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EVALUATION OF SEALING PERFORMANCE OF METAL GASKETS USED IN DUAL PURPOSE METAL CASK UNDER NORMAL TRANSPORT CONDITION CONSIDERING AGEING OF METAL GASKETS UNDER LONG-TERM STORAGE

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ABSTRACT

If a metal gasket used in a dual purpose metal cask was subjected to high temperature for a long term, the residual linear loads and total spring back distance of a metal gasket might decrease due to the creep deformation of the outer jacket made of soft metal. Therefore, when the cask would receive the vibration force during normal transport operation on land or sea, the sealing performance of metal gaskets might be affected.

In this paper, to examine the compressive creep characteristics of the outer jacket made of a 99.5% pure aluminum with a heat treatment, the compressive creep tests were executed under various levels of stresses, temperatures and loading durations. Based on these test results, a creep constitutive model was proposed. Moreover, in order to establish the numerical methodology of the ageing phenomena on sealing performance of the metal gasket over the long term, the compressive creep characteristics of the aluminum were introduced in the Finite Element Method code(ABAQUS), as a user subroutine. A relaxation analysis was performed considering actual over-all gasket complex configuration to calculate residual linear loads and total spring back distance of the metal gasket for a storage period of 60 years.

In order to evaluate the deformation response of the metal gasket subjected to the acceleration profile measured during an actual sea transport, the impact analysis by LS-DYNA code was executed. As a result, it was found that the opening displacement of the gasket was negligible as compared with the evaluated spring back distance of metal gasket used for 60 years.

INTRODUCTION

Transport and storage dual purpose metal casks of spent nuclear fuel used in nuclear power plants will be stored in interim storage facilities for a long term. The casks usually use metal gaskets for safety and steady sealing performance for the long term as shown in Fig.1. Metal gaskets generally consist of helical metal spring, inner and outer metal jackets. The outer jacket is made of flexible metal material, such as aluminum or silver, and aluminum is adopted to outer jackets for adhesion between the gasket and lids or cask body surface in Japan. As high temperature due to decay heat of spent nuclear fuel will impose to the seal area of cask lid systems during storage, the high temperature can accelerate ageing, such as creep deformation of the outer jacket and corresponding relaxation of the linear load of the gasket complex [1]. Therefore, when the cask and the heated gasket received the vibration force during normal transport operation on land or sea, the sealing performance of metal gaskets might be affected [2].

To evaluate the sealing performance of the metal gasket used for long term at high temperature, it is important to comprehend creep characteristics of aluminum at high temperature under compressive loading. In this paper, the compressive creep characteristics were obtained by compressive creep tests using aluminum at 6 different temperatures under several stresses. In order to establish the numerical methodology of the ageing phenomena on sealing performance of the metal gasket over the long term, the compressive creep characteristics of the aluminum were introduced in the Finite Element Method code(ABAQUS), as a user subroutine. The relaxation analysis using the subroutine was executed considering the actual over-all gasket complex configuration to calculate residual linear loads and spring back distance of the metal gasket used for 60 years. Moreover, to evaluate the deformation response, such as opening displacement, of the metal gasket subjected to acceleration measured during actual sea transportation, the impact analysis by LS-DYNA code was executed. Finally, the influence due to the vibration during sea transportation on the sealing performance was evaluated by comparing the opening displacement with the spring back distance of the gasket.

1. NUMERICAL METHOD FOR GASKET SEALING PERFORMANCE

It is important to grasp creep characteristics of outer jackets sufficiently in order to evaluate the sealing performance of the gasket used for a long term at high temperature. In this chapter, the compressive creep tests to obtain the creep characteristics of aluminum used as outer jacket are presented. A numerical methodology of the sealing performance of the gasket considering the creep characteristics using a finite element method code proposed. It demonstrates the applicability by comparing with the CRIEPI's relaxation test results in the past.

Moreover, the residual linear load and spring back distance of the gasket used for 60 years are evaluated by the proposed numerical methodology.

1.1 Compressive Creep Tests of Aluminum

(1) Test Specimen and Test Equipment

To evaluate the relaxation characteristics of the metal gasket complex, a compressive creep tests at high temperature were executed using a 99.5% pure aluminum with heat treatment at about 250°C for 4 hours. The shape of test specimens was columnar shape with a diameter of 9mm and a height of 13.5mm. The test equipment had displacement gauges, a thermostat (max 250°C) and weights (300-3000N) and could give the test specimen applied stresses at high temperature. Thermostat temperature was adjusted by PID control system within ±3°C referring the Japanese material standard JIS Z 2271 [3]. The creep strain of the test specimen was measured as compressive deformation by displacement gauges. The test specimen and the test equipment are shown in Fig.2.

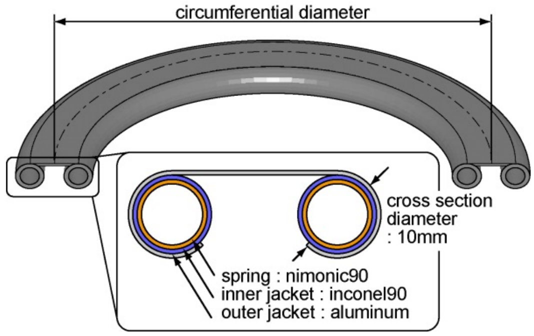
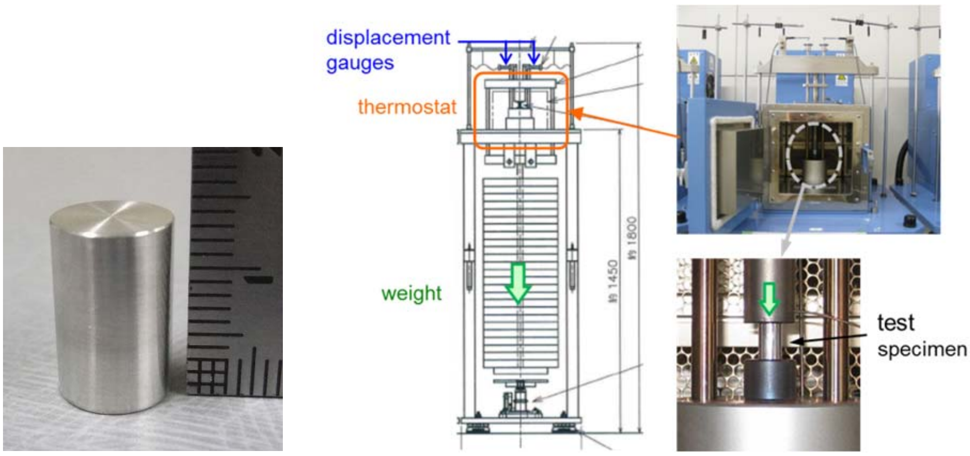


Fig.1 Overview of a metal gasket

(2) The Creep Test Condition

The creep tests were performed at 6 different temperatures (150-200°C) under 3 different



(Test Specimen) (Test Equipment)

Fig.2 Test specimen and test equipment of compressive creep test

applied stresses. The applied stresses were determined, using proof stress $\sigma_{0.2}$ and ultimate strength σ_u gained in tensile tests at each temperatures, as $0.8 \times \sigma_{0.2}$, $\sigma_{0.2}$ and $0.5 \times (\sigma_{0.2} + \sigma_u)$. The temperatures and applied stresses of the creep tests are shown in Table 1. The creep tests were continued until holding time reached 400 hours or creep strain reached 1% (some tests were continued for 2000 hours).

(3) The Creep Test Result

The creep strain curves at 150°C and 190°C obtained in the creep tests are shown in Fig.3 by the solid lines. The creep strain curves in the same test condition showed repeatability and increased slowly with time.

According to the creep strain curves, strain hardening creep equation can be expressed, referring the Sassoulas's creep equation, as follows [4].

Table1 Temperature and applied stresses in the creep tests

Temperature (°C)	Applied stress (MPa)
150	20, 25, 33
160	20, 24, 31
170	18, 23, 30
180	17, 22, 28
190	17, 22, 27
200	17, 21, 26

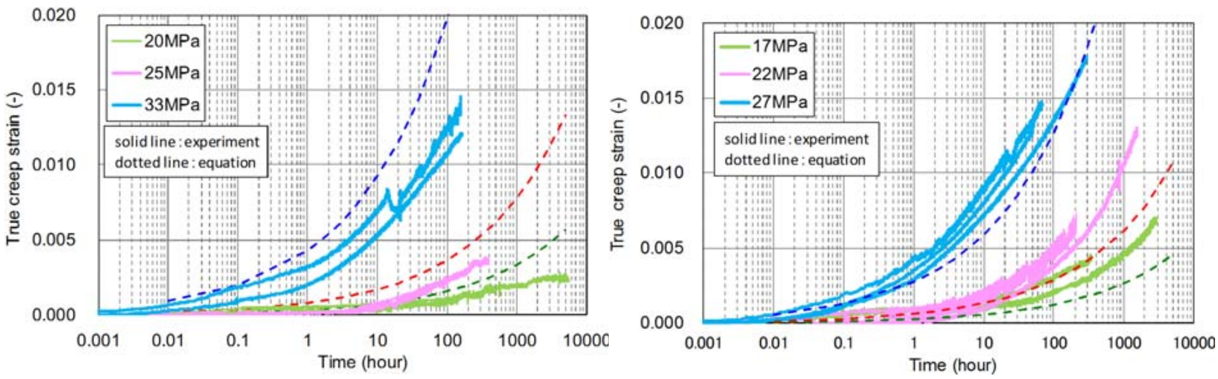
$$\dot{\varepsilon}_c = C_1 \cdot e^{C_2 \cdot \sigma} \cdot \varepsilon_c^{C_3} \cdot e^{-C_4/T} \quad , \quad \varepsilon_c = (\alpha t)^{1/(1-C_3)}$$

Where, $\dot{\varepsilon}_c$:creep strain rate (/hour), ε_c : creep strain (-)

σ : mises stress (N/mm^2), t : time (hour) , T : Kelvin temperature (K) ,

$\alpha = C_1 \cdot e^{C_2 \cdot \sigma}(1-C_3)/e^{C_4/T}$, e: Napier's constant

Fig.4 and Fig.5 show the stress dependency (coefficient C_2) and temperature dependency (coefficient C_4), respectively. According to those test results, these coefficient values were



(150°C) (190°C)

Fig.3 Compressive creep tests results at 150°C and 190°C under various applied stresses for aluminum material

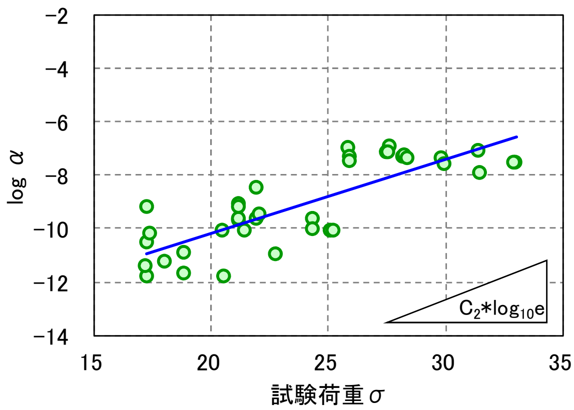


Fig.4 Stress dependency of creep strain rate

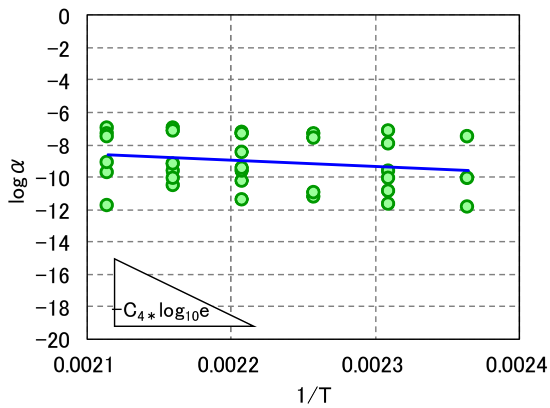


Fig.5 Temperature dependency of creep strain rate

obtained as follows.

$$C_1 = 4.302 \times 10^{-8}, C_2 = 0.637, C_3 = -2.008, C_4 = 9124$$

The creep equation for creep strain curves at 150°C and 190°C are shown in Fig.3 by dotted line with the creep test results. Although the creep equations under estimate the test results at 190°C, the equation conservatively estimate the test results at 150°C.

1.2 Applicability of Numerical Methodology

In this chapter, the numerical methodology of sealing performance of the metal gasket aged for long term is presented. The numerical methodology calculate the representative data of sealing performance, such as residual linear load and spring back distance, by the relaxation of the metal gasket complex under compressive load and heat. The applicability of the numerical method was confirmed by comparison of the representative data calculated and the relaxation test results conduct by CRIEPI. Moreover, the linear load and spring back distance of the gasket used for 60 years were evaluated by the proposed numerical methodology.

(1) Relaxation Tests of Aluminum Gaskets

In order to gain the representative data for sealing performance of the gaskets used at high temperature, CRIEPI carried out relaxation tests using the metal gasket with aluminum outer jacket. Fig.6 shows the relaxation test appearance. The gaskets used in these tests had double O-ring with full scale cross section diameter but smaller circumferential diameter. The gasket set in a 1/10-scale flange model was loaded with compressive deformation to the design value, 1.1mm and heated at 160°C for 1079 hour. In the tests, representative data, such as relationship between gasket linear load and deformation of the gasket, residual linear load

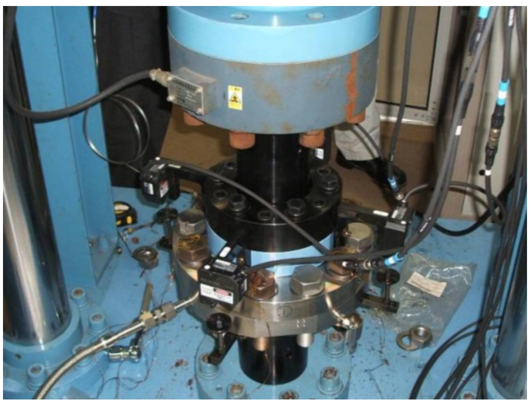


Fig.6 The relaxation test appearance using aluminum gasket

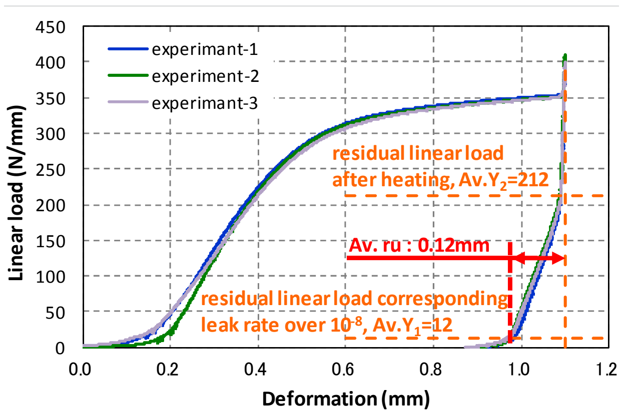


Fig.7 Measured representative data in the relaxation tests

after heating (Y_2), residual linear load with a leak rate exceeding 10^{-8} Pa·m^3/s (Y_1) during load relieving, and effective spring back distance (r_u) from maximum deformation up to a leak rate exceeding 10^{-8} Pa·m^3/s, were measured as shown in Fig.7. As a result, the residual linear load decreased to 212 N/mm from 350 N/mm due to the relaxation of heated gasket complex. Measurements of Y_1 and r_u were 12N/mm and 0.12mm, respectively. Thus, the threshold value of residual linear load Y_1 to maintain sealing performance was determined to 12N/mm.

(2) Model Description of Relaxation Analysis

In the relaxation analysis, non-linear 2D axis symmetric model was used as shown in Fig.8. Outer and inner jackets, upper and lower flanges and spring were modeled by isotropic material, rigid body and equivalent ring pipe, respectively. Maximum deformation of the gasket complex was set to the design value, 1.1mm as well as the relaxation tests.

(3) Analysis Procedure and Material Description

Table 2 shows two cases of relaxation analysis. The analytical case1 was to confirm the applicability of proposed numerical methodology by comparison of calculated values and test results and relaxation analysis targeting the gasket set in 1/10 scale flange model heated at 160°C for 1079 hours was performed. The analytical case2 was to evaluate sealing performance of gasket used for 60 years assuming the storage period, and the relaxation analysis was executed at time history of temperature as shown in Fig.9 and holding time was 60years. Table 3 shows analytical procedure that simulated an actual gasket loading process. This procedure is divided into 4 main loading steps to reproduce compressive loading, bolts tightening, heating and heat holding procedures. Material properties and stress-strain curves used in the analysis are shown in Fig.10. Nimonic spring was described with an equivalent toroidal tube and considered as equivalent elastic-plastic material. Inconel600 inner jacket is considered as elastic-plastic material. Aluminum outer jacket is considered as visco-plastic material. According to the analytical results, Y_2 (residual linear load of gasket) after Step3 and r_u (spring back distance, see Fig.7) at Y_1 reaching 12N/mm during Step4 were evaluated.

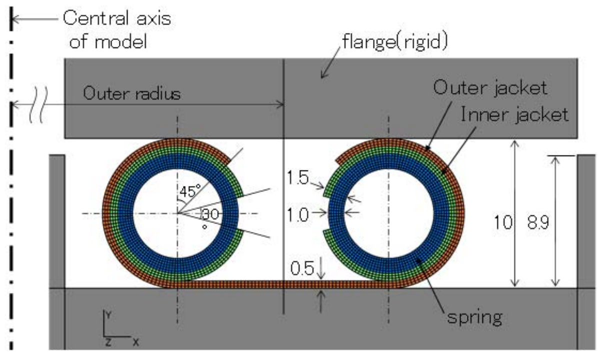


Fig.8 Non-linear 2D axis symmetric model used in the relaxation analysis

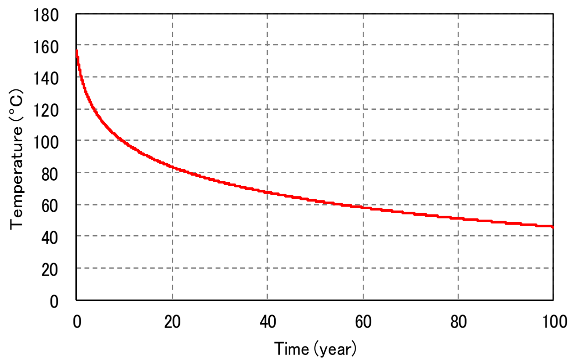


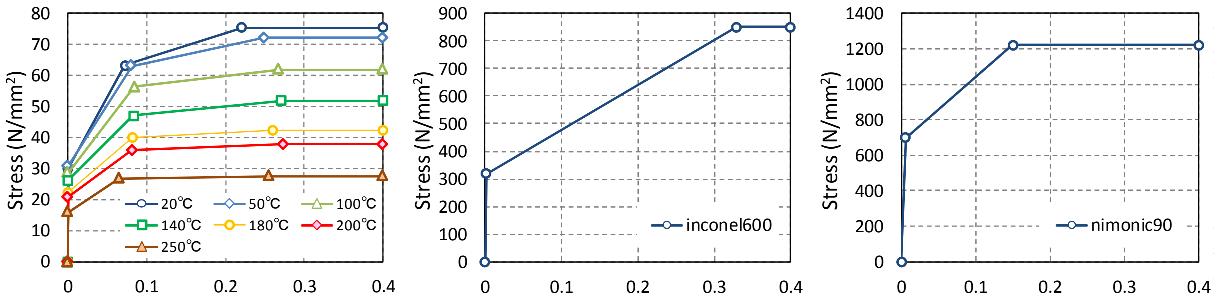
Fig.9 Time history of temperature used in analysis case2

Table 2 Analytical case

Analytical Case	Circumferential diameter	Cross section diameter	Holding time	Temperature	Remarks
Case1	1/10 scale	10mm	1079hours	160°C (constant)	For verification of the analysis
Case2	Full scale	10mm	60years	Time history of temperature (Fig. 9)	For evaluation of the actual case

Table 3 Analytical Procedure

Step	Temperature	Process	Creep
Step1	Constant (22.6°C)	Compressive loading	Non
Step2	Heating to test temperature	Considering thermal deformation and material temperature dependency	Considered
Step3	Case1: 160 constant Case2: time history of temperature (Fig.9)	Heat holding period	Considered
Step4	Temperature on the last time of Step3 (Fig.9)	Unloading	Non



(outer jacket) (inner jacket) (spring)

Fig.10 Stress-Strain relationship used in numerical model

(4) Relaxation Analysis Results

Fig.11 shows a result of analytical case1 on the relationship between deformation and linear load of gasket with experimental results. Maximum linear load Y_{20} and Y_2 values by analysis were in good agreement with experimental results. The linear load by analysis increased more rapidly than the experimental results in an early stage. This difference is because there would be microscopic gap between the adjacent members of an actual gasket. By assuming the Y_1 value was 12 N/mm in relaxation analysis, spring back distance r_u of analytical result was evaluated as 0.11mm which is close to the experimental results. As a result, it was clear that the proposed numerical methodology could evaluate sealing performance with sufficient accuracy. The advantage of the numerical evaluation is the easy applicability to different configuration of metal gasket and temperature condition. Fig.12 shows a result of the analytical case2 result. The external load would not affect the sealing performance if vertical displacement of gasket due to an external load is smaller than the spring back distance, r_u=0.09mm.

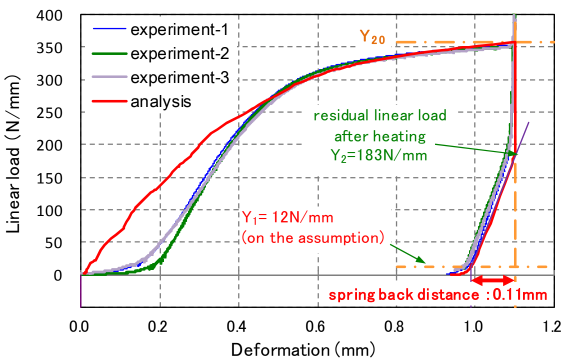


Fig.11 Relationship between deformation and linear load in case1

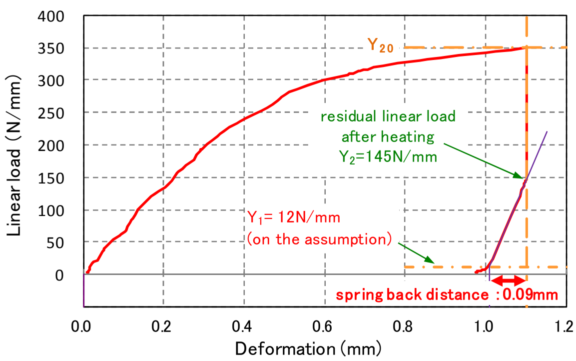


Fig.12 Relationship between deformation and linear load in case2

2. DYNAMIC ANALYSIS FOR CASK LID SUBJECTED TO VIBRATION FORCE DUE TO SEA TORANSPORT

It has been known that the sealing performance of a metal gasket is influenced by external load or displacement [5]. Especially, the aged gasket with reduced residual linear load and spring back distance subjected to vibration force during transportation is concerned. Therefore, to evaluate the influence of vibration during normal transportation on sealing performance of the gasket, the opening displacement perpendicular to the flange surface of the gasket during normal transportation was compared with the spring back distance r_u of the gasket used for 60 years. The displacement of the gasket due to vibration force was calculated by dynamic analysis using Finite Element Method code LS-DYNA.

(1) Dynamic Analytical Model

The cask used in dynamic analysis is a full scale transport and storage dual purpose metal cask as shown in Fig.13. This cask was designed as reference model of dual purpose cask by JNES. The cask has two lids and metal gaskets between lids and body. The cask had a diameter 2.3m, a height 5.4m and total weight 120 tons including inner contents. In dynamic analysis, the body, lids, lid bolt, trunnions, etc, were modeled by hexahedral elements, and the metal gaskets were replaced with spring elements having reaction force due to compressive deformation. Analytical model employed elastic materials. To simulate accurately the deformation response of the gaskets, the initial condition around lids of the cask, such as tensile force of lid bolt, reaction force of gaskets, He gas pressure in the space between primary and secondary lids were considered in the analytical model.

(2) Loading Condition

The time history of acceleration employed in the analytical model was the measurement by gauges set on support frame of cask during actual marine transportation [5][6]. The measured accelerations as shown in Fig.14 were of three directions including axial, horizontal and vertical directions. The duration of accelerations used in the dynamic analysis was 10ms comprising maximum accelerations of about 3G in the horizontal direction. The input data was the measurement without wave filter processing. In the dynamic analysis, the accelerations were input at the trunnion of the cask model and the gravity acted on over-all analytical model.

(3) Dynamic Analysis Result

Fig.15 shows time history of opening displacement at primary and secondary lid. In primary lid, the peak displacement was very small, less than 0.001mm. In secondary lid, the peak displacement was about 0.003mm and the amplitude of the displacement gradually decreased.

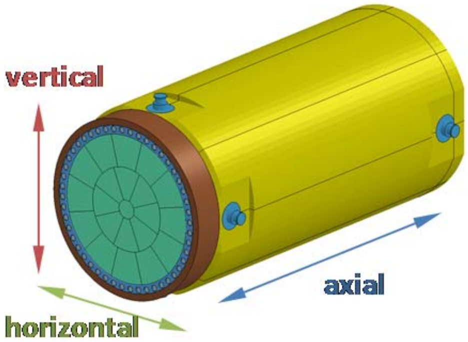


Fig.13 Overview of cask model

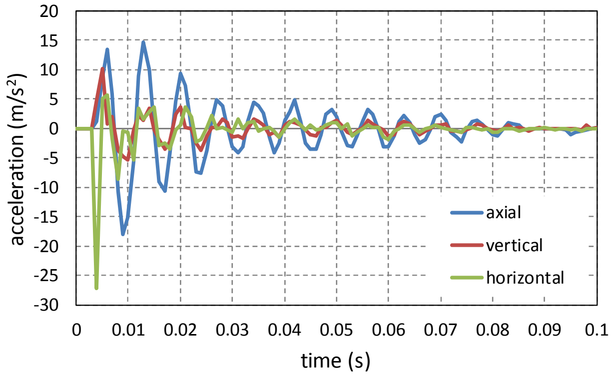
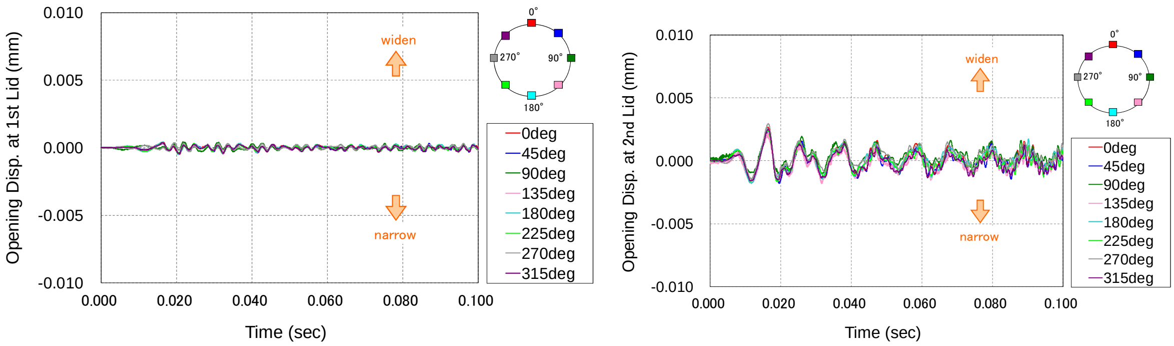


Fig.14 Time histories of accelerations in three direction during a sea transport



(a) Primary lid (b) Secondary lid

Fig 15 Dynamic analysis result on lid opening displacement

These displacements were compared with spring back distance (r_u = 0.09mm) of the gasket used for 60 years evaluated in the chapter 1. The results revealed the displacements were much smaller than the spring back distance. Therefore, the sealing performance will not be lost by lid opening during the sea transportation within the acceleration measured.

CONCLUSION

The creep characteristics of aluminum were obtained by compressive creep tests. To verify the proposed numerical method of sealing performance of the metal gasket using the creep characteristics, the calculation results are compared with relaxation test results. It was found that the proposed numerical methodology could evaluate sealing performance with sufficient accuracy. The influence of vibration during sea transportation on sealing performance of metal gasket was evaluated by comparison of the spring back distance and response displacement of the gasket analyzed by LS-DYNA. As a result, the opening displacement of the gasket due to vibrations was negligible as compared with the spring back distance. The sealing performance will not be lost by lid opening during the sea transportation within the acceleration measured.

ACKNOWLEDGEMENT

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