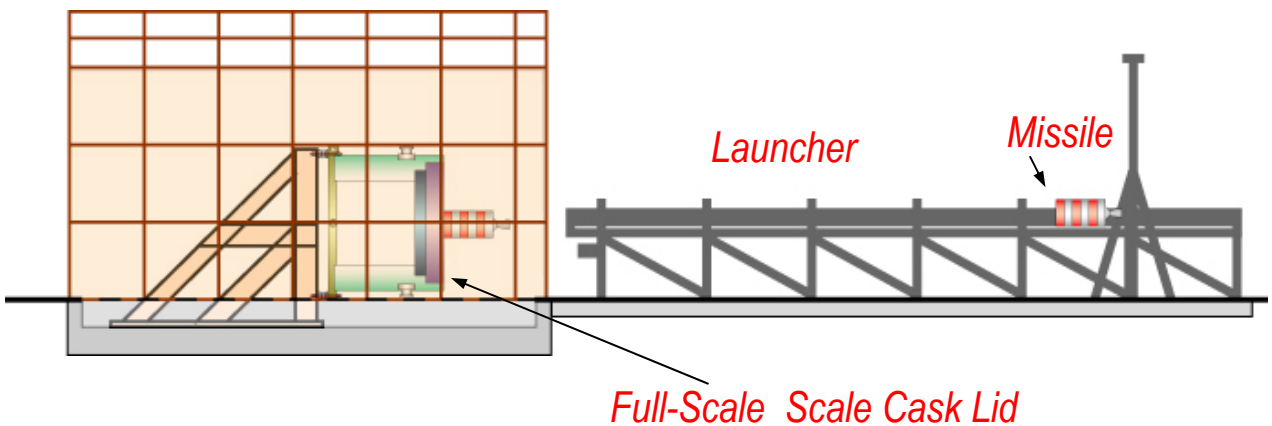
Horizontal impact test of 2/5 reduced cask model crashed by a simulated engine (Jan. 2008)



Vertical impact test of full scale model cask lid crashed by a simulated engine (Nov. 2008)

Vertical Impact Test

- **Objective**
  - Verification of simulation code to estimate the behavior of a cask under extreme impact load
- **Test Apparatus**
  - Full-scale metal cask lid structure for vertical impact test
  - Deformable missile
  - Test apparatus in the open air



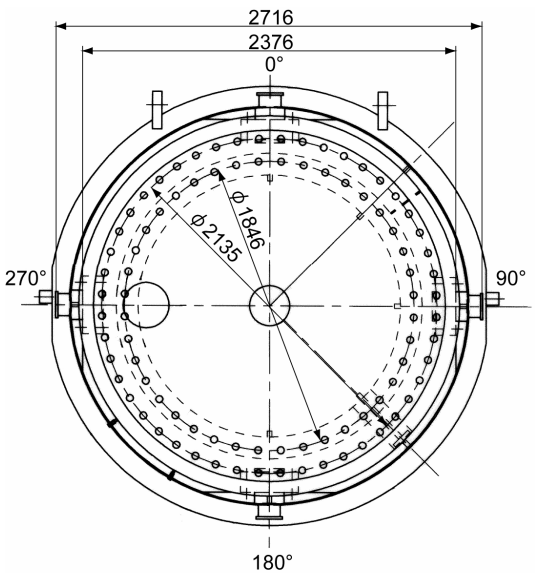
Full-scale metal cask lid structure

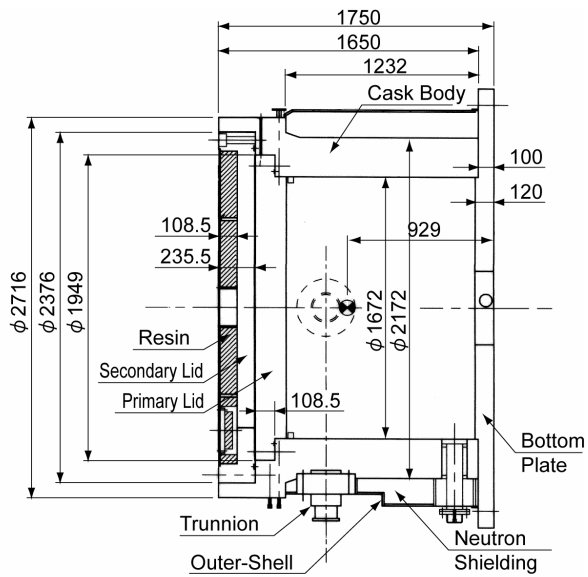
Specification

- Double lids
- Outer Diameter 2.5m, Height 2m
- Weight : Body 28ton
  Primary lid 4ton, Secondary Lid 4ton
- Metal gasket : Double Al Gasket

(Full-Scale Cask)

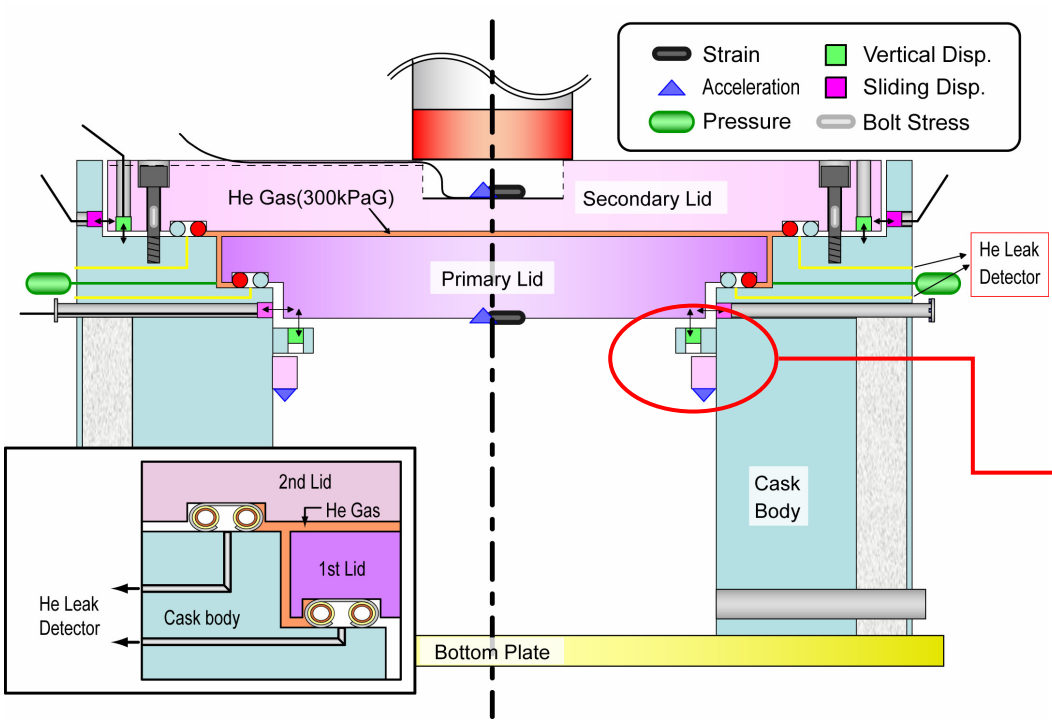
(Test Model)

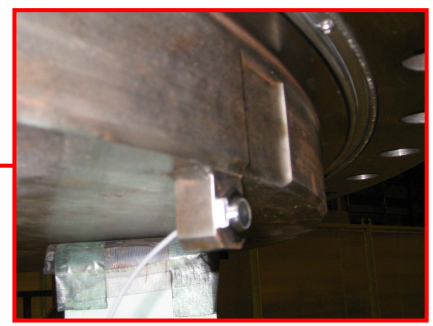




Measurement items

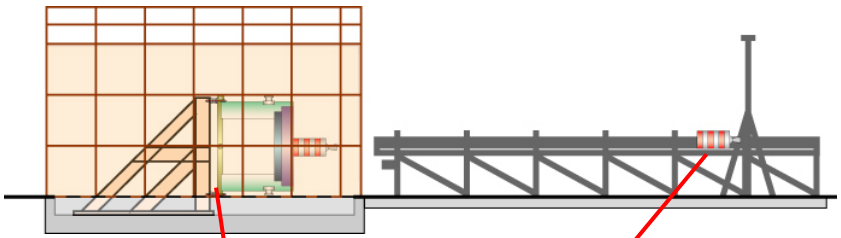
- Impact Load
- Lid Bolt Stress
- Sliding/Vertical Lid Disp.
- Inner body Strain
- Acceleration
- Leak Rate
- Inner Pressure between two lids

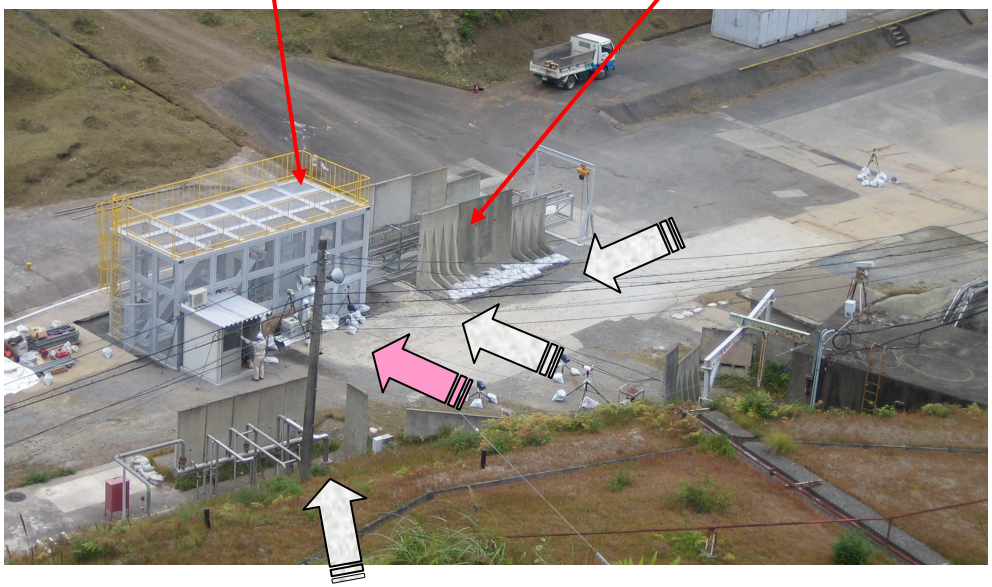


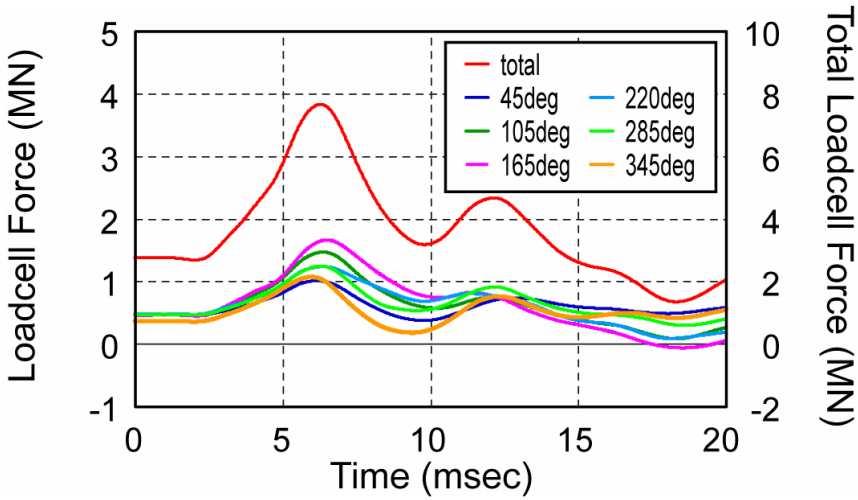


(Eddy Current Sensor)

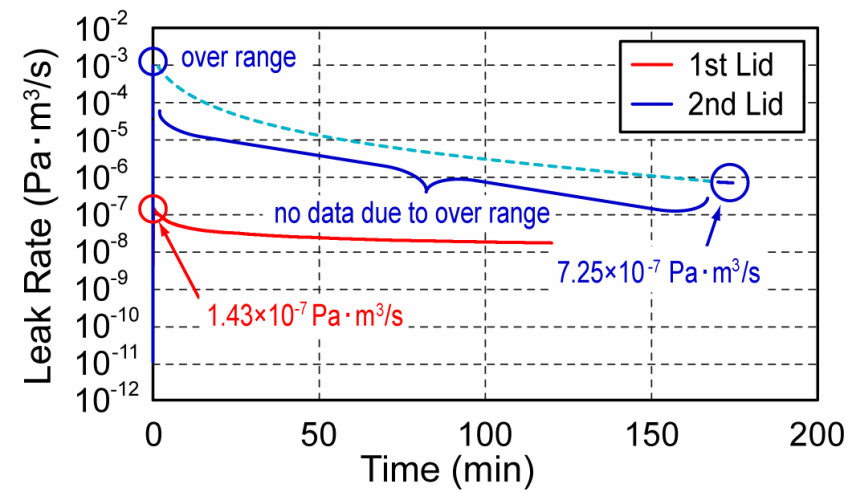
Vertical Impact Test







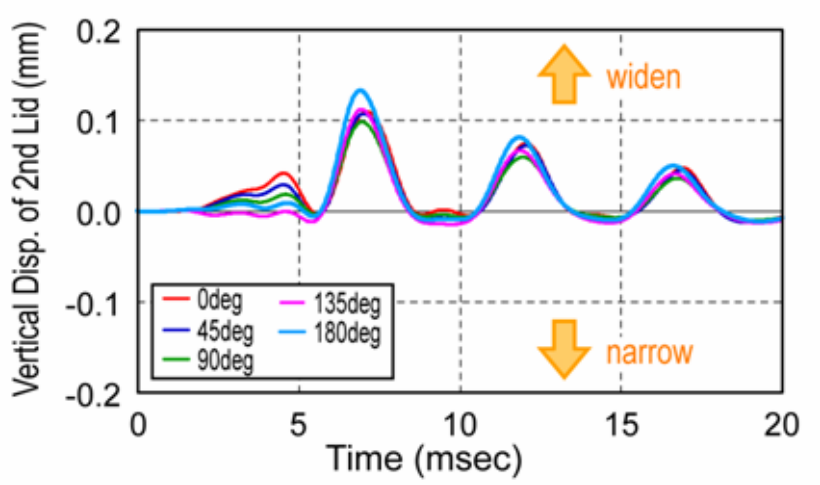
(Impact Force :Load Cell)



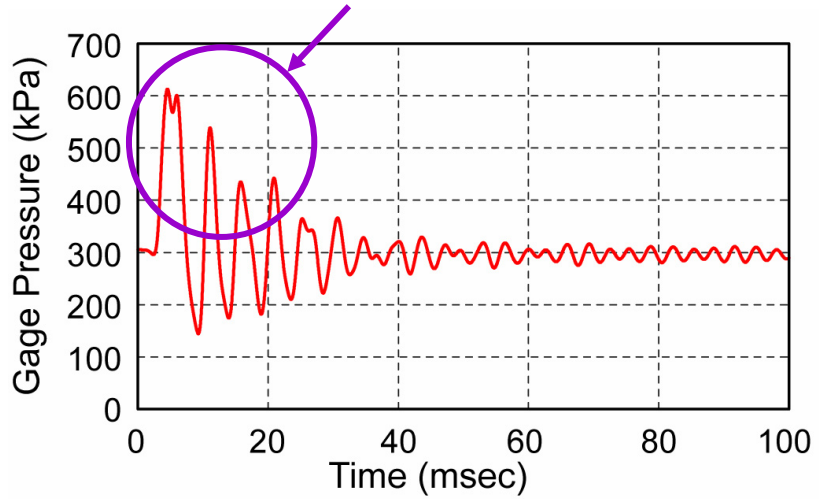
(He Leak Rate)

Vertical Impact Test Results

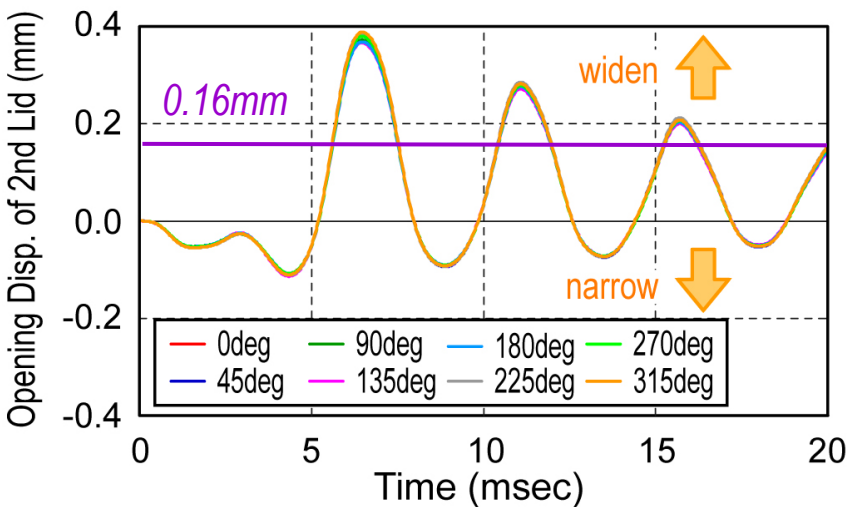
An instantaneous leakage was occurred.



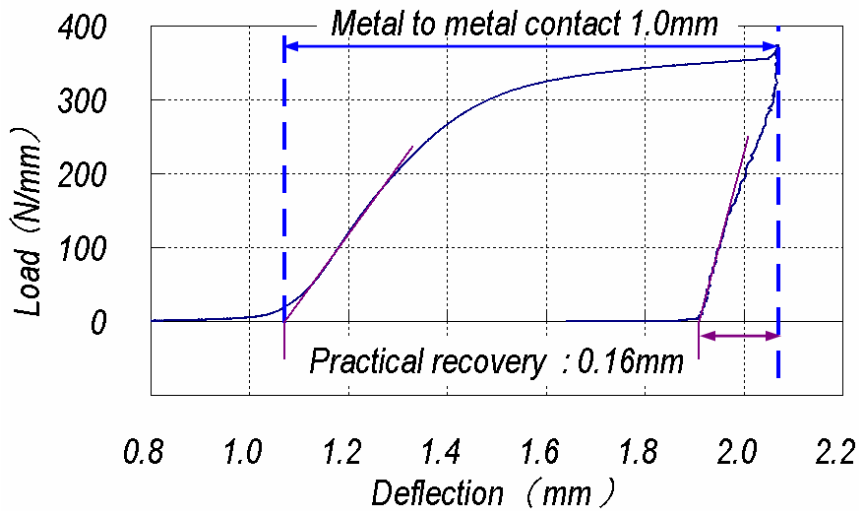
(Lid Displacement :2nd lid)



(Inner Pressure)



(Gasket Opening by LS-DYNA)



(Metal Gasket : Load vs. Deflection Curve)

Summary

- ***The experimental study for aircraft engine crash onto the metal cask without impact limiters, impact tests using full-scale lid structure and engine missile, have been executed to clarify the extent of reducing the cask integrity and the leakage increase.***
- ***After the lid behaviours have been evaluated, it was found that the leakage rate from the lid would be low and release of radioactive substances in the cask would be avoided in the extreme impact loading conditions.***