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Lifetime evaluation of elastomeric seals for high-voltage switchgear using SF6 and its application to synthetic air insulated equipment.

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SUMMARY

In general, an elastomeric seal is used for the O-ring, which is a gas-tightness parts for GIS. Gas seal characteristics decrease as material deterioration progresses with ageing. This deterioration mechanism is considered to be a dominant factor deciding equipment lifetime, although it is difficult to detect the O-ring conditions from outside. Therefore, a lifetime estimation method for elastomeric seals would be an effective measure for aged equipment that is gradually deteriorating. Also, it is expected that the estimation method will be utilized for SF_6 alternative equipment.

In this paper, the authors propose an O-ring lifetime evaluation method based on the survey of GIS field data, considering the statistical evaluation of compression set, which is an index of O-ring deterioration, and the equivalent temperature during operation. In addition, the lifetime of O-ring in synthetic air insulated equipment is estimated by using the above estimation method.

KEYWORDS

SF_6 gas, Synthetic air, O-ring, Gas leakage, Compression set

1 Introduction

SF_6 gas is widely used as an insulating/arc-quenching medium for gas-insulated switchgear (GIS). However, due to the facts that the Global Warning Potential (GWP) of SF_6 is 25,200 times higher than CO_2, SF_6 alternative development and SF_6 emission reduction are being carried out worldwide. GIS flanges are hermetically sealed by elastomeric seals such as O-rings, but the gas-tightness deteriorates because of the flange face corrosion and permanent deformation of O-rings with ageing. In general, the permanent deformation cannot be diagnosed externally, which may lead to unexpected sudden leakage [1]. This paper reports on the lifetime evaluation of O-rings in GIS and synthetic air insulated equipment based on the experimental and survey data.

2 Gas leakage mechanism as aging phenomena

2.1 Classification of gas leakage

The gas seal configuration of GIS is shown in Figure 1. The O-ring, which consists of elastomers such as Chloroprene Rubber (CR) and Ethylene Propylene Diene Monomer (EPDM), maintains gas-tightness through a counter force against the tightening force of the flange. Gas leakage paths in the O-ring can be classified into two types: permeation leakage related to the gaps in polymer chains and boundary leakage related to the interface between the flange and O-ring.

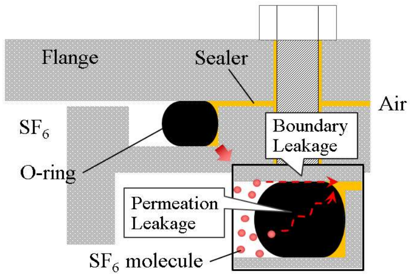


Figure 1: Outline of the gas seal configuration

1. Permeation leakage

   Permeation of gas molecules progresses on the basis of a "dissolution-diffusion mechanism [2]," and the leakage rate depends on the gas molecule size, cohesive energy, gas pressure, and temperature. In the case of a gas medium with a large molecule size like SF_6, it is necessary to analyse long-term trends by using a gas pressure sensor with a high resolution because the amount of permeation is very small in general.

2. Boundary leakage

   Boundary leakage is caused not only by the presence of dust, hair and rust on the flange and O-ring, but also by the aging of the O-ring. Since gas leakage occurs suddenly as soon as a leak path is formed, it is difficult to predict the leakage. Also, once a leakage occurs, it is difficult to completely stop it from outside. The occurrence of rust and other contamination can be prevented by waterproof construction and work environment control, but the aging of O-rings is inevitable in operation.

2.2 Evaluation method of boundary leakage

In general, amount of the gas leakage can be evaluated by the measurement of gas pressure and leakage gas concentration. On the other hand, calculation method of the gas leakage is different between permeation and boundary leakage. In the case of permeation leakage, it is considered as "Mass transfer caused by a gradient of concentration" and can be calculated by using Fick's law. However, calculation method has to be considered depending on the size of leakage path in the case of boundary leakage.

As O-ring deterioration progresses, the flexibility of the rubber decreases, and the true contact area of an O-ring with a flange surface also decreases with the loss of elasticity. According to a study based on the percolation theory by Persson et al., a "non-contact channel" corresponding to a leakage path is formed in the relative contact area of the order 0.4 when elastic solid with randomly rough surface are squeezed together as a function of decreasing squeezing pressure [3]. Under high-pressure gas-filled conditions, a gas leakage path is forced to be formed when the true contact area is at a higher ratio. Assuming that the gas flow through the "non-contact channel" is a viscous laminar flow in a cylindrical conduit with compressible fluid, it is possible to calculate the boundary leakage volume by using Hagen-Poiseuille law as in Equation (1).

$$Q = \frac{\pi a^4}{16\eta L}\frac{M}{RT}\left({P_o}^2 - {P_i}^2\right) \quad \dots (1),$$

where Q is the amount of gas leakage, a is the diameter of the conduit, η is the viscosity coefficient, L is the length of conduit, P_0 is the ambient gas-pressure, P_1 is the internal gas-pressure, M is the molar mass, R is the gas constant, and T is the absolute temperature.

The compression set is an indicator of permanent O-ring deformation, which causes leakage paths. Also, it has been reported that the amount of gas leakage increases rapidly when the compression set exceeds 80 % regardless of the elastomeric material [1]. In this paper, the time to reach an 80 % compression set is considered as the sealing lifetime of the O-ring. The method for calculating the compression set is shown in Figure 2 and Equation (2).

$$C_S = \frac{t_0 - t_1}{t_0 - t_2} \times 100\ [\%] \quad \ldots (2),$$

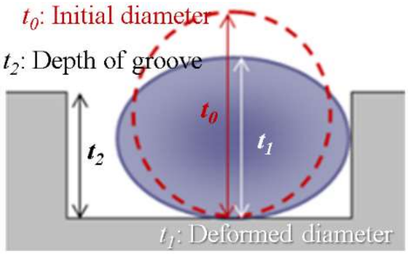


Figure 2: Compression set of O-ring

where C_s is the compression set, t_o is the initial diameter, t_1 is the deformed diameter and t_2 is the depth of groove.

2.3 Progression of compression set by oxidation

Elasticity is imparted to the O-ring by the three-dimensional cross-linking of elastomer molecules. However, the molecules are separated by exposure to solar radiation and oxygen. Also, autoxidation by the generation of radicals leads to the additional cross-linking, thus the separation and cross-linking reaction of the molecule chains progress. These chemical equations are shown in Figure 3. This autoxidation reaction occurs in compressed O-ring, resulting in the progression of the compression set and decrease in the compression counter force. Such reactions occur in structures with intramolecular carbon double bonds, called unsaturated structures, and elastomers with no or few double bonds (Fluorocarbon, EPDM, Hydrogenated-NBR etc.) have excellent oxidation resistance. The flow of the progression of the compression set leading to gas leakage is shown in Figure 4.

Initiation reaction

$RH + O_2 \overset{\Delta}{\rightarrow} R\cdot + HOO\cdot$

$ROOH \overset{\Delta}{\rightarrow} RO\cdot + \cdot OH$

Δ : Thermal stress

Propagation reaction

$R\cdot + O_2 \rightarrow ROO\cdot$

$ROO\cdot + RH \rightarrow ROOH + R\cdot$

$ROOH \rightarrow RO\cdot + \cdot OH$

$RO\cdot + RH \rightarrow ROH + R\cdot$

Termination reaction

$2R\cdot \rightarrow R - R$

$R\cdot + ROO\cdot \rightarrow ROOR$

$2ROO \rightarrow ROOR + O_2$

Figure 3: Autoxidation reactions [4]

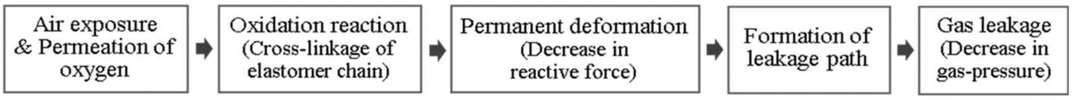


Figure 4: Progression of compression set leading to gas leakage

3 Sealing lifetime evaluation of O-rings for GIS

3.1 Survey result on gas leakage of GIS in Japan

According to an investigation of aged GIS conducted by utilities and manufacturers in Japan, the average number of failures due to natural deterioration was reported as 0.0034 per GIS unit per year from 2011 to 2022. In addition, 13 % of those failures are related to gas leakage. In a questionnaire to utilities and manufacturers, the deterioration of O-rings is considered to be one of the dominant factors deciding equipment lifetime [5].

3.2 Compression set characteristic of O-ring for GIS

Time dependencies of the compression set of CR O-rings in air at ambient pressure are shown in Figure 5 [6]. This test was carried out by using a test equipment simulating a flange structure for GIS. Assuming the time to reach an 80 % compression set as O-ring lifetime, the lifetime at 25 °C was estimated to be more than 10,000 days. The relationship between lifetime and temperature is defined by the Arrhenius law in Equation (3), and the degradation reaction rate is characterized by the activation energy. The activation energy E of a CR O-ring was calculated to be

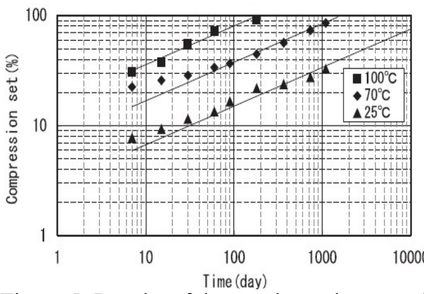


Figure 5: Results of the accelerated test on the compression set of polychloroprene O-ring [6]

about 57,000 J/mol, and noting that, the diffusion process of oxygen in rubber molecules is dominant in the progression of deterioration [6].

$$\frac{1}{\tau} = k = A \times exp\left(-\frac{E}{RT}\right) \quad \ldots (3),$$

where τ is the sealing lifetime, k is the constant of the reaction rate, A is the constant, E is the activation energy, R is the gas constant, and T is absolute temperature.

3.3 Survey data of O-rings in GIS

1. Compression set of O-rings in highly aged GIS

Time dependencies of the compression set of a CR O-rings attached to a 145 - 550 kV GIS installed in the outside are shown in Figure 6. The dotted line is the estimated approximation line obtained by the least-squares method [7] - [9].

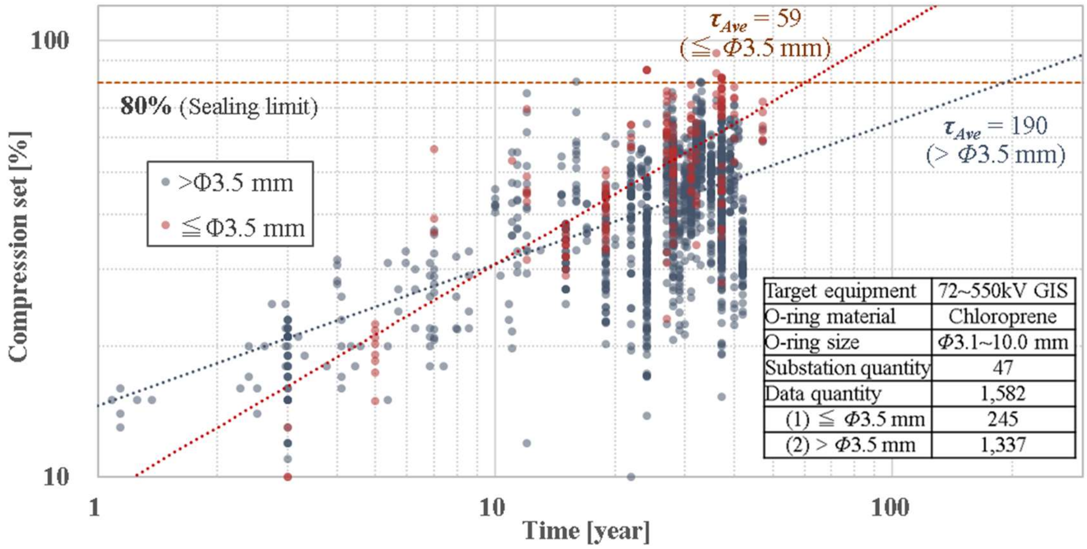


Figure 6: Time dependencies of compression set of O-rings in aged GIS

O-rings of ϕ3.5 mm or smaller, shown in red, are mainly applied to gas piping and are easy to overhaul. However, due to their small diameter, the ratio of the area exposed to ambient air to the O-ring volume is large, and the lifetime tends to be short. It is necessary to accumulate the additional data for accurate evaluation because the amount of data is less than for other sizes of O-ring. On the other hand, the average of reaching time to an 80% compression set of O-rings over ϕ3.5 mm was calculated to be about 190 years. It is much longer than the experimental results shown in Figure 5. The reasons are considered as the difference in O-ring temperature between laboratory tests and field operation, and both sides of O-rings in laboratory tests are exposed to ambient air.

2. Lifetime estimation by statistical approach

To evaluate the percentage of O-rings that exceed an 80 % compression set in the total, the compression set of O-rings over ϕ3.5 mm was converted to that for an arbitrary age using the approximation line in Figure 6. And two parameters, the average and standard deviation, were obtained by considering the data dispersion as a normal distribution. After that, the percentage of O-rings over the 80 % compression set was calculated on the basis of a normal distribution. Statistical evaluation of the compression set and percentage of O-rings over the 80 % compression set are shown in Figures 7 and 8, respectively.

On the basis of the normal distribution of the compression set of O-rings in Figure 7, the average and standard deviation (σ) were calculated to be 44.0 % and 11.8 %, respectively. Assuming that the percentage of O-rings over an 80% compression set is 0.15 % (+3σ) as a measure of statistical lifetime, the time to reach an 80% compression set was estimated to be 31 years as shown in Figure 8. For accurate estimation, it is necessary to accumulate O-rings classify the compression set data as per O-ring types and gas seal configuration.

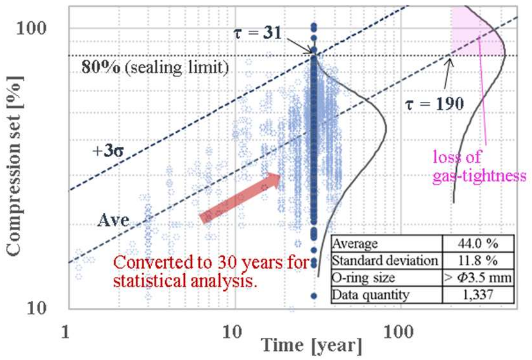


Figure 7: Statistical evaluation of the compression set

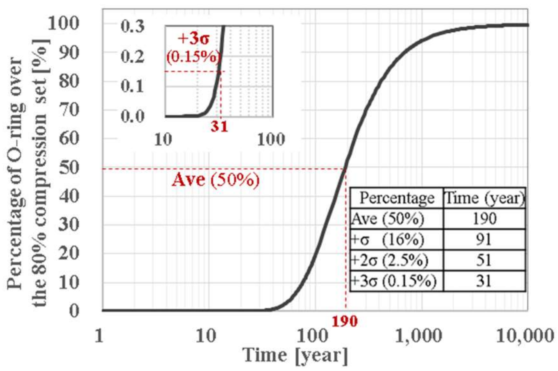


Figure 8: Transition of the percentage of O-rings over the 80% compression set in GIS

3.4 Improvement of the lifetime estimation

1. Equivalent temperature

In the previous section, lifetime estimation was performed by statistical evaluation using an approximation line. In this section, we introduce a method for lifetime estimation taking into account thermal effects to the O-rings. Examples of thermal effects in actual equipment are ambient temperature, solar radiation, current load, and heaters. At any rate, seal lifetime is exponentially fluctuated depending on temperature changes from thermal effects, as shown in Equation (3). Therefore, to accurately estimate the O-ring seal lifetime, it is necessary to utilize equivalent temperature which is an index of temperature taking into account the contribution of Arrhenius law, rather than the average temperature. The process of calculating the equivalent temperature is shown in Equation (4) [6].

$$T_{EQ} = -\frac{E}{R\ ln\left[\frac{1}{t_1 - t_0}\int_{t_0}^{t_1} exp\left\{-\frac{E}{RT_{(t)}}\right\}dt\right]} \qquad \ldots (4),$$

where T_{EQ} is the equivalent temperature, E is the activation energy, R is the gas constant, t_0~t_1 is the measuring time, and $T_{(t)}$ is the temperature fluctuation at the O-ring location. $T_{(t)}$ can be calculated by using Equation (5) as below.

$$T_{(t)} = \theta_{ay} + Asin\frac{2\pi t}{365\times 24} + Bsin\frac{2\pi t}{24} + T_S sin\frac{2\pi t}{24} + T_{LC} + T_h \qquad \ldots (5),$$

where θ_{ay} is the average temperature on the field, A is the annual variation in average daily temperature, B is the daily temperature fluctuation range, T_s is the temperature rise due to sunlight, T_{LC} is the temperature rise during load current flow, and T_h is the external heat input.

By collecting O-ring information including load current and weather conditions from survey data as seen in Figure 6, the equivalent temperature of each O-ring was calculated. Also, time to reach an 80 % compression set of O-rings were estimated based on approximation line of Figure 6, and the dependence of the seal lifetime on the equivalent temperature was evaluated as shown in Figure 9.

From the gradient of the approximation line obtained from the least-squares method of the Arrhenius plot in Figure 9, the activation energy was calculated to be 69,447 J/mol. This activation energy, which is 20 % higher than the experimental value in Figure 5, indicates that the progression in deterioration in the field was slower than the laboratory test. This may be related to the difference in the filling gas medium and existence of sealer between laboratory tests and field GIS. The average of the equivalent

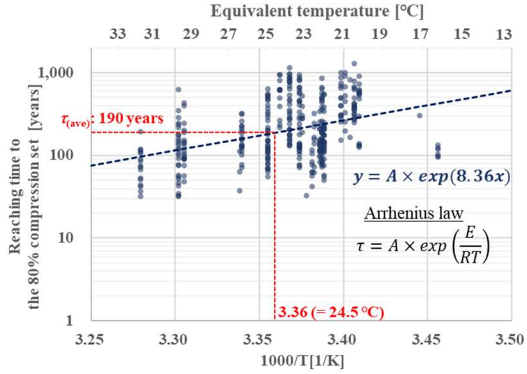
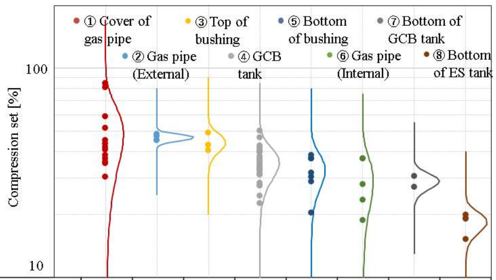


Figure 9: Arrhenius plot of O-rings in GIS based on the equivalent temperature

temperature in the field was estimated to be 24.5 °C by using the above activation energy because of the average time to reach an 80 % compression set is 190 years in Figure 6. By using this method, time to reach an 80 % compression set of O-rings can be estimated from the equivalent temperature of the target GIS.

2. Influence of O-ring location in GIS

The cross-section diameter and thermal affects to the progression of O-ring deterioration. The O-ring location dependency of the compression set is shown in Figures 10 and 11 [9]. O-ring attached to the gas pipes deteriorates in rapidly because the cross-section diameter is small and there is no sealer as a barrier to atmospheric exposure. Excluding these O-rings easy to overhaul, the O-ring on the top of the bushing, which is exposed to solar radiation and high temperature rise due to load current, deteriorates the fastest. There results indicate that the deterioration is affected by temperature rise due to load current and solar radiation, the cross-section diameter, and existence of sealer.



Compression set (ave)		48%	47%	44%	35%	33%	29%	29%	18%
Aging factors	Temperature rise (Solar radiation)	Low	Mid	High	Mid	Mid	Low	Low	Low
	Temperature rise (Load current)	Low	Low	High	Mid	Mid	Low	Mid	Low
	O-ring diameter	≦3.5	≦3.5	>3.5	>3.5	>3.5	≦3.5	>3.5	>3.5
	Sealing gas medium	Air-Air	SF_6-Air	SF_6-Air	SF_6-Air	SF_6-Air	SF_6-Air	SF_6-Air	SF_6-Air
	Silicone sealer	W/O	W/O	W	W	W	W/O	W	W

Figure 10: Evaluation of compression set by the locations of O-ring in GIS [9]

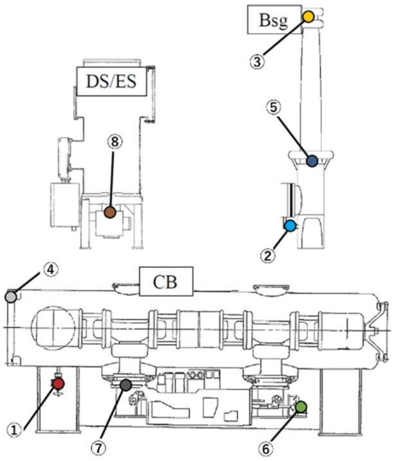


Figure 11: O-ring locations for GIS [9]

4 Lifetime estimation of alternative gas equipment

4.1 Gas seal configuration of alternative gas equipment

For equipment filled with highly pressurized synthetic air, an elastomeric seal superior to oxidation resistance is proposed. Therefore, it is necessary to consider not only the difference in gas medium and gas pressure, but also material-specific deterioration characteristics for appropriate lifetime estimation. In this paper, EPDM is evaluated as an oxidation-resistance elastomer.

4.2 Seal lifetime of O-rings for synthetic air insulated equipment

To clarify the characteristics of the deterioration of EPDM, O-rings of ϕ5.7 mm were attached to a test equipment simulating actual flanges, as shown in Figure 12, and the time dependencies of the compression set were evaluated under constant temperature controlled by thermostatic bath. Also, synthetic air of 0.1 and 0.8 MPa-abs was filled into the test equipment in order to evaluate an impact from gas pressure. The compression set characteristics and Arrhenius plot of EPDM are shown in Figures 13 and 14, respectively.

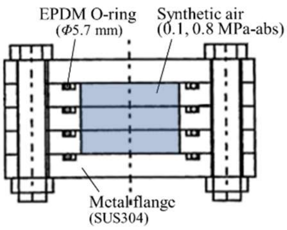


Figure 12: Test configuration

Figure 13 indicates that the progression of deterioration of EPDM is much slower than CR, and the time to reach an 80 % compression set of EPDM in 100 °C/0.1 MPa-abs is about 40 times longer than that of CR shown in Figure 5. Also, the compression set tends to progress with the rise in temperature and pressure. The impact on the acceleration of the oxidation reaction is considered to be the increase in collision frequency between oxygen and elastomer molecules. From the gradient of the approximation line at a temperature above 80 °C in Figure 14, the activation energy of EPDM was calculated to be 134,081 J/mol. Since the average equivalent temperature was 24.5 °C as described in the previous section, it was observed that the time to reach an 80 % compression set will be much longer than expected equipment lifetime, which is 30 - 40 years, as shown in Figure 14. Since a rapid increase in activation energy was observed below 70 °C, there is a possibility that the deterioration mechanism changes around 70 °C.

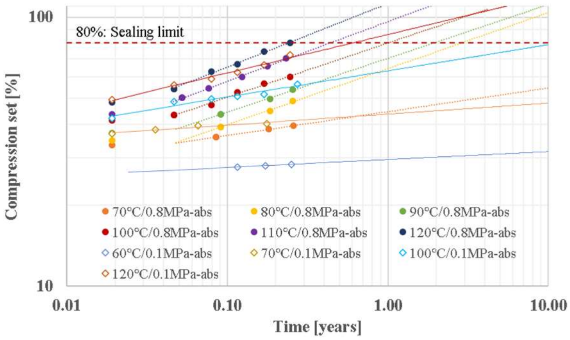


Figure 13: Temperature and gas pressure dependencies on compression set of EPDM O-rings

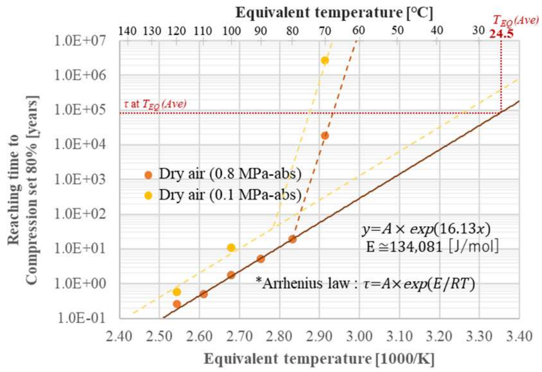


Figure 14: Arrhenius plot of EPDM O-rings

4.3 Statistical evaluation of seal lifetime

Since the progression of compression set depends on equivalent temperature, the variance of equivalent temperature in the field GIS can be obtained by the conversion of compression set data in the field shown in Figure 7. Assuming that thermal effects in synthetic air insulated equipment is equivalent to SF_6, lifetime of EPDM O-ring can be evaluated statistically by using Arrhenius law according to this variance. The variance of the equivalent temperature and compression set is shown in Figure 15. The average and +3 σ (0.15 %) of the equivalent temperature were calculated to be 24.5 °C and 44.9 °C, respectively. The compression set of EPDM in the field will also be fluctuated as per this variance. Time dependencies of compression set of EPDM with statistical distribution and the transition of the percentage of O-rings over the 80 % compression set in the synthetic air insulated equipment are shown in Figures 16 and 17, respectively.

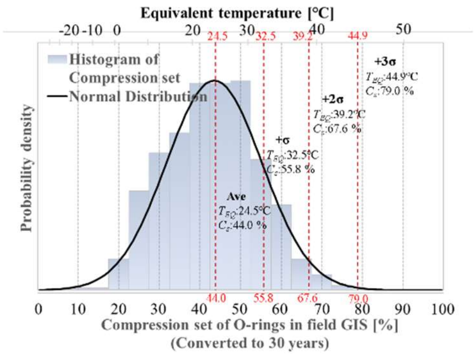


Figure 15: Variance of equivalent temperature based on compression set data in the field GIS

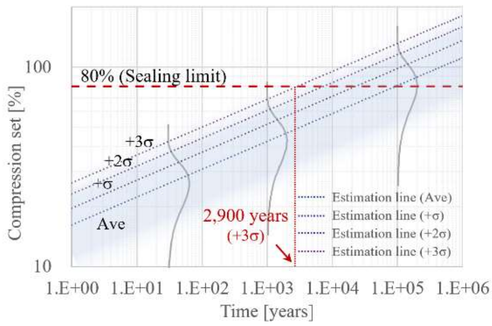


Figure 16: Time dependences of compression set of EPDM in synthetic air

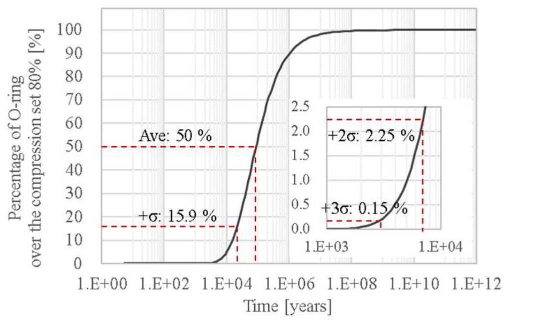


Figure 17: Transition of the percentage of EPDM O-rings over the 80 % compression set in synthetic air

As shown in Figures 16 and 17, +3 σ (0.15 %) seal lifetime of EPDM was considered to be sufficiently longer than expected equipment lifetime, which is 30 - 40 years. The activation energy of 134,081 J/mol was used in this calculation, but it is considered that the progression of EPDM deterioration below 70 °C becomes more slowly because of the change of activation energy.

5 Conclusions

The time to reach an 80 % compression set of CR O-rings in GIS and EPDM O-rings in synthetic air insulated equipment, which are equivalent to the sealing lifetime of O-ring, were investigated through statistical analysis of GIS field data and laboratory test results of EPDM. These evaluations yield the following conclusions. Further accumulation of O-ring data and classification as per the cross-section diameter and influence of sealer are expected to improve the accuracy of the lifetime estimation.

- The time to reach an 80 % compression set of CR O-ring over ϕ3.5 mm was estimated to be 190 years as average and 31 years as +3 σ (0.15 %), based on statistical evaluation of survey data in the field GIS. Also, it was confirmed that the O-ring at the top of bushing tends to deteriorate rapidly, excluding the O-rings of ϕ3.5 mm or smaller.
- Equivalent temperature of the O-rings in the field equipment was calculated to be 24.5 °C as average and 44.9 °C as +3 σ (0.15 %) based on the normal distribution of O-ring compression set in field GIS.
- It was confirmed that the progression of EPDM deterioration is slower than CR based on the laboratory tests, and time to reach an 80 % compression set of EPDM is equivalent to about 40 times of CR in the synthetic air of 100 °C/0.1 MPa-abs.
- As a result of statistical evaluation taking into account the variance of compression set at the field, it was estimated that reaching time to an 80 % compression set for +3 σ (0.15 %) of EPDM O-rings attached in synthetic air insulated equipment is sufficiently longer than the expected equipment lifetime, which is 30 - 40 years.

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