# LONG-TERM MECHANICAL BEHAVIOUR OF RUBBER O-RINGS FOR MOX FRESH FUEL TRANSPORT PACKAGES BY EXPERIMENT AND FEM NUMERICAL SIMULATION

**Akihiro Matsuda**
University of Tsukuba

*1-1-1 Tennodai, Ibaraki, Tsukuba, Japan*

**Chihiro Ito**
Central Research Institute of Electric Power industry
*1646 Abiko, Abiko, Chiba, Japan*

**Toshiari Saegusa**
Central Research Institute of Electric Power industry
*1646 Abiko, Abiko, Chiba, Japan*

## ABSTRACT

This paper shows evaluation of the long-time mechanical behavior of selected rubber O-rings for transport package by experiment and FEM numerical simulation.

We applied a concept of the accelerated thermal aging tests to the experimental evaluation. The concept of the thermal accelerating test is that rather higher temperature than real one is applied to the specimen though the duration time is shorter the real situation. This method is based on that progress of the plastic deformation and stress relaxation of rubber follows the Arrhenius equation. From the result of accelerated thermal aging tests of the rubber O-ring, it can be concluded that the rubber O-ring which is used in real packages, will keep its integrity, at least, for five years at temperature at $70C^{\circ}$.

Additionally, the FEM analysis was applied to the numerical simulation to predict the compression set of an EPDM O-rings. The nonlinear visco-elastic model was applied to the material modeling. The material moduli of hyperelasticity were obtained by the tensile test of EPDM O-rings. The material moduli of viscous relaxation were obtained by stress relaxation tests of the O-rings in high temperature chamber.

## INTRODUCTION

Japanese regulation requires Periodic Inspection Check (PIC) on the transport packages for MOX fresh fuels within a year. The items and interval of the PIC should be settled considering the performance of the packages. In this study thermal aging tests of the rubber O-rings were performed under a predicted condition of loading period of five years and the temperature at the gaskets of $70C^{\circ}$. The durability of containment system of the package depends on stress relaxation property and plastic deformation of the rubber O-rings. It might be desirable to conduct the demonstration test under the real condition of $70C^{\circ}$ for five years. However, due to the necessity of immediate evaluation of rubber O-ring's containment, the methodology of accelerated aging tests was adopted to evaluate the durability of the rubber O-rings. The concept of the accelerated aging tests is that rather higher temperature than real one is applied to the specimen though the duration time is shorter the real situation. This cause is that progress of the compression set of rubber is follows the Arrhenius equation.

Therefore, the test results of the accelerated aging test was determined by the Larson-Miller Parameter (LMP) that is a modified equation of the Arrhenius equation, as shown bellow[1)].

$$LMP = T(C + \log t) \tag{1}$$

where、$T$ is temperature ($K$) of the specimen, $C$ is the material constant （＝11） , $t$ is time (hour), respectively. In this study, several combinations of temperature and holding time were set taking accounts of the LMP corresponding to $70\,C^{\circ}$ and five years (*LMP=5367*). The durability tests were conducted after the preliminary tests to discern the weakest O-rings for thermal aging.

Additionally, the finite element analysis was applied to the evaluation of the effect of lid groove on the mechanical deformation of EPDM O-rings. The O-rings which is applied to the numerical simulation was manufactured by the NIPPON Valqua Industrials, LTD. The material model of rubber O-rings was obtained from the tensile tests of the O-rings and the nonlinear visco-elastic model was applied to finite deformation analysis.

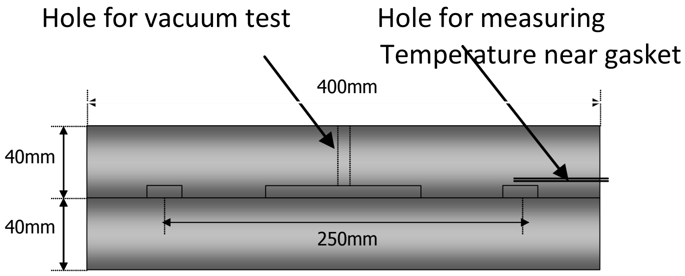



Fig. 1 Lid Scale Model

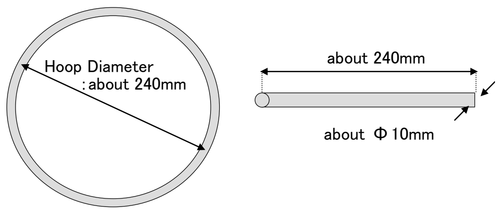



Fig. 2 Specimen of the gasket

## DULABILITY TESTS OF RUBBER-ORINGS[2)]

Thermal acceleration tests were conducted using the FKM and EPDM O-rings in order to confirm the soundness of the gaskets being subjected to ambient temperature of $70\,C^{\circ}$ for five years[3)]. The specimens for thermal acceleration test were selected by the preliminary tests. The test condition was set as combinations of temperature and holding time using the Eq. (1) considering the real condition (five years at $70\,C^{\circ}$) and corresponding LMP.

1/5 scale models of which groove shape is same scale as the lid of package, were applied to the thermal aging tests (ref. Fig. 1). As mentioned, two types of gaskets (FKM and EPDM) were employed for the tests (Table 1). They have the same cross section as the real one, but are scaled down in hoop diameter as shown in Fig. 2.

The accelerated aging tests were conducted under combinations of temperature ($80\,C^{\circ}$, $100\,C^{\circ}$, $120\,C^{\circ}$, $150\,C^{\circ}$) and elapsed time (18hr, 150hr, 200hr, 2000hr, 3000hr, 5000hr) simulating the real condition (five years at $70\,C^{\circ}$) and the corresponding LMP. The test conditions of the durability test were summarized in Table 2. The test procedures are shown in Fig.3. The gasket was set at the lid scale model by bolting after measuring the diameter of the cross section of the gasket. Then, it was put into the electric oven for heating. Before and after the heating, leak rate was measured by vacuum test and compression set ($D_p$) of the gasket were measured using the diameter of the cross section of the gasket.

The leak rate before and after heating and the compression set ($D_p$) measured in the tests were summarized in Table 3 and the $D_p$ were plotted against LMP in Fig.4. It seems no long-term effect of heating on the soundness of the gasket as there is basically no change in leak-rate before and after heating and the leak rates seem to be good enough. As shown in Fig.4 the compression set ($D_p$) are less than 75%~80% which is generally considered as a service limit Dp for containment at the level of 5690 in LMP that is larger than 5367.

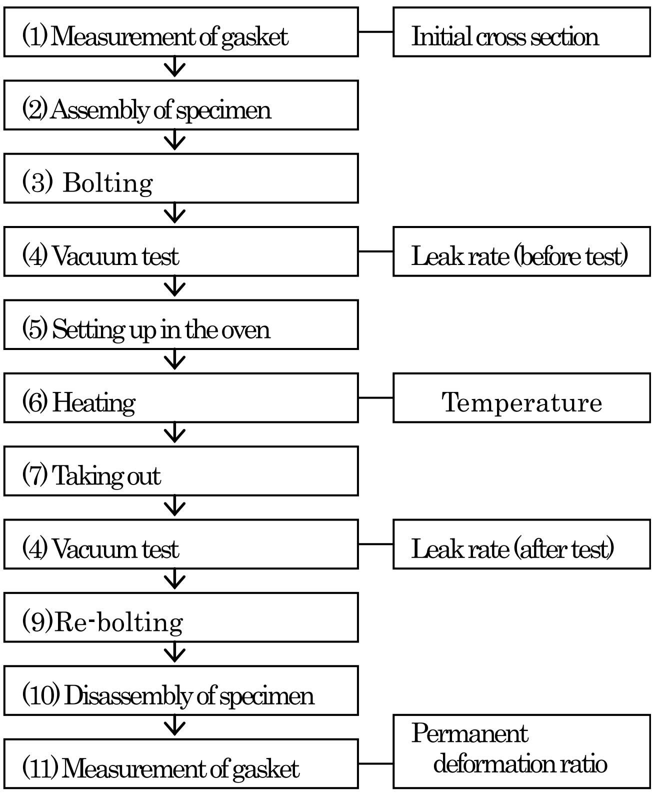
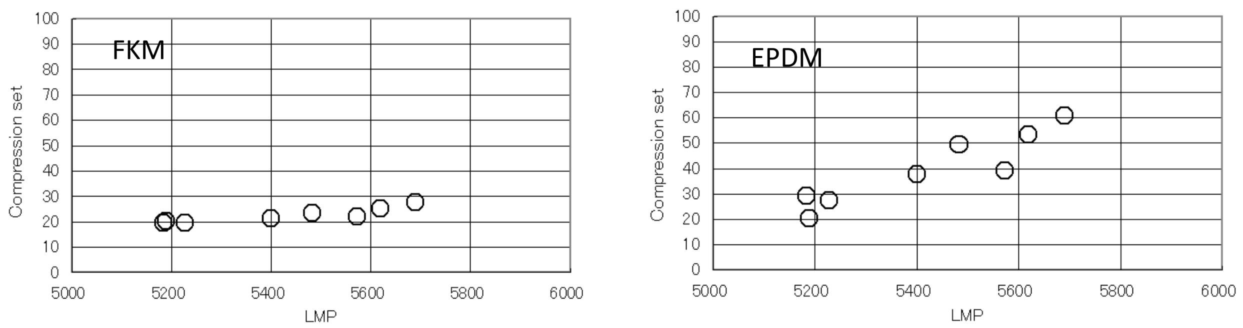



Fig. 3 Test procedure of dulability test




(a) FKM (b) EPDM

Fig. 4 Compression set after dulability test

Table 1 Test results of durability test

| Gaskets | Test condition(LMP) | Leak rate (Pa・$m^3$/s) | | Compression set(%) | Exposed years* |
|---|---|---|---|---|---|
| | | Before heating | After heating | | |
| FKM | 150℃-18hr(5184) | $1.00\times10^{-7}$ | $8.75\times10^{-8}$ | 19.7 | 1.5 |
| | 150℃-150hr(5573) | $2.78\times10^{-7}$ | $4.11\times10^{-8}$ | 22.1 | 20.3 |
| | 120℃-200hr(5227) | $2.25\times10^{-7}$ | $4.45\times10^{-8}$ | 19.4 | 2.0 |
| | 120℃-2000hr(5620) | $1.09\times10^{-7}$ | $6.01\times10^{-8}$ | 25.2 | 27.7 |
| | 100℃-3000hr(5400) | $8.27\times10^{-7}$ | $8.13\times10^{-8}$ | 21.2 | 6.3 |
| | 100℃-5000hr(5483) | $9.86\times10^{-8}$ | $6.23\times10^{-8}$ | 23.3 | 11.0 |
| | 120℃-3000hr(5690) | $4.58\times10^{-7}$ | $7.91\times10^{-8}$ | 27.7 | 44.2 |
| | 80℃-5000hr(5189) | $1.57\times10^{-7}$ | $5.04\times10^{-8}$ | 20.2 | 1.5 |
| EPDM | 150℃-18hr(5184) | $3.35\times10^{-7}$ | $5.42\times10^{-7}$ | 29.4 | 1.5 |
| | 150℃-150hr(5573) | $4.18\times10^{-7}$ | $1.51\times10^{-7}$ | 39.1 | 20.3 |
| | 120℃-200hr(5227) | $3.63\times10^{-7}$ | $1.69\times10^{-7}$ | 27.3 | 2.0 |
| | 120℃-2000hr(5620) | $2.58\times10^{-7}$ | $1.62\times10^{-7}$ | 53.2 | 27.7 |
| | 100℃-3000hr(5400) | $3.40\times10^{-7}$ | $2.82\times10^{-7}$ | 37.6 | 6.3 |
| | 100℃-5000hr(5483) | $3.62\times10^{-7}$ | $2.13\times10^{-7}$ | 49.4 | 11.0 |
| | 120℃-3000hr(5690) | $3.95\times10^{-7}$ | $1.44\times10^{-7}$ | 60.9 | 44.2 |
| | 80℃-5000hr(5189) | $3.53\times10^{-7}$ | $2.10\times10^{-7}$ | 28.1 | 1.5 |

＊Years corresponding to 70℃

## FEM SIMULATION OF EPDM O-RINGS

FEM numerical simulation using nonlinear visco-elasticity was carried out to predict the compression set of EPDM O-rings for transport package. The Maxwell type visco-elastic model which was applied to the simulation was shown in Fig. 5. The second Piola-Kirchhoff stress tensor $\boldsymbol{S}$ of the visco-elastic model in Fig.5 is given by[4,5]:

$$\boldsymbol{S} = 2\frac{\partial W(\overline{\boldsymbol{C}})}{\partial \boldsymbol{C}} - \frac{\partial \overline{\boldsymbol{C}}}{\partial \boldsymbol{C}}\sum_{i=1}^{N}\boldsymbol{Q}_i + Jp\boldsymbol{C}^{-1} \tag{2}$$

where $\boldsymbol{C}$ and $\overline{\boldsymbol{C}}$ are the right Cauchy-Green tensor and volume-preserving of the right Cauchy-Green tensor, respectively. $W$ and $p$ are the strain energy function of elastic deformation and hydrostatic pressure, respectively. $\boldsymbol{Q}_i$ and $N$ are the viscous stress tensor and the number of dashpots in Fig. 5, respectively. The viscoelastic stress $\boldsymbol{Q}_i$ satisfies the following evolution equations including material temperature $\boldsymbol{T}$ (K) as follows:

$$\begin{gathered}\dot{\boldsymbol{Q}}_i(t) + \frac{1}{\tau_i(T)}\boldsymbol{Q}_i(t) = \frac{\gamma_i}{\tau_i(T)}DEV\left\{2\frac{\partial W}{\partial \boldsymbol{C}}\right\},\\ \lim_{t\to-\infty}\boldsymbol{Q}_i(t) = 0,\end{gathered} \tag{3}$$

where $\tau_i(T)$ is the relaxation time of a dashpots and the notation $DEV$ is given by

$$DEV[\bullet] = (\bullet) - \frac{1}{3}[(\bullet):\boldsymbol{C}]\boldsymbol{C}^{-1} \tag{4}$$

From the results of the stress relaxation tests on EPDM O-rings, we applied the following relationships to the temperature-dependent stress relaxation behavior of rubber materials using the Arrhenius equation.

$$\tau_i(T) = \frac{\tau_i(T_0)}{\alpha} = A\,exp\left(\frac{E}{RT}\right)\tau_i(T_0) \tag{5}$$

where $\alpha$ is the rate constant of the chemical reaction depending on the temperature of the rubber, R is the gas constant (=8.31447J/K/mol), $T_0$ is the referenced temperature(=423K), $E$ is the activation energy, and $A$ is the prefactor. Eq. (5) means that the relaxation time $\tau_i(T)$ of all dashpots shortens uniformly with an increasing temperature. Here, relationships between time and stress of a element composed by an elastic spring and a dashpot under constant deformation is given by

$$\sigma_i = \gamma_i \sigma_0\, exp\left(-\frac{t}{\tau_i(T)}\right) \tag{6}$$

Here, $\sigma_0$ and $\gamma_i$ are the initial stress of the spring and material constant, respectively. The total stress of the Maxwell visco-elasticity under constant deformation is given by,

$$\frac{\sigma}{\sigma_0} = \sum_{i=1}^{N} \gamma_i\, exp\left(-\frac{t}{\tau_i(T)}\right) \tag{7}$$

Tensile loading tests of EPDM O-rings were conducted to estimate the elastic characteristics of EPRM rubber. Results of Tensile loading test and approximated numerical model of EPDM O-ring was shown in Fig.6. Following elastic potential function of hyperelasticity was applied to the numerical modeling.

$$W = \sum_{i+j=1}^{2} \mathrm{C_{ij}} \left(\bar{I}_1 - 3\right)^i \left(\bar{I}_2 - 3\right)^j \tag{8}$$

Simultaneously, stress relaxation tests in the high-temperature electric oven were carried out (Fig. 7). Stress relaxation characteristics of $150\,C^\circ$ were approximated by Eq. (7) and relaxation times and material constants were shown in Table 2. Acceleration rate of relaxation characteristics that determined by test results of $150\,C^\circ$ were shown in Fig.8 as the Arrhenius plot. Relationships between the logarithm of acceleration ratio and *1/T* show good linearity and it mean that the relaxation of the rubber was motivated by the Arrhenius equation.

FEM simulation of compressed EPDM O-ring was conducted to predict the compression set. The diameter of O-ring was 10mm and rigid lines were set in the top and bottom of FEM model. Vertical displacement of 3mm was applied to the top rigid line to compress to 70%. After 150 hours pass in the simulation, the vertical displacement of top line was released and compression set was calculated. Mean stress distributions of initial state and after 150h ($150\,C^\circ$) were shown in Fig. 9. Initial shape and released deformation after 150h ($100\,C^\circ$ and $150\,C^\circ$) were shown in Fig.10. Stress was decreased by stress relaxation characteristics and permanent deformation was observed when the top rigid line was released.

In Fig. 11, experimental and simulated results of compression set were shown. Simulated results have enough accuracy to predict of the compression set of the EPDM O-rings.

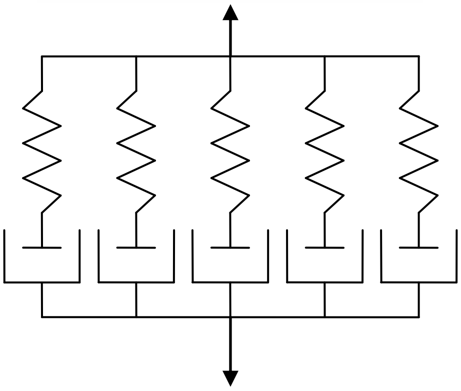
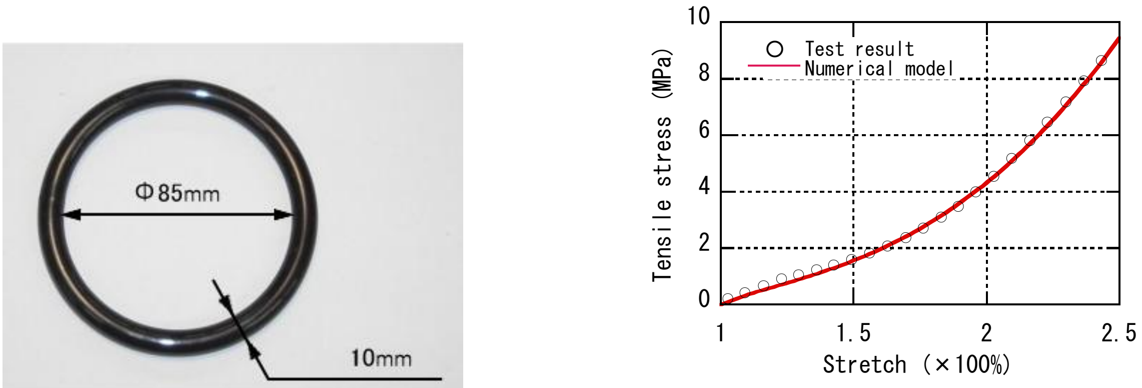
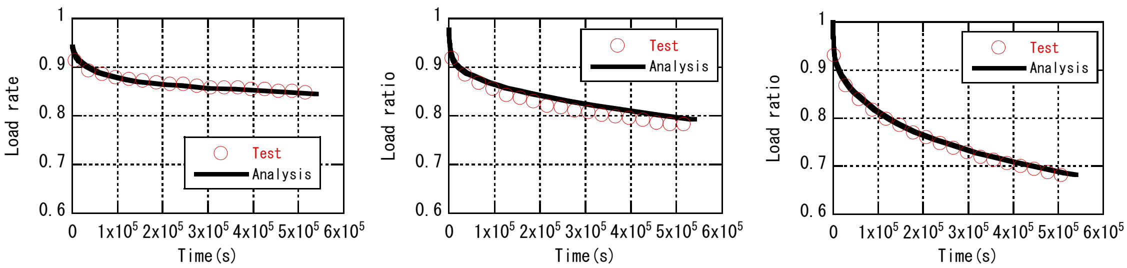


Fig.5 Maxwell visco-elastic model




(a)EPDM O-ring specimen (b) Relationships between stretch and tensile stress

Fig. 6 Loading test result of EPDM O-rings




(a) 90℃ (b) 120℃ (c) 150℃

Fig.7 Loading test result of EPDM O-rings.

Table.2 Relaxation time and material constant(150℃)

| i | $\tau_i$ | $\gamma_i$ |
|---|---|---|
| 2 | $10^2$ | 0.018989 |
| 3 | $10^3$ | 0.046144 |
| 4 | $10^4$ | 0.032897 |
| 5 | $10^5$ | 0.10812 |
| 6 | $10^6$ | 0.20619 |
| 7 | $10^7$ | 0.58766 |

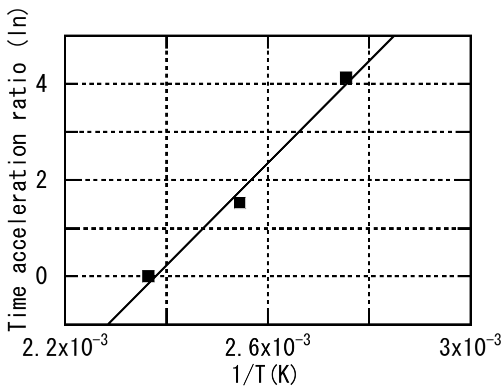
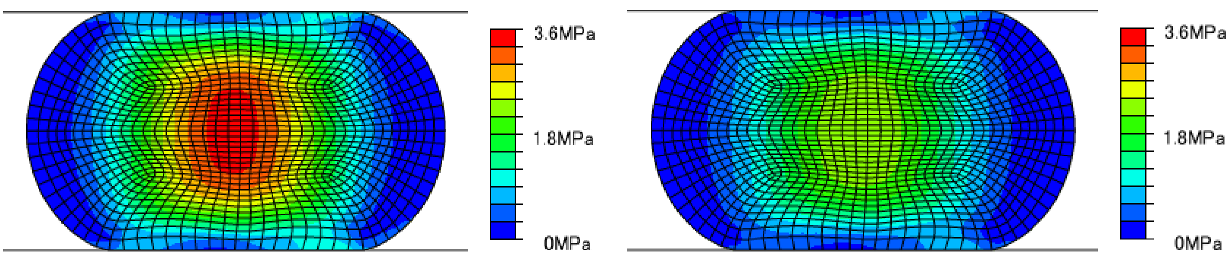


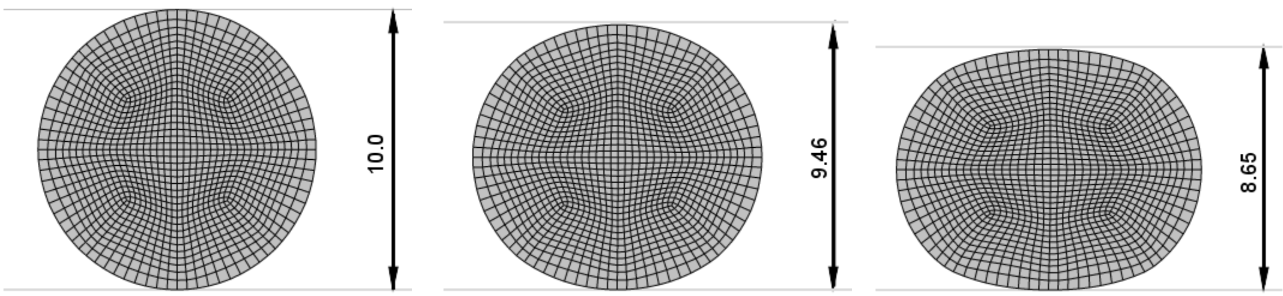

Fig 8. Arrhenius plot of stress relaxation




(a) Initial stress distribution

(b) After 150h under 150℃

Fig.9 FEM mesh of EPDM O-ring




(a) Initial shape

(b) 100℃

(c) 150℃

Fig.10 Initial configuration and after 150h

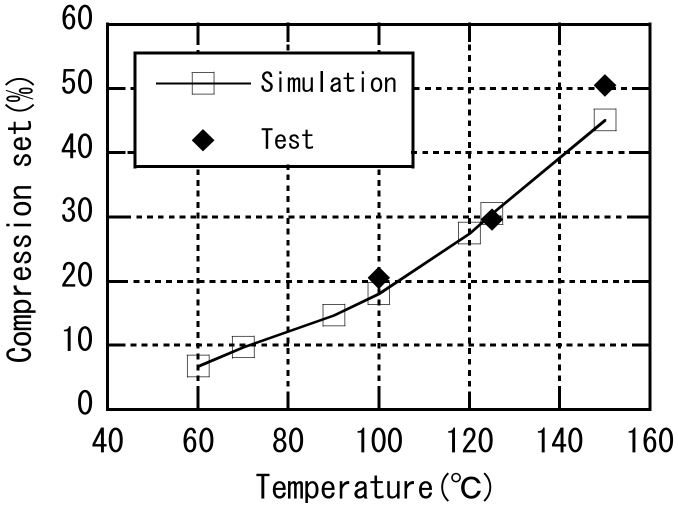


Fig.11 Simulation and test result of compression set

## CONCLUSIONS

In order to confirm the durability of the confinement of package, durability test for EPDM and FKM O-rings, and FEM simulation of EPDM O-ring were conducted.

In durability test, the accelerated aging tests on gaskets were carried out. Test results show that any changes in the leak rate before and after the heating were not observed and the compression set (plastic deformation rates):$D_p$ (about 24% for FKN and 40% for EPDM) corresponding to $70C^{\circ}$-five years （LMP=5367） are less than 75%~80% which is generally considered as a service limit Dp for leak tightness. Therefore, it can be concluded that the rubber O-ring will keep its integrity, at least, for five years at temperature at $70C^{\circ}$.

In FEM simulation, the nonlinear visco-elasticity was applied to prediction of compression set of EPDM O-rings. The master curve of stress relaxation was approximated by the Maxwell visco-elastic model and accelerated ratio by temperature was calculated by the Arrhenius equation. The predicted compression set shows good agreement with experimental results.

## REFERENCES

1) Larson, F. R. and Miller, J., A time-temperature relationships for rupture and creep stresses, Transaction of ASME, vol. 74, pp. 765−775

2) CRIEPI Report N09002, Long-Term Leak-Tightness of Transport Casks for MOX Fresh Fuel, (2009) in Japanese

3) CRIEPI Report U97101, High Temperature Performance Limit of Containment System of Transport Cask (1997) in Japanese

4) Simo, J.C., On a fully three-dimensional finite-strain viscoelastic damage model, Computer methods in applies mechanics and engineering 60:153-173(1987).

5) Simo, J.C. & Hughes, T.J.R. Computational Inelasticity New York: Springer(1997).