Analysis of accelerated ageing of non-ceramic insulation equipments

Article in IET Generation Transmission & Distribution · January 2012
DOI: 10.1049/iet-gtd.2011.0078

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Analysis of accelerated ageing of non-ceramic insulation equipments

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Abstract: Ageing of non-ceramic insulation can conduct into failures of the power system, where usually pollution plays an important role in the degradation process. These failures cannot be evaluated by applying IEC 61109 ageing tests, because such tests are considered as screening tests and up to now these tests are quite questionable. Therefore research of new test methods and diagnostic tools are needed to predict long-term performance of non-ceramic insulators. A non-standard method for insulation ageing is modified and used in this work to evaluate non-ceramic components of breakers, bushings and surge arresters. Different diagnostic tests are proposed to analyse the evolution in the degradation process of these apparatus. The results showed that the applied methodology and the proposed tests may evaluate in a more realistic way the performance of new non-ceramic insulating material used in electrical equipment.

1 Introduction

The use of non-ceramic insulators (NCIs) has increased significantly since the early 1990s because of many advantages they provide [1–9]. The main advantages are: NCIs can be installed with a reduced labour force, they are easier to handle than porcelain or glass insulators [10–14]. NCIs perform well under polluted conditions and they are cheaper than equivalent porcelain or glass strings. Another key point is their hydrophobicity, particularly those manufactured with silicone rubber (SiR) [9, 15, 16]. The SiR helps to prevent the formation of a water films on the insulator surface, even when that surface is polluted. However as the insulation ages, dry band arcing may cause erosion and tracking on the surface of these insulators [5–7, 17–20]. This damage or ageing may lead to the failure of the insulator.

Various scenarios of the ageing process of NCIs have been established, and several factors that contribute to the ageing process have been identified [2, 21–25]. These factors are: ultraviolet radiation, moisture, mechanical breach of the housing, thermal stresses, corona, dry band arcing, pollution level and the pollution type. Up to now, most researchers agree that these parameters affect the ageing of NCIs.

NCIs made of SiR have performed well under polluted conditions, particularly in regions where porcelain or glass conventional insulators have had problems [2, 7, 26, 27]. Under conditions of prolonged and constant wetting, a temporary loss of hydrophobicity can occur on the NCIs. During this period dry band arcing can occur; however, when wetting ends and after a few hours, the surface layer will recover its hydrophobicity, thereby regaining its most important characteristic for the next wetting period.

At the moment, there are no standardised tests than allow us to know the long-term performance of NCIs [1–4]. Also, there is no suitable diagnostic methodology to evaluate when the NCI has reached its useful life [2, 4–8].

The Mexican utility CFE reports that lightning and contamination are the top two causes of power outages, respectively. Different alternatives have been attempted to solve the pollution problem using conventional glass or porcelain insulators. These methods include installing insulators with increased arcing or leakage distance, the use of hydrophobic coatings, preventive maintenance using water washing and the use of NCIs. NCIs have been installed in heavily polluted conditions where their hydrophobic property was lost after being subjected to pollution and wetting, leading to degradation by erosion and tracking. In these areas, some insulators were removed from the transmission lines before failure; however, in a few cases the insulators failed even with preventive maintenance [28]. This suggests that pollution levels are extremely high even for NCIs in spite of these insulators passed successfully international standard design tests. Apparently, the standard test methods do not appear to reflect properly the field conditions.

The advances in manufacturing methods and better insulating materials have allowed non-ceramic components to be included in electrical equipment such as circuit breakers, transformer bushings, surge arresters and station posts. These equipments work mainly in substations where reliability requirements are higher than for transmission lines. Therefore it is important to determine the long-term performance of NCIs under heavily polluted conditions and to develop diagnostic tools for monitoring their operative conditions [4]. These research actions will allow establishing maintenance programmes in order to prevent
failures and to keep the reliability of the electrical system. On this basis, the aim of this work is to evaluate in laboratory the performance of non-ceramic components commonly used in substations using a methodology that accelerates ageing of the insulating material. The test method was developed by the Instituto de Investigaciones Eléctricas for aging NCIs [29]. In the methodology used in this paper, UV periods were added and the diagnostic of the ageing on the non-ceramic components was monitored by different techniques.

2 Ageing test methodology

As mentioned before, the ageing test methodology was outlined in an earlier publication [29] and briefly mentioned here for clarity. Basically, the methodology consists of three cycle sequences: the first one is to stress the insulation for a period of 24 h in a salt-fog chamber, followed by a 12 h dry period with UV. Finally, after switching off the UV, 24 h of clean fog is applied; for a total time of 60 h per cycle. The test sequence is given in Table 1. Then, the cycle is repeated for a total time of 5000 h with the components continuously energised at nominal phase-to-ground voltage and 60 Hz.

Before starting the ageing test, the insulations are washed off and then a pollution layer is deposited on their insulation surface by using the solid layer method. Slurry is prepared with 20 g of kaolin and 10 g of salt per 50 ml of demineralised water. A sponge is used to apply the slurry by hand. At the half-way through the test, namely, after 2500 h of testing, the insulations are washed off again and after that, the pollutant layer is reapplied. After applying the new pollutant layer on the insulation surface, the apparatus is allowed to rest for 48 h prior to restarting the test, thereby allowing the contaminant layer to dry and to recover hydrophobicity.

During the ageing test, the leakage current is measured; the frequency and range of the leakage current peaks are recorded and classified by a custom-made data acquisition system [30]. The current peak measured is the highest value at each semi-cycle of the 60 Hz signal. The electric field is also measured before the test and again at 2500 and 5000 h with a DayCor II corona camera developed by EPRI Solutions, which helps to validate the obtained results. Corona observations are also made at 2500, 3260 and 5000 h, with a DayCor II corona camera developed by EPRI Solutions, which helps to identify possible damage in the insulation [2, 4, 32].

At several times during the test, the static contact angle and a microstructure analysis of the insulating surface of each specimen is carried out. Digital imaging analysis is used to measure the contact angle. The microstructure analysis is done by applying the replica technique, a technique used in metallurgy.

Traditionally, leakage current measurement is carried out in insulators energised at the nominal voltage throughout by a suitable power supply. The sensor is connected in series with the insulator and the leakage current is measured through a shunt resistor or current transformer. Leakage current value depends on the variations of humidity and the accumulated pollution. This technique allows continuously registering the different waveforms of the leakage current (basic and peak current, magnitude, etc.), until flashover. Harmonic analysis shows that the main components of the leakage current are the 60 Hz fundamental and the third harmonic. There are smaller amounts of the fifth, seventh and ninth harmonics. Based on these results, the measurement bandwidth was fixed at 1 Khz. On the other side, the system revised during 2.5 ms in the ascending rectified sinusoidal waveform the amplitude to detect a peak and takes 2 ms to restart the counter peak; moreover, every semi-cycle of the leakage current is measured [30]. Peak values were analysed in different levels during the test. As wetting of the pollution layer increases, higher peak values and peak numbers are registered.

To measure electric field, a composite insulator tester developed by Hydro-Québec was used to measure the field distribution along the insulator. The field probe of this tester is mounted on a carriage which must be slid manually along the insulator. The measured data are stored in the memory of the tester which is later transferred to a computer and according to the shape of the curve it may be determined if the insulator is damaged, because damage is assumed to affect the electric field.

With the static contact angle measurement, it is possible to determine the hydrophobic properties of the NCIs surface. The hydrophobicity is the degree of the water repellency of the insulator surface. In this work, the sessile drop technique was used for measuring the static contact angle on the insulators, using the digital image analysis. A precision pipette was used and the volume of each droplet was 10 μl. For each sample ten droplets were put on the top surface and the contact angle was measured.

Replication, a non-destructive technique, is generally used to detect service failures in both ceramic and metallic materials. It records and preserves the topography of a micro-structural surface as a negative on a thin film of cellulose acetate. In this technique, the film is first softened using acetone and then applied to the surface. In the soft state, the structure of the surface is replicated and preserved when the film hardens after the solvent evaporates. In this way, the technique is useful in preserving the microstructure surface at various times during ageing [33].

Table 2 shows the main characteristics of the test chamber. The UV radiation was simulated with 40 type UVA-340 fluorescent lamps and the UV irradiance at the insulation apparatus is in the range of 0.65 W/m². The design of the salt-fog nozzles is as per IEC 601109, and the salinity of the brine is 3 kg/m³.

Table 1 Cycle sequence in the ageing test of non-ceramic apparatus

<table>
<thead>
<tr>
<th>Cycle sequence</th>
<th>Exposure</th>
<th>Time duration, h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>salt-fog</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>UV (dry)</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>clean-fog</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 2 Main parameters in the aging test

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal test voltage</td>
<td>66.4 kV&lt;sub&gt;phase-ground&lt;/sub&gt;</td>
</tr>
<tr>
<td>volume of the chamber</td>
<td>203 m³</td>
</tr>
<tr>
<td>water flow rate</td>
<td>0.4 lt/h m³</td>
</tr>
<tr>
<td>salinity of salt-fog</td>
<td>3.0 kg/m³</td>
</tr>
<tr>
<td>IEC nozzle air pressure</td>
<td>588.4 KPa</td>
</tr>
<tr>
<td>radiation UV</td>
<td>≃0.65 W/m²</td>
</tr>
</tbody>
</table>
3 Non-ceramic apparatus evaluated

The polymeric apparatus evaluated in this project are two substation surge arresters and two bushings. Table 3 includes the main characteristics of the equipments and Fig. 1 shows the set-up for the salt-fog chamber. These apparatus voltage classes are used in 115 kV ac systems. Therefore these equipments are evaluated under this voltage level (66.4 kV phase-to-ground). Each bushing is mounted on a small steel tank, and both the bushing and the tank are pressurised with nitrogen to avoid moisture ingress into the tank. The test voltage of 66.4 kV phase-to-ground is applied at the upper flange, and the tank is grounded.

3.1 Electric field simulation

To know if the electric stress on the surface of the tested insulations can cause degradation, a two-dimensional simulation of the potential distribution and electric field at nominal 60 Hz voltage is performed for each evaluated non-ceramic apparatus, without pollution applied and with axial symmetry, using COMSOL Multiphysics. The corresponding potential distribution and electric field strength along the bushing 2 and surge arrester 3 surfaces are shown in Fig. 2. For the bushing (Figs. 2 a and b), about 54% of potential is distributed at the top zone from 1.2 to 1.4 of its arc length, and normal electric field strength at the last shed is 3.3 kV/cm, while for the surge arrester 3 (Figs. 2 c and d), the potential distribution is almost uniform along its insulating housing, and its highest value of electric field is 2.7 kV/cm. On the surface of the surge arrester 4, the highest computed value of the electric field is 5.1 kV/cm. According to Phillips et al. [34], the maximum electric field strength to prevent surface degradation is 4.5 kV/cm. It means that under non-polluted conditions, surface significant degradation may not develop itself on the bushing and on the surge arrester 3, but it may occur on the surge arrester 4. However, when the insulation surface is polluted, the electric field may be strong enough at the insulation’s surface to produce partial discharge activity during wet conditions. These discharges together with dry band arcing can accelerate the ageing of the insulation.

3.2 Measurement of leakage current

The frequency of leakage current pulses was classified in eight ranges and includes the complete 5000 h period for all the tested apparatus, as shown in Fig. 3. In the first leakage current range, 50–120 mA, the highest number of leakage current pulses were recorded for the bushing without kaolin layer, namely sample number 2 (Fig. 3 b). The effect of a non-solid layer of contaminant appears to be responsible for the high frequency of peaks in the lowest current range, 50–120 mA, and for the low number of pulses in the higher current ranges above 120 mA. For leakage current pulses higher than 120 mA, the highest number of pulses occurred on the apparatus with pollutant layer, namely samples 1 and 3 (Figs. 3 a and c). The surge arrester without the polluted layer (Fig. 3 d) showed the lowest number of leakage current pulses. The result of visual evaluations performed during the test confirmed that hydrophobicity of this surge arrester did not diminish during the 5000 h of testing.

The obtained results imply that the hydrophobicity in the surge arrester without polluted layer helped to avoid surface discharges on its surface and consequently, a small amount of leakage current pulses as shown in Fig. 3 d, compared to the other tested equipments. In the range of current pulses higher than 260 mA, the accumulated pulses are practically zero; consequently, the flashover probability under these conditions is very low. The number of pulses recorded for the 50–120 mA and 120–250 mA ranges indicates that degradation in the insulation because of surface discharges (pollution) may be insignificant in this case.

As the leakage current interval increases (Fig. 3), the current peak’s behaviour is similar in both bushings and in the surge arrester with pollutant layer. In the ranges from 50–120 to 320–380 mA, the number of pulses decreases as the magnitude of current peaks increases. In the 380–440 mA range, the number of peaks increases slightly and then diminishes to the 440–500 mA range. After this range, the number of peaks tends to increase from one range to another starting at 440 mA. According to results obtained in other research projects [2, 35, 36], it has been observed that polymeric insulation is aged mainly by low-energy surface discharges. Hence, by considering the number of pulses recorded in the 50–120 and 120–250 mA intervals, it can be said that these leakage current peaks accelerate the ageing of the non-ceramic components. According to Figs. 3 a and b, the non-solid layer of contaminant on sample 1 caused the increase of leakage

![Insulation arrangement inside the salt-fog chamber](image)

Table 3 Characteristics of the evaluated non-ceramic apparatus

<table>
<thead>
<tr>
<th>Sample</th>
<th>Apparatus</th>
<th>Housing material</th>
<th>Sheds</th>
<th>Leakage distance, mm</th>
<th>Arcing distance, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>bushing with pollutant layer</td>
<td>SIR</td>
<td>29</td>
<td>2810</td>
<td>1380</td>
</tr>
<tr>
<td>2</td>
<td>bushing without pollutant layer</td>
<td>SIR</td>
<td>29</td>
<td>2810</td>
<td>1380</td>
</tr>
<tr>
<td>3</td>
<td>surge arrester with pollutant layer</td>
<td>EPDM</td>
<td>24</td>
<td>4770</td>
<td>1670</td>
</tr>
<tr>
<td>4</td>
<td>surge arrester without pollutant layer</td>
<td>SIR</td>
<td>22 + 21</td>
<td>3530</td>
<td>1030</td>
</tr>
</tbody>
</table>

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current pulses from 120 to 250 mA current range. By adding the number of pulses in these two intervals, the highest activity of current pulses occurred on the surge arrester with pollutant layer with $5.825059 \times 10^6$ pulses. The sum of pulses in the bushing without pollutant layer is $5.580349 \times 10^6$, and in the bushing with pollutant layer, it is $3.109533 \times 10^6$ pulses. In this case, the activity in the surge arrester is attributed to hydrophobicity lost through this evaluation, as is shown later. Therefore the surge arrester’s insulation is most susceptible to ageing.

From the 260–320 mA current range and higher ranks, the highest peak frequency is recorded in the bushing and the surge arrester with pollutant layer (Figs. 3a and c). The lowest number of pulses on the surge arrester is because of its longer leakage distance compared to that of the bushing, which is about 69% as shown in Table 3. Therefore the development of a pollution flashover is of lower probability in the surge arrester than in the bushing. Based on this, the pollution flashover process in polymeric insulation depends mainly on both the leakage distance and the insulating material type for the tested apparatus.

### 3.3 Corona activity

Another parameter that can cause degradation on the polymeric insulation is the corona activity. It is analysed by detecting corona on the testing insulators several times along the ageing test. The first inspection with the DayCor II camera was performed after 2500 h of testing. The test was stopped and when the pollutant layer was dry, the first inspection was made. No corona was observed on the surface of any of the four apparatus. Several small regions of degradation about 6 mm in diameter were observed visually in sample number 4 (surge arrester without pollutant layer) along the housing between the sheds, as shown in Fig. 4a. For this insulation, corona inspection was carried out again during the clean fog period of the cycle as shown in Fig. 4b.
**Fig. 3** Number of leakage current peaks on

- **a** Sample 1 with pollutant layer
- **b** Sample 2 without pollutant layer
- **c** Sample 3 with pollutant layer and
- **d** Sample 4 without pollutant layer

**Fig. 4** Clean fog on sample number 4 after 2 500 h of testing

- **a** Degradation
- **b** Corona activity
Following this observation, corona inspection was done during the clean fog periods at 3260 and 5000 h. In these inspections, corona was detected in all the apparatus insulation. On both bushings, corona was observed in the region of the first few sheds from the energised terminal where the simulation in Figs. 2a and b show the highest electric field. In the surge arresters, corona occurred mostly between the sheds along the housing. The simulations shown in Figs. 2c and d indicate that the electric potential distribution is similar along the surge arresters, but the electric field strength on the surge arrester without pollution layer (sample 4) is higher because it has a shorter arcing distance (Table 3). For this reason, it is probable that the higher electric field strength caused the early degradation in sample 4.

At the end of the test, the four insulations showed degradation along the surface as shown in Fig. 5. On the bushing with pollutant layer, sample 1, a puncture in shed no. 2 was observed (from the energised end). On the bushing without pollutant, sample 2, erosion was evident on shed no. 1 (from the energised end). On the surge arrester with pollutant layer, sample 3, erosion was observed along all the housing. The tracking damage that was observed on sample 4 at 2500 h, Fig. 4a, changed very little after 5000 h of testing, as evidenced in Fig. 5.

The obtained results showed that corona activity can damage the polymeric insulation under dry and wet (clean fog) conditions. Therefore the corona effect must also be considered to evaluate ageing, in addition to the leakage current pulses.

### 3.4 Electric field measurement

The electric field distribution was measured on the four apparatus at 2500 and 5000 h of testing. In each measurement period, the test was stopped and 24 h later, when the samples were dry, the electric field was measured at test voltage (66.4 kV\textsubscript{phase-ground}). Nearly 5000 h after the ageing test was completed, another electric field measurement was only made on sample 4 in order to validate the obtained results. During this period, the sample mainly rested in dry conditions without voltage. In this case, before doing the measurement, sample 4 was cleaned up in order to remove the carbonised residues from its insulating surface, and the achieved results are referred to 10 000 h.

Fig. 6 shows the obtained results for the different test periods and each curve represents a period. For the measurements carried out during the 2500 and 5000 h periods, the curve corresponding to the 5000 h period for sample 4 (Fig. 6d) shows abrupt changes from one point to another, closer to the high-voltage electrode. It is considered that such change is because of the tracking damage observed on the insulation after 2500 h of testing (Fig. 4). Therefore the performance of this curve could indicate that the tracking is a risky condition for a further failure, and that the equipment should be either replaced or monitored frequently. The other curves, including those for samples 1–3, show a smooth change from one point to another, which is the expected performance for insulations in good operating condition. These curves indicate that, for the period in which they were obtained, the level of ageing produced in the apparatus by this testing process is not a failure risk.

The easy detachment of the carbonised residues on the surface of sample 4 showed that erosion was slight, having a depth less than 1 mm. For this reason, it is supposed that such erosion is not a failure risk for the integrity of the insulation, as long as the tracking is removed. The above was verified with the electric field measurement at 10 000 h as shown in Fig. 6d. The curve for the 10 000 h period shows a smooth change from one point to another. Therefore it can be said that the deformation observed after
5000 h of testing was because of the carbonised residues on the insulation surface.

According to the above, the analysis of electric field measurements in the four samples indicates that the level of degradation after 5000 testing does not represent a risky condition for these apparatus.

### 3.5 Static contact angle measurement

In order to estimate the hydrophobic properties of the housed insulating materials, the static contact angle was measured on samples 3 and 4: EPDM and SiR surge arresters, respectively. The measurements were performed immediately after finishing a salt-fog cycle on a surface cleaned by using ethylic alcohol. The evaluation was done on the top surface of the sheds located on the top and in the middle of each surge arrester: sheds no. 1 (top) and no. 12 (middle) for sample 3 and sheds no. 1 (top) and no. 11 (middle) for sample 4.

Fig. 7 shows the trend of the static contact angle as a function of ageing test time for EPDM and SiR surge arresters. The hydrophobicity is similar at the different shed positions for the same apparatus, but the behaviour is different for EDPM and SiR material. On the EPDM surge arrester, the hydrophobicity decreases drastically after 3000 h of testing. This hydrophobicity reduction is attributed to polymer degradation caused by the salt fog conditions and electrical stresses. On the other hand, the SiR arrester did not lose hydrophobicity during the test.

According to visual observations performed around 2500 h of testing, the SiR surge arrester showed higher deterioration than the EPDM surge arrester. After this testing time, its deterioration almost did not grow, while on the EPDM surge arrester, it grew significantly. However, the contact angle on SiR did not change very much during the whole test as it does on EPDM insulating material. It can be said that the static contact angle does not give enough information about the ageing process in SiR as it does in EPDM surge arrester.

### 3.6 Microstructure analysis by replica technique

Fig. 8 shows replica micrographs of shed and of sheath for the EPDM and SiR surge arresters. The shed micrographs
Fig. 7  Static contact angle of the surge arresters in 5000 h of testing
a EPDM surge arrester with pollutant layer
b SiR surge arrester without pollutant layer

c 0 hour  2500 hours  3280 hours  4150 hours

Fig. 8  Surface microstructures obtained by replica technique of insulating material of the surge arresters on shed (a and b) and on sheath (c and d) at different ageing times
a EPDM surge arrester with a pollutant layer
b SiR surge arrester without a pollutant layer
c EPDM surge arrester with a pollutant layer
d SR surge arrester without a pollutant layer
of the EPDM surge arrester (Fig. 8a) show the effects of ageing in the level of erosion at different test time. The electrical stress and the aggressive environment simulated in laboratory have promoted degradation of the polymer matrix in the housing composite. As indicated by the rows in Fig. 8a, filler microparticles on EPDM insulating material are seen after 2500 h until the end of the test, while on the shed micrographs of the SIR surge arrester (Fig. 8b), fillers are shown after 4150 h of test.

The replica technique has the advantage of making a surface analysis of the sheaths which is almost impossible by other methods. Figs. 8c and d show microstructures observed by replication of EPDM and SIR sheaths at 4150 h of accelerating ageing. The environmental and electrical stresses are more aggressive on this side of the surge arresters because more eroded areas were observed on the replica. In the case of SIR material, the degradation process was caused mainly by corona activity, according to results obtained from the measurement of visible corona. In the replica, it was shown by the corona camera. The worst degradation was observed on the surge arrester with pollutant layer, which was subjected to the highest activity of surface discharges in the range from 120 to 260 mA, as it was shown by the replica technique, but it did not severely damage the insulation.

According to the replica technique, erosion was identified on the insulating material of the surge arresters, and this erosion was more severe on their sheaths.

The developed test allows the evaluation of the accelerated ageing of different polymeric insulation materials and profiles. The cycles considered in the test help to know the effect of the hydrophobic property of the polymeric material on the performance under wetting and pollution conditions. The results show that a good hydrophobic property does not always mean a good performance to the ageing resistance, but it also depends on the material composition. The application of a pollutant layer on the insulation surface in the beginning and in the middle of the test is an important factor to ageing the insulating material. The pollutant layer causes a high electric activity close to the insulation surface which may age the insulation in a short time.

The hydrophobic property of the insulating surface can decrease the degradation caused by the surface discharges (dry bands) if it is maintained, as it happened with the SIR surge arrester (sample 4). However, if the arcing distance is not longer than 1 m, the electric field could damage the insulating surface. Therefore the arcing distance must also be selected accordingly to avoid that the electric field strength magnitude be higher than values that may cause surface degradation.

Non-ceramic components of breakers bushings and surge arresters in service can suffer damage under heavily polluted conditions. Therefore the performance of this equipment must be monitored periodically in order to keep a reliable electrical system. The diagnostic techniques considered in this work can be used to monitor such performance. Furthermore, the results obtained from different inspections using these techniques could help us to settle on the life assessment of non-ceramic insulation. The inspection periods will depend on the results obtained from each inspection.

The methodology applied in this research may evaluate in a more realistic way the performance of new non-ceramic insulating material used in electrical equipment.

5 Acknowledgments

The authors thank the CFE by their contribution in the development of the project, and also the invaluable advice provided by Dr. Carlos Romualdo Torres is appreciated.

6 References

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