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Numerical Evaluation of the Long-term Sealing Performance of the Silver Gasket for Dual Purpose Metal Cask under High Temperature

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ABSTRACT

It is important to evaluate the effect of thermal ageing on the sealing performance of metal gaskets under high temperature for long-term usage. Therefore, in order to gain representative data for this kind of metal-sealed lid system, BAM is currently performing laboratory tests of different gasket types with aluminum and silver jackets at three different temperatures under static conditions up to four years so far, using test flanges for gaskets with full scale cross section diameter but much smaller outer diameter. On the other hand, in order to investigate the applicability of the numerical methodology to evaluate the long-term behavior of the metal gaskets, such as a correlation between seal pressure force and holding time, CRIEPI is developing a modeling method including material tests (tensile and creep tests) at high temperature. In this paper, the applicability of the finite element method (ABAQUS) to predict the recovery displacement and residual seal pressure force of the gasket complex was verified by comparing the calculated values with BAM's laboratory test results under the joint research agreement between BAM and CRIEPI.

INTRODUCTION

Although dry interim storage of spent nuclear fuel in transport and storage metal casks has been licensed for time period of 40-60 years internationally, extended periods may be necessary considering the uncertainties for future energy strategy (e.g. implementation of sufficient reprocessing capacity and/or establishing a final repository). Metal gaskets are generally used for the safe and long-term stable closure of metal casks. Such gaskets generally consist of an inner helical metal spring and two metal jackets. The outer metal jacket is made of flexible aluminum or silver to maintain tight contact between seal and lid or cask body surfaces. As higher temperatures of more than 100°C will appear in the seal area of cask lid systems during storage, it is well-known that higher temperatures accelerate ageing mechanisms, such as creep deformation of the outer jacket and corresponding relaxation of the seal pressure force of the gasket complex [1]. It is important to evaluate the effect of the thermal ageing on the load-deformation curve under high temperature for long-term usage. Therefore, in order to gain representative data for this kind of metal-sealed lid system, BAM is currently performing long-term gasket sealing performance tests of different gasket types with aluminum and silver jackets at three different temperatures of 20°C, 100°C and 150°C under static conditions up to 48 months so far, using test flanges for metal gaskets with full scale cross section diameter but much smaller outer diameter [2-4]. Due to creep effects, the gasket pressure force decreases over time depending on the temperature. According to the test results, clear decline correlations between gasket pressure forces and holding time for each gasket type at different temperatures have been obtained. In this paper, in order to investigate the applicability of the numerical methodology to evaluate the long-term behavior of the silver gasket, such as a correlation between gasket pressure force and holding time, the modeling method including material tests (tensile and creep tests) at high temperatures were developed by CRIEPI. Moreover, the applicability of the finite element method (ABAQUS) to predict the recovery displacement and residual gasket pressure force of the seal complex was verified by comparing the calculated values with BAM's sealing performance test results.

1. SEALING PERFORMANCE TESTS

Metal gaskets of the Helicoflex® type as illustrated in Fig.1 are generally used for safe and long-term stable closure of metal casks. Such gaskets consist of an inner helical metal spring and two metal jackets. The outer metal jacket is made of flexible aluminum (Al-gaskets) or silver (Ag-gaskets) to maintain tight contact between seal and lid or cask body surfaces. Higher temperatures, depending on cask design and spent fuel decay heat, appear in the seal area of cask lid systems with maximum temperatures at the beginning of storage. It is well-known that higher temperatures accelerate ageing mechanisms, such as creep deformation of the outer jacket and corresponding relaxation of the seal pressure force of the seal complex.

The characteristic mechanical behavior of Helicoflex® gaskets can be illustrated by their load-deformation relationship during compression and relieving procedures. Fig.2 shows gasket conditions before, during and after compression (points A, B and C). Furthermore, the corresponding load-deformation curve including the characteristic values Y_0, Y_1 and Y_2 is given with respect to the standard helium leakage rate during compression and relieving process. It is important to evaluate the effect of the thermal ageing on the load-deformation curve under high temperatures for long-term usage.

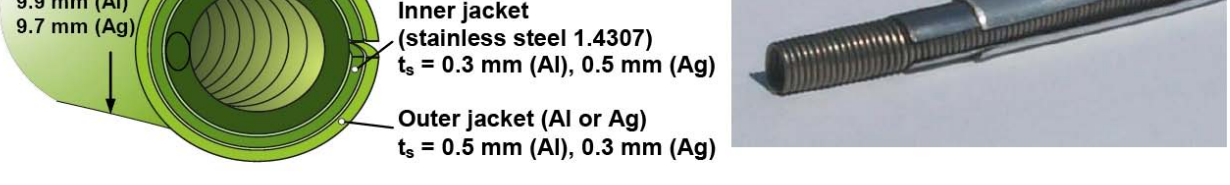
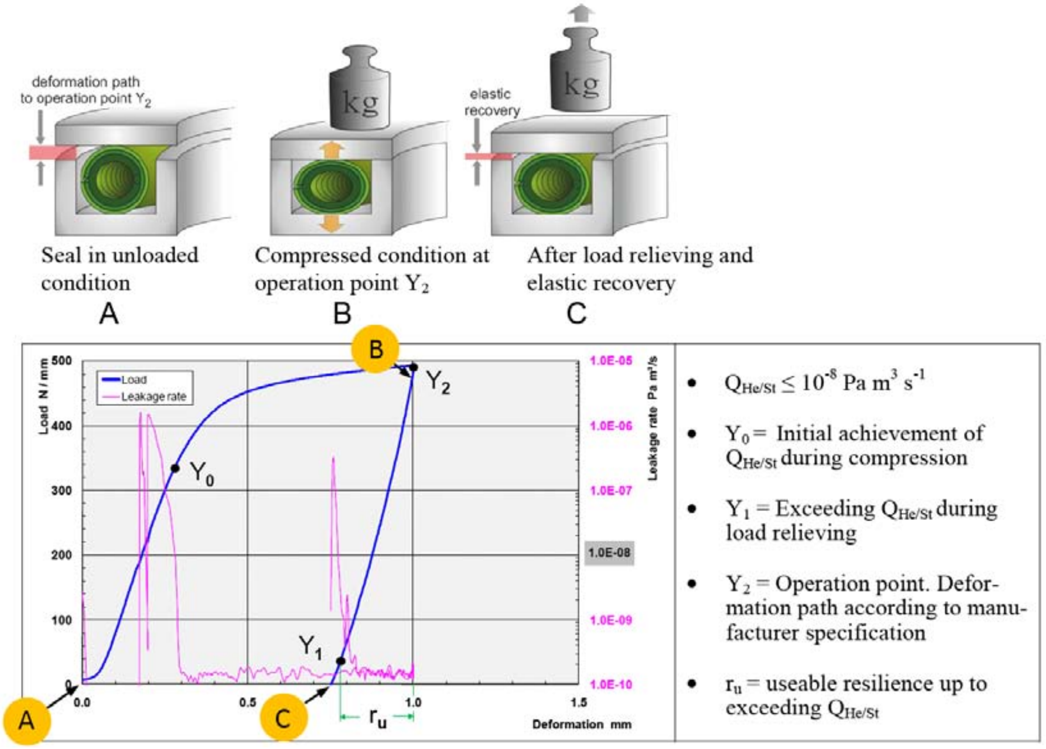


Fig.1 Helicoflex® gasket type applied in test series, typical for applications in dry storage metal casks [3, 4]

To gain representative data for this kind of metal-sealed lid systems, BAM has developed test flanges for gaskets with full scale cross section diameter but much smaller outer diameter. Moreover, using these test flanges, BAM is currently performing long-term gasket seal performance tests of different gasket types with aluminum and silver jackets at three different temperatures of 20˚C, 100˚C and 150˚C under static conditions over longer periods of time. Due to creep effects, the seal pressure force decreases over time depending on the temperature. According to current test results up to 48 months [4], clear decline correlations between gasket pressure forces and holding time for each gasket type at different temperatures are indicated as shown in Fig.3, allowing for extrapolating to much longer periods of time.



- $Q_{He/St} \leq 10^{-8}$ Pa m^3 s^{-1}
- Y_0 = Initial achievement of $Q_{He/St}$ during compression
- Y_1 = Exceeding $Q_{He/St}$ during load relieving
- Y_2 = Operation point. Deformation path according to manufacturer specification
- r_u = useable resilience up to exceeding $Q_{He/St}$

Fig.2 Characteristic load-deformation relationship of a Helicoflex® seal with outer silver jacket with respect to seal condition (A, B and C) and standard helium leakage rate at Y_0, Y_1 and Y_2 [3]

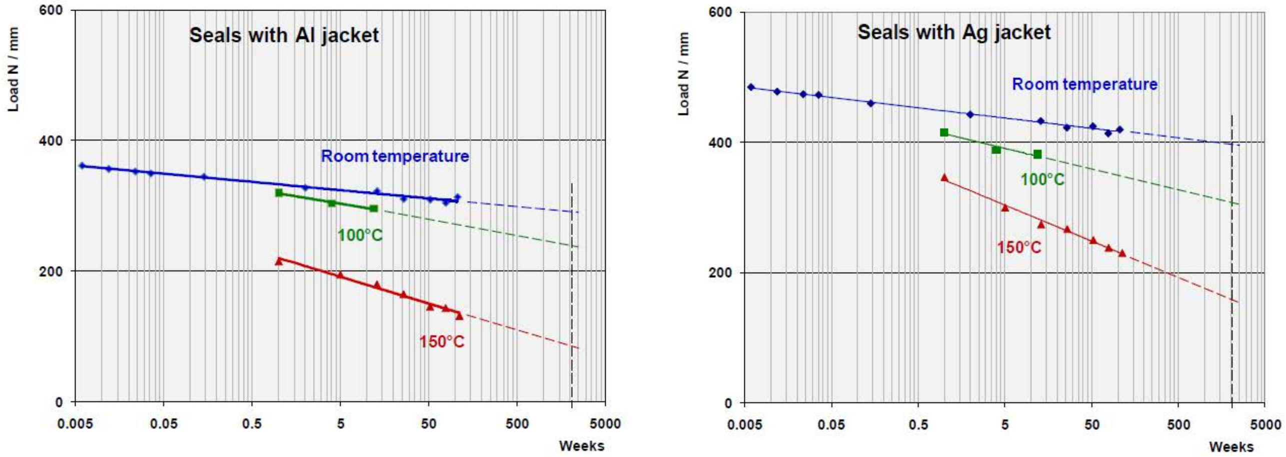


Fig.3 Restoring seal force reduction depending on holding time (logarithmic scaling) and temperature for selected test periods and extrapolation up to 40 years (dashed lines) [3]

2. NUMERICAL APPROACH FOR GASKET SEALING PERFORMANCE

In this chapter, in order to investigate the applicability of the numerical methodology to evaluate the long-term behavior of metal gaskets, such as a correlation between gasket pressure force and holding time, the modeling method for Ag-gaskets including the material tests at high temperature and the preliminary numerical results are presented.

2.1 Material Tests of Silver

(1) Test Specimen

In order to evaluate the relaxation characteristic of the metal gasket complex, the material tests including tensile test and tensile creep test at higher temperatures were executed using the outer jacket material (99.9% pure silver with heat treatment). In both types of tests, the same configuration of the test specimen with a gauge diameter of 6mm and a length of 30mm, was used as shown in Fig. 4.

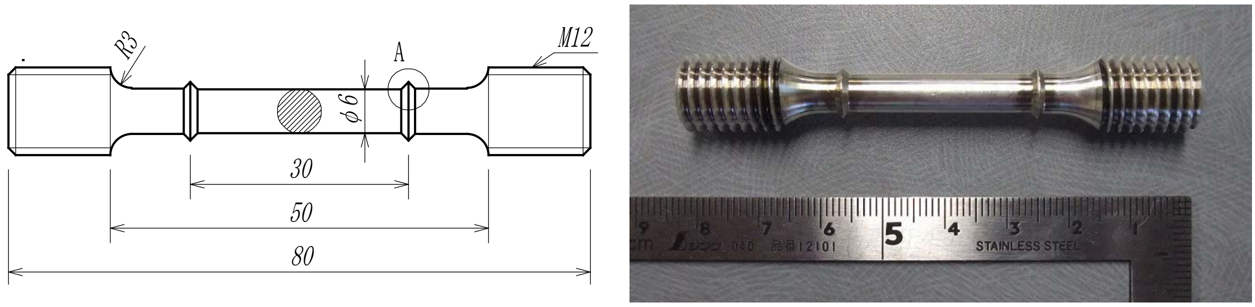


Fig.4 Dimension of the test specimen for tensile and creep tests for pure silver material

(2) Tensile Test

Tensile tests were performed at three different temperatures (RT, 100˚C, 150˚C) and at least three test samples were used for each temperature condition. Loading rate was set to 2.25mm/min (7.5%/min) referring the Japanese Industrial Standard JIS G 0567 [4]. Fig.5 shows the relationship between true stress and true strain at RT, 100˚C, 150˚C. The open circles show the regression curve fitted by the Krupkowski's law as follows.

$$\sigma = K \cdot (\varepsilon_{plastic} + \varepsilon_0)^n$$

Fig. 6 shows the temperature dependency of material properties (Young's modulus, 0.2% proof stress and ultimate stress). Although Young's modulus has no temperature dependency, 0.2% proof stress and ultimate stress slightly declined as the temperature increases

(3) Tensile Creep Test

Tensile creep tests were performed at 150˚C under various applied stresses (60-100 N/mm^2) in the furnace attached to the creep test equipment. Pre-heating time of 1 hour for sample temperature homogenization was applied. Furnace temperature was adjusted by PID control system within ±3˚C referring the Japanese Material Standard JIS Z 2271 [5]. Although the heating time was set up to 100 hours, in all of the creep tests the minimum steady creep strain rates were obtained as shown in Fig.7.

Strain hardening creep equation at 150˚C can be expressed as follows [6].

$$\dot{\varepsilon}_{Creep} = C_1 \cdot \sigma^{C_2} \cdot \varepsilon_{Creep}^{C_3} \quad at \quad T = 150°C$$

σ : Mises stress, ε_{Creep} : Creep strain, $\dot{\varepsilon}_{Creep}$: Creep strain rate

Fig.8 shows the stress dependency (coefficient C_2) of the minimum steady creep strain rate at 150˚C. According to these test results, the coefficient values were obtained as follows.

$C_1 = 4.41\text{x}10^{-21}$, $C_2 = 8.322$, $C_3 = -1.270$

Fig.9 shows the validation results of the proposed equation for creep strain evolutions. Although in the lower loading region, the estimated creep strains are in good agreement with the experimental values, in the higher loading region the estimated creep strains differ from the experimental values, and because of different curve characteristics the tertiary creep, evident for stresses of 80MPa and higher, cannot be described satisfactorily.

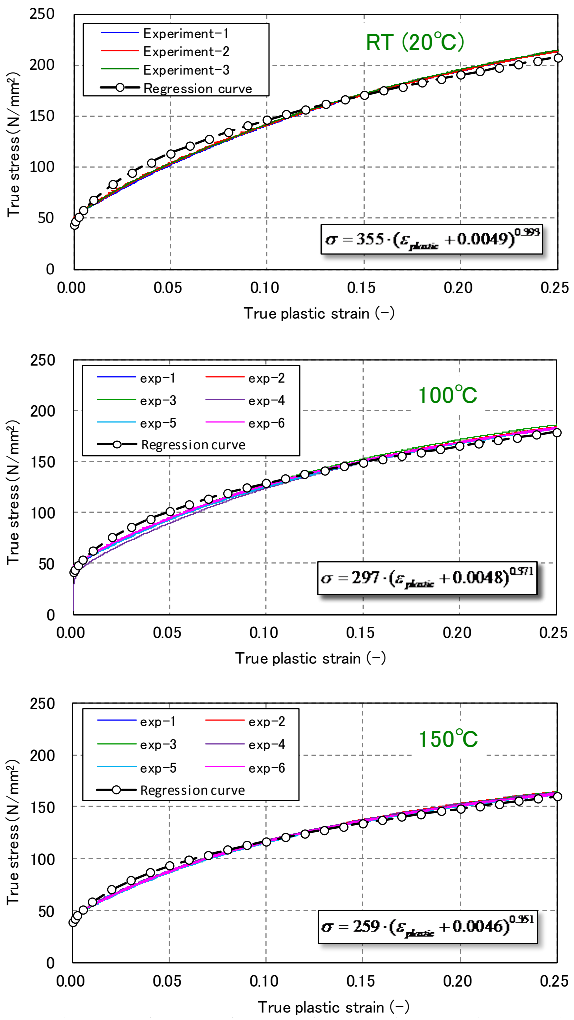


Fig.5 Measured relationship between true stress and true strain at RT, 100˚C, 150˚C for silver material

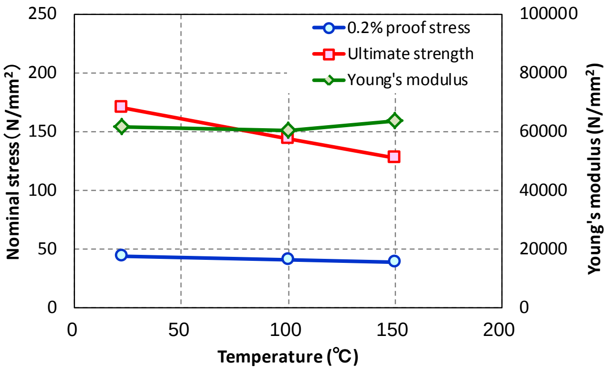


Fig.6 Temperature dependency of silver material properties

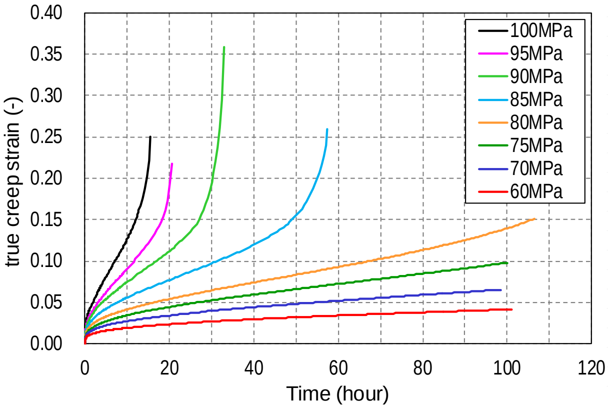


Fig.7 Tensile creep test results at 150˚C under various applied stresses for silver material

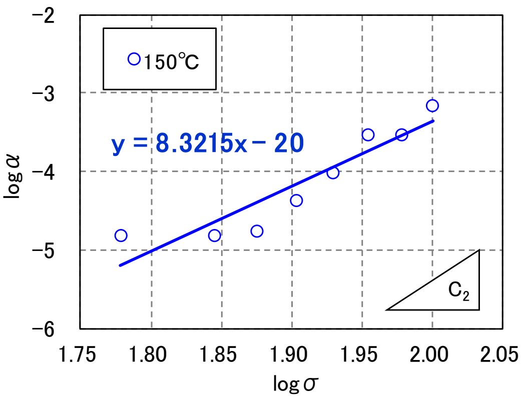


Fig.8 Stress dependency of the minimum steady creep strain rate at 150°C

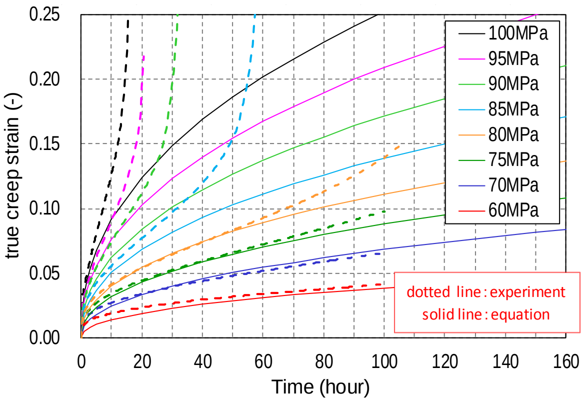


Fig.9 Validation results of the proposed equation for creep strain evolutions

2.2 Applicability of Finite Element Method

In order to establish the numerical methodology of the ageing phenomena on sealing performance of silver gaskets over the long-term by use of the Finite Element Method, the tensile and creep characteristics of the silver material were introduced to the user subroutine of the FEM code (ABAQUS). Moreover, the preliminary relaxation analyses were performed considering actual over-all gasket complex configurations to calculate residual linear loads and total spring back of gaskets, and benchmarked by BAM's gasket performance test results.

(1) Model Description

In the relaxation analysis a non-linear 2D axi-symmetric model was used as shown in Fig.10. Outer and inner jackets, upper and lower flanges and spring were modeled by isotropic material, rigid body and equivalent ring pipe, respectively, and the friction coefficient was uniquely set to constant, 0.17. Maximum deformation of the gasket complex was set to the design value of 1.0 mm.

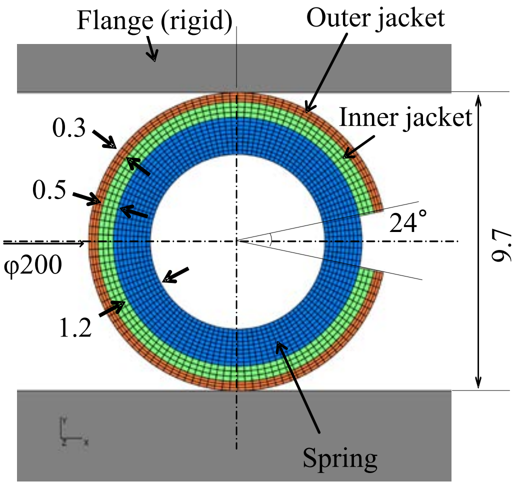


Fig. 10 Non-linear 2D axi-symmetric model used in the relaxation analysis

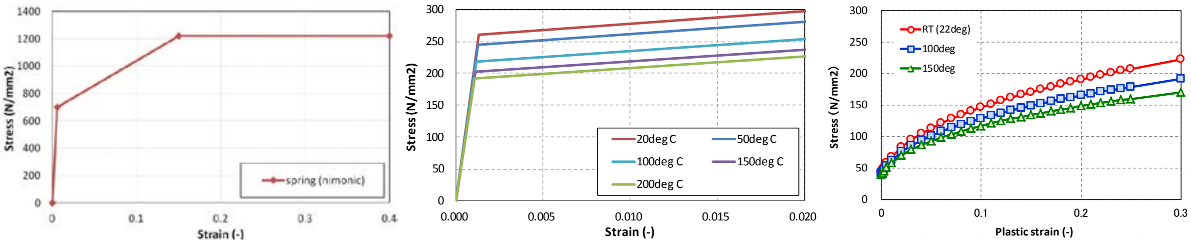
(2) Analysis procedure and Material Description

Table 1 shows the analysis procedure for the relaxation tests. This procedure is divided into 4 main loading steps to reproduce press-loaded bolts tightening and heating procedures used for the tests.

Material properties and stress-strain curves are shown in Fig.11. Nimonic spring was described with an equivalent toroidal tube and considered as equivalent elastic-plastic material. Stainless steel inner jacket is considered elastic-plastic material. Silver outer jacket is considered visco-plastic material. According to the analysis results, Y_{2R} (residual linear load of gasket) after Step3 and r_u (recovery displacement, see Fig. 2) after Step4 were evaluated.

Table 1 Analysis procedure for the relaxation tests

Step	Temperature	Contents	Creep
1	20˚C (Constant)	Loading	Non
2	Heating to 150˚C	Considering thermal deformation and material temperature dependency	Non
3	150˚C (Constant)	Heating period	Considered
4	150˚C (Constant)	Unloading	Non



(Nimonic) (SUS304L) (Outer Silver Jacket)

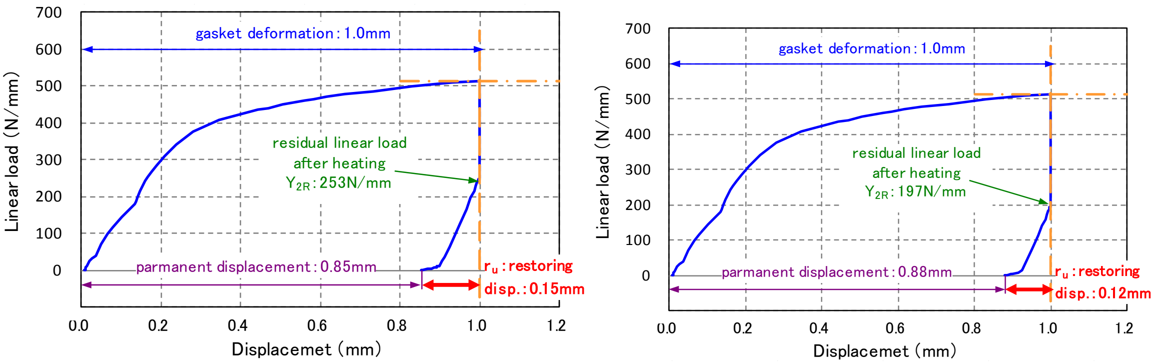
Fig.11 Stress - strain relationship used in numerical model

(3) Analysis Results

Calculated Y_{2R} and r_u values are summarized as shown in Table 2. Fig.12 shows analysis results of the load-deflection curves. Fig.13 shows the extrapolation results of Y_{2R} decreasing along times up to 40 years. Since the numerical model underestimates Y_{2R} values due to the underestimation of the minimum steady creep strain rate in the higher stress regions a modification of the creep law model would be needed to get more precise results. In any case the extrapolation of both test and calculation results do not indicate that remaining seal loads may reach the leakage rate limit value at Y_1. Therefore it is obvious that the sufficient leak-tightness of silver type gaskets will be maintained even under high thermal loads with a temperature of 150˚C over 40 years.

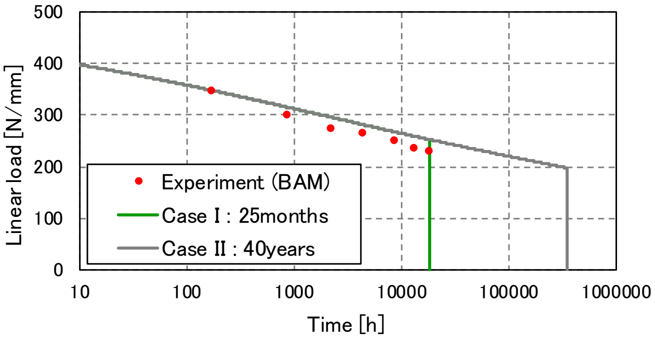
Table 2 Calculated Y_2 and r_u values

Case# (period)	Case I (25months)	Case II (40years)
Y_{2R} : Residual linear load	253N/mm	197N/mm
r_u : Total residual spring back	0.15mm	0.12mm



(Case I : 25months) (Case II : 40years)

Fig.12 Calculated load-deflection curves



Time (h)	load (N/mm)		Ana./Exp. (%)
	Experiment	Analysis	
0	495	485	0.98
168	347	348	1.00
840	300	316	1.05
2160	274	296	1.08
4320	267	282	1.06
8640	250	267	1.07
12960	238	259	1.09
18000	230	253	1.10

Fig.13 Extrapolation results of Y_2 values for silver gaskets at 150˚C for time periods of up to 40 years

CONCLUSIONS

BAM is currently performing long-term gasket performance tests of different gasket types with aluminum and silver jackets at three different temperatures of 20˚C, 100˚C and 150˚C under static conditions for up to 4 years so far. In these tests, the remaining pressure forces of the metal gaskets have been measured periodically and the test results have been extrapolated to longer periods of time. In parallel, CRIEPI has performed tests with silver gasket materials to gain material data to be implemented in a finite element simulation model. To verify the calculation results (Y_2 values) they were compared with the experimental data. The principal decrease of the gasket load over time is found in both cases whereas the current numerical model underestimates the experimental findings. In any case no failure of gaskets with regard to their proper seal function is to be expected during the so far considered time span of up to 40 years. The advantage of the numerical evaluation is an easy applicability to different configurations of metal gaskets and temperature conditions in case adequate basic material data are available and the numerical model is finally verified sufficiently.

ACKNOWLEDGEMENT

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