Brittle Fractures of Composite Insulators
an Investigation of their Occurrence and Failure Mechanisms and a Risk Assessment

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Abstract : The paper deals with the failure phenomenon called “BRITTLE FRACTURE” that has been observed with composite insulators. The total number of known brittle fractures is discussed in relation to the number of composite insulators that are in service. Results of field tests to simulate brittle fractures are described and simplified models of the complex physical-chemical deterioration processes revealed by laboratory studies are presented. The findings from laboratory brittle fracture tests are supplemented by field observations on existing networks. Discussion of test procedures and a risk assessment for installed insulators provide information relevant to utility.

Keywords : composite insulator, FRP rod, brittle fracture, glass fibre, epoxy, hardener.

1- Introduction

Composite insulators have been in service on distribution lines since the late 60’s and on transmission systems since the early 70’s. Since then, the general design, the materials used as well as the manufacturing technologies have improved. The use of composite insulators as alternative to conventional ceramic insulators for all voltage levels has increased steadily. Over the past 30 years, a number of composite insulators have failed by brittle fractures. The first reported failures have occurred on transmission lines in South Africa and Italy, where the first generation of composite insulators had been installed. The failures occurred after a short period of service and at load levels well below the rated mechanical strength. An analysis performed by CIGRE WG 22-03 and by an IEEE Brittle Fracture Task Force indicated that the total number of insulators that have failed by brittle fractures is between 100 and 200 units.

This paper is divided into several sections, which are as follows:

- presentation of the work of CIGRE WG 22-03 and of an IEEE Task Force,
- evaluation of the results of tests conducted by WG 22-03 on composite insulators with built-in defects in 2 laboratories and at the Dungerness outdoor station,
- overview of the present knowledge on the physical-chemical processes that may explain brittle factures,
- discussion of the design and test philosophies recommended to avoid brittle factures and suggestion for qualification test,
- are post and hollow core composite insulators unlikely to be affected by brittle fracture,
- evaluation of risk associated with existing lines.

2- Worldwide Occurrence of Brittle Fractures

Very few brittle fractures have occurred in service. However in the case of a single insulator arrangement, a brittle fracture means a loss of the mechanical integrity and the conductor can drop to the ground. Such events can have dramatic consequences, especially in the framework of de-regulated markets and their rules. For this reason, in the late 90’s, CIGRE WG 22-03 and an IEEE Brittle Fracture Task Force have conducted a survey with many utilities around the world [1, 2]. The results of these surveys showed that the total number of reported brittle fractures ranged between 100 and 200 (Figure 2-1). It is in the USA that the highest number of failures has been recorded. This can be attributed to the widespread application of composite insulators made with a variety of designs and manufacturing technologies. As far as a direct comparison is possible, there seems to be a certain tendency that the propensity for brittle fractures increases with the voltage level. This may be due to higher local stresses caused by the electrical field distribution.

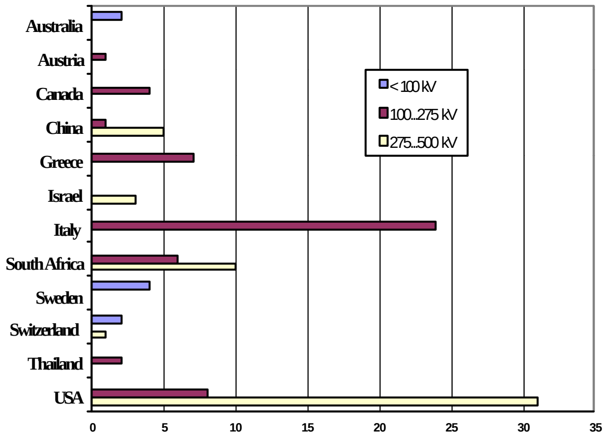

Fig. 2-1: Number of brittle fractures on lines [1, 2]

The unambiguous identification of brittle fractures was an essential condition for the validity of the surveys. The Guide [3] published in 1992 has proven to be very valuable in this respect.

At the end of 1997, the total number of composite insulators installed a voltage level > 100 kV was approximately 3 million units (Figure 2-2) [1]. This corresponds to a brittle fracture failure rate of approximately 0.005 %, which is slightly less than the failure rates for traditional cap and pin insulators. However, it should be realized that a fairly high number of insulators have been in service for only a short time (especially in Asia), so this failure rate needs to be confirmed by further surveys.

Furthermore, in [2] an attempt is made to distinguish between brittle fractures that could be related to utility’s practices or to the composite insulator design or technology. This tends to show that 2/3 of the cases could be related to the manufacturers and the balance to utilities (installation or handling problems). However, it should be noted that the ratio was established on a fairly subjective basis. For example, in

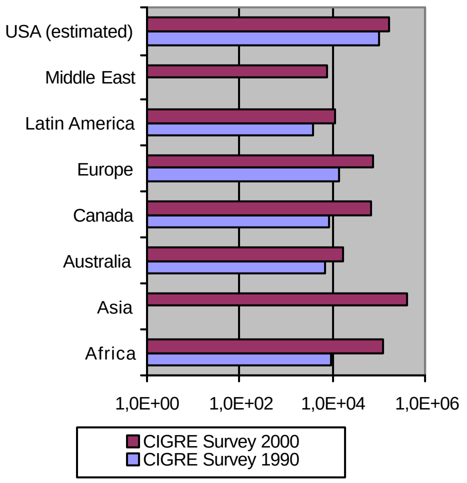

Fig. 2-2 : Composite insulators in the world, (>100 kV) [1]

one case, all 13 brittle fractures of a group of 345 kV insulators have been attributed to a defective seal between the polymeric housing and the end fitting. This would point to a systematic problem with the design of that insulator type. It is worthwhile to mention that the failures happened only after 1 year of service.

The following chapters will show that the brittle fracture phenomenon has been comprehensively investigated. The findings are sometimes inconsistent with the propose failure models but provide sufficient information for improvements that could be implemented by both manufacturers and utilities.

To help utilities to prevent failures associated with the stocking, transportation and installation, a Handling Guide [4] was produced by CIGRE 22-03 and has been published in April 2001 by CIGRE.

3- Laboratory and Field Tests performed by WG 22-03

WG 22-03 has been studying brittle fractures since the 70's, when the first events occurred. A number of experimental investigations have been performed. Tests have been conducted in laboratories [5, 6] or outdoor under severe environmental conditions [7]. These investigations provide not only information about the brittle fracture phenomenon, but also reflects on the further development of the composite insulator technology with regards to the relationship between the intrinsic mechanical strength of the rod and the design and material of the end fittings as well as the attachment method to the rod. The insulators were made with 16 mm diameter rods.

In two laboratories, insulators without and with built-in defects have been subjected to high static loads [5] or cyclic tension loads superimposed on different levels of static loads [6] combined in some cases with voltages equal to nearly 3 times the normal service voltage. The built-in defects were :

- insufficient impregnation of the rod fibres by the resin
- lack of bonding between the polymeric housing and the rod near the HV end fitting

The insufficient impregnation or the lack of bonding were chosen to simulate a possible failure mechanism involving organic acids created by partial discharges in voids [8].

The results of the laboratory investigations can be summarized as follows:

- fractures have been obtained at the expected load levels, most of them being within the end fittings,
- the fracture mode corresponds to the usual mechanical failure without the typical aspect of brittle fracture,
- the accelerating effect of the high mechanical loads and the elevated voltage stress (without the presence of an electrolyte) has not lead to the brittle fracture of any of the composite insulators investigated,
- there was no evidence of electrical discharges in any of the built-in defects.

Subsequently, starting in 1995, field tests were performed at Dungerness (UK) where the pollution level may be classified as "very heavy". Composite insulators with and without the same built-in defects were tested at this outdoor station. To avoid frequent pollution flashovers, the voltage applied during the test corresponded to a specific leakage distance of 15 mm/kV. Static loads were applied at levels that varied from 40 kN to 80 kN. Two of the insulators tested had been previously energized at nearly 3 times the service voltage for about one year (no mechanical load). This was meant to produce electrical discharges in the built-in defects.

The failures occurred away from the built-in defect, at locations where the bond between the polymeric housing and the rod was found to be adequate. Due to the low leakage distance in relation to the high pollution level, the polymeric housing sustained some damage (puncture), but this affected only slightly the rod, and should not be considered as the cause of the mechanical failure, because the damage area was not congruent with the failure location.

The results of these field tests can be summarized as follows:

- fractures have been obtained under high tension loads, elevated electrical stress and harsh environmental conditions,
- the fracture mode corresponds to the usual mechanical failure without the typical aspect of brittle fracture,
- the accelerating effect of the high mechanical loads and the elevated voltage stress without the presence of an electrolyte has not lead to the brittle fracture mode for any of the composite insulators investigated
- it is unlikely (but not proven) that a reduction of the mechanical stress to prolong the test time and possibly permit the creation of the acid would have lead to a brittle fracture.

4- Physical-chemical Considerations of the Brittle Fracture Phenomenon

The phenomenon of brittle fracture has been under investigation since the 70's. The first results from systematic studies of long rod insulators have been published in 1986 [9]. It is at that time that the term "brittle fracture" was used to describe the visual appearance of the failure produced by electrolytic corrosion combined with a tension mechanical load. Such a process would better be described by the term "stress corrosion". Here, both terms are considered to be equal; but since the term brittle fracture is more familiar to both utilities and manufacturers, it will be used in this paper. A typical example of a rod that failed by brittle fracture in a laboratory test is shown in Figure 4-1 [10]. On the front side of the fractured area, the smooth surface has failed by the stress corrosion process; the tension load was transferred to the remaining fibres that broke instantaneously when the specific strength was exceeded. More details regarding the identification of brittle fractures are found in [3].

Fig. 4-1 : Failure pattern of a brittle fracture

4. 1 Laboratory Investigations

A considerable number of systematic investigations [11] have been performed to understand the complex processes of brittle fracture. The findings are summarized below.

4.1.1 Influence of the rod

The rod, despite appearing as a simple part of the insulator, is a complex system. Macroscopically it consists of glass-fibres and a resin matrix. Microscopically there are interfaces between glass-fibre and resin as well as resin and filler (if used). In [12, 13, 14 and 15], detailed investigations describe the factors influencing the rod performance. They are:

- resin matrix and hardener
- curing temperature and post curing
- filler in the matrix
- glass fibre grade
- fibre sizing

In [10 and 16] it has been shown that the hardener of various epoxy formulations used for the impregnation of glass fibres of the rod can be turned into an acid by moisture. This hydrolysis of the hardener can take place during the rod manufacture or later during the life of the insulator if unreacted hardener is still present in the rod. This process implies that an external source of acid is not needed to produce the brittle fracture of composite insulator.

4.1.2 Influence of acid

The presence of an electrolyte is the pre-condition for the damage of the rod by electrolytic stress corrosion. Early investigations used a number of acids to measure their effect on the FRP rods [11]. Depending on the composition of the rod, it was found that E-glass fibres can fail when subjected to oxalic, sulphuric, nitric or hydrochloric acids. The time to failure depends on the acid concentration and the tension load level. The combination of E-glass and polyester resin has shown the shortest time to failure [13]. This raised the question as to which acid should be used for the investigations. In [17], the analyses of service-failed insulators indicated that nitric acids with a pH-level of less than 3.5 could have lead to the observed brittle fractures. This is in agreement with [12] where pH-levels lower than 4 had been used. Tests have also been performed with dry partial discharges on a pre-conditioned rod but there was no brittle fracture for weeks. By adding some drops of tap water close to the partial discharge source (metallic tip), brittle fractures were initiated within 7 hours [13]. From these findings and the known abundance of molecular nitrogen in the atmosphere, degradation products can be formed according to some of the following equations:

Primary reactions

$N_2 + O_2 \rightarrow$ corona $\rightarrow$ oxides of nitrogen

$3O_2 \rightarrow$corona $\rightarrow 2O_3$

Some examples of secondary reactions to create acids

$2NO_2 + H_2O \rightarrow HNO_3\ (aq) + HNO_2\ (aq)$

$N_2O_5 + H_2O \rightarrow 2HNO_3$

$NO + O_3 \rightarrow NO_2 + O_2$

$HNO_2 + O_3 \rightarrow HNO_3 + O_2$

Recently performed investigations [18], which utilized a 4-point-bending-stress instead of a pure tensile stress and ultra-pure water has shown an attack in a time shorter than with tap or de-ionised water. These tests performed on today’s materials confirm previous investigations on E-glass and ECR-glass [15]. This result was found to be somewhat in contradiction with the service performance of insulators made with identical rods. Probably pure water causes a concentration gradient, which leads to an attack of the fibre in order to achieve ion equilibrium in the solution. This scenario is not expected under outdoor condition because even vapour condensation underneath a polymeric housing will solve ions, which reduces the attack probability.

4.1.3 Electrolytic corrosion process

The glass-fibre is an amorphous material. It is constituted of different elements that give it the desired properties. More than 50% of the network is SiO_2. Additional ions are placed within the network in order to influence the glass properties. They are:

- CaO : reduction of the melting point and viscosity, reduction of the de-gassing,
- Al_2O_3 : improvement of the thermal and mechanical properties, and of the chemical resistance,
- B_2O_3 : reduction of the brittleness, improvement of the thermal and hydrolytic properties, possible improvement of the chemical resistance,
- Na_2O : improvement of the manufacturing process.

B_2O_3 is considered to be an integral part of the network. Alkali-ions such as Na+ or K+ play an important role for the behaviour of the network. The mobility of the Na+-ions is of particular importance because in a number of models, the Na+-behaviour is thought to also be representative of the other ions [19]. The known percentages of the individual ions are average values for a certain volume. In reality the “networkdisturbing" ions will be on the circumference of the fibre and form clumps to achieve an energy minimum of the network. Therefore the ions are in an area where moisture or hydrogen ions can interact easily with them.

A simplified model is shown in Figure 4.1-1. The concentration of sodium ions is higher on the surface of the fibre than in the rest of the network. In case of an electrolyte with a given hydrogen content (pH-level), the sodium ions can be dislodged. What remains is a damaged structure, which is unable to transmit tensile loads and the undamaged part of the fibre has to assume this duty. The individual fibre suffers from swelling and leaching and it takes a typical spiral aspect [9].

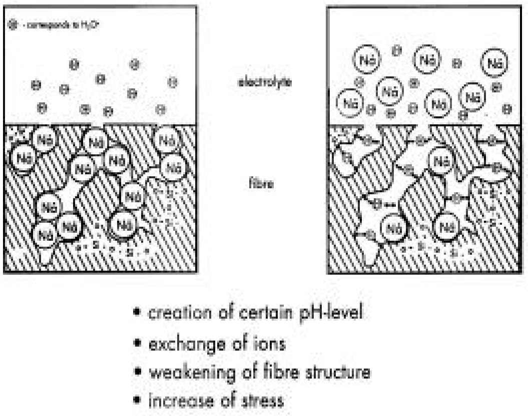

Figure 4.1-1: simplified model of ion exchange in case of acid attack to glass fibres

Empirically, it has been found that the elimination of boron improved significantly the acid resistance [9, 12, 15 and 20]. On the other hand, replacing Na_2O by corresponding mol-equivalents of B_2O_3 leads to a higher chemical resistance of the network especially against alkali solutions. The best behaviour is provided by Boron in a quadruple coordination fitting perfectly into the silica network. Unfortunately the acid resistance is relatively low because of the susceptibility of the Si-O-B group to hydrolysis, which is confirmed by the brittle fracture phenomenon [21]. In [22], comprehensive investigations have been performed on various sodium borosilicate glass grades at different pH-levels. Leaching test results provide the indication that the molecular structure of the glass controls the glass dissolution by establishing the distribution (occurrence) of ion exchange sites, hydrolysis sites and the access of water to those sites. In most environments, the hydrolysis of the network is the dominating factor for the kinetics of the glass dissolution. It was found that borosilicate glasses are more susceptible to an aqueous attack, if the ratio between B and Na is different from 1.

In case of excess Na there exist non-bridging oxygen (nbo), which can be attacked by hydrolysis followed by water intrusion and ion exchange. If Na is associated with the nbo`s, a selective leaching can be observed in neutral solutions as shown in Figure 4.1-1.

For a ratio B/Na exceeding 2, the glass tends to form two separate phases, a silica rich and a boron rich phase. The borate phase leads to a higher deterioration rate of the glass. The leached layers formed under such circumstances tend to be porous and do not act as a diffusion barrier, which is in line with the visual observation of acid-aged E-glass fibres.

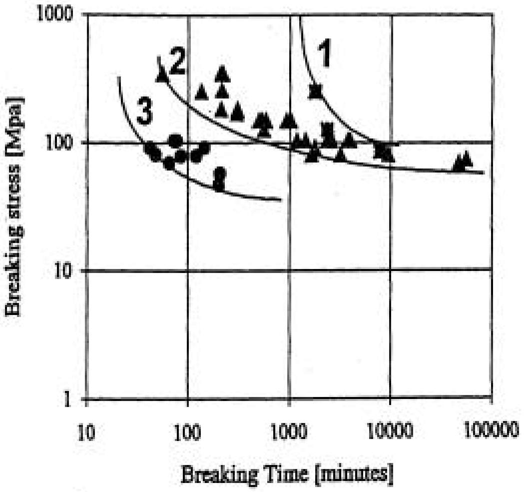

Figure 4.1-2: time load curves of different E-glass rods

The above discussion dealt with the glass fibre/rod performance in the presence of acids. For this reason the alkali-ions play the dominating role in the process. In case of an alkali attack, the silica network is directly affected by hydroxyl ions. The differences between an E-glass and an E-CR-glass are minor under these circumstances.

An interesting threshold was found in one of the investigations of [12] (Figure 4.1-2) :

Curves 1 and 2 are obtained by stressing a bare rod with the acid placed away from the end fittings. In curve 3 the acid is placed in the vicinity of the end fitting. Curve 1 represents a very high mechanical resistance material composed of E-glass and a resin; curve 2 is a system very susceptible to brittle fracture. Curve 3 is a similar system but the test shows that the additional stress near the end fitting (end fitting design with a wedge) area can worsen the brittle fracture scenario. The threshold levels are 60 MPa for cases 1 and 2 and 15 MPa for case 3. In comparison, every day stresses can be in the range of 180 MPa. The existence of a threshold in the process of electrolytic corrosion means that the failure will not take place below a certain stress level. For the practical case of composite insulator, this is unfortunately out of technical relevance. It should be noted that these threshold levels have been obtained with tests using 1N nitric acid. The threshold levels with weaker acid may be high enough to become technically relevant.

4. 2 Brittle Fractures in Service

The processes described in the previous chapter show clearly that the attack by an acid of the complex rod system causes electrolytic corrosion and eventually leads to a brittle fracture failure.

In [10, 11, 23 and 16], the observations and reasons for brittle fracture can be summarized as follows:

- evidence of electrical discharge degradation in the failed area of insulators,
- sheath thickness of about 1.5 mm were prone to be damaged mechanically or by discharge activity,
- lack of corona rings (161 kV) to control the electrical field,
- insufficient sealing between housing and end fitting,
- -mechanical damage of the housing near the affected area,
- failure after only a few years of service at low loads (1 kN to 20-30 % of SML),
- exposed rod due to defective seal or partially destroyed housing,
- failures reported only with E-glass fibres,
- failures without visual damage of seal,
- fracture located at a certain distance from the end fitting or within the end fitting, where low electrical field are expected (Figure 4.2-1),
- in service, the number of brittle fractures is smaller than the number of insulators with exposed rods (Figure 4.2-2),
- among insulators from the same batch, installed on the same line, one can fail and the others provide trouble-free service.

Some of the above observations are mutually inconsistent and required the search for another source of acid as discussed in chapter 4. 1. 2. Recent investigation [10 and 16] focused on an internal source of acid. It was found that for certain hardeners (anhydride) that are part of the epoxy formulation used for the impregnation of the glass fibres, if their hydrolysis takes place it leads to the creation of acid crystals which have a melting temperature of more than 200°C. Consequently, they remain as salt crystals during the pultrusion process. But they are solvable in water and can be turned into liquid organic acids. Considering the energy-minimizing effort of a system, the crystals can form clumps and get preferentially lodged on the circumference of the rod. Alternatively, if the resin matrix of the finished rod still contains some unreacted hardener, hydrolysis can take place later during the life of the insulator and create liquid organic acids that can lead to the brittle fracture of mechanically stressed rods. This assumption is supported by the recent findings [16] of the study of the rod of a 500 kV-insulator which failed after 15 years of service. The failed rod was examined by infrared spectroscopy and the results are presented in Figure 4.2-3.

Fig.4.2-1 : Brittle fracture about 1 cm inside the end fitting.

Fig. 4.2-2 : no damage after more than 10 years in service with an exposed FRP rod.

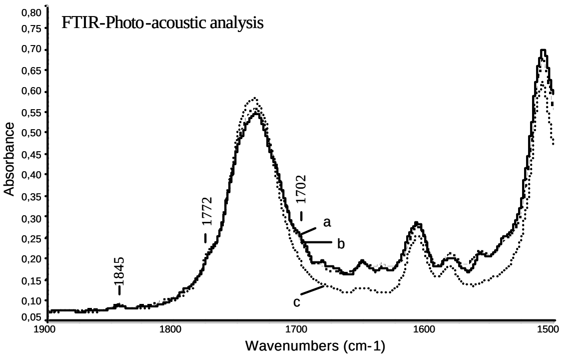

Fig. 4.2-3 : IR spectra of area a, b and c of the FRP rod.

The curves relate to different rod areas, “a” and “b” correspond to the fracture face and “c” to the unaffected bulk of the rod. The peaks at 1845 cm^{-1} and 1772 cm^{1} found on all three curves correspond to unreacted hardener. The small increase for curves “a” and “b” at 1702 cm-1 is associated with the acid formed from the hardener. This increase was not found for curve “c” (inside the rod, no contact with water). A visual inspection of the insulator indicated a faulty seal between the polymeric housing and the end fitting, which led to the ingress of moisture followed by acid creation. Probably due to the small load and the progressive loss of sealing integrity the insulator took 15 years to fail.

This “acid from the rod” scenario calls for liquid water to reach the rod surface. This can be done through faulty seals or a damaged housing. It is unlikely (but theoretically possible) that vapour diffusion through the polymeric housing would lead to sufficient liquid water accumulating at the housing-rod interface and then generate liquid organic acids. However, the direct access of water is supported by the observations of most failures. More than 80 % of the failed insulators in the USA [2] had defective seals, which permitted the ingress of moisture especially to the area where, in case of a corrosive attack, the rod is considered to be very vulnerable due to the superimposed mechanical and electrical stresses (see curve 3 of Figure 4.1 2 and Figure 4.2-1).

5- Test Procedures and Improved Designs

For the evaluation of the acid resistance of composite structures [15] describes a number of test procedures. A procedure recommends the direct immersion of the composite structures without the simultaneous application of a mechanical stress (ASTM C.581). Another calls for combined stresses (ASTM D.3681) applied to individual fibres. For “composite insulator”, the simultaneous application of mechanical stress and electrolytic attack has to be used. The laboratory and field tests as well as the service experiences show that moisture must be in contact with the rod.

Thus there can be three main avenues that could lead to an optimum insulator design:

1- prevention of moisture access to the interface between rod and polymeric housing and perfect seal of the ends,

2- similar to 1 with the additional use of electrolytic corrosion resistant glass grades,

3- use of rods made with resins that cannot generate organic acids by hydrolysis.

When the total number of composite insulators that are in service are compared to the number of insulators that failed by brittle fractures, these three avenues appear promising.

Avenue 1 is general and its principle checked by the interface design tests required in IEC 61109 or ANSI 29.11. However, there is no routine interface evaluation of each insulator. It is assumed that an adequate interface is obtained by a high and constant manufacturing quality.

For avenue 2, a test set-up has been proposed in the mid-80s [9] that calls for the testing of a bare rod (Figure 5-1). To ensure reproducibility, the chosen acid is 1N HNO_3. This test does not evaluate the suitability of an insulator design against brittle fracture. It is purely a screening test that measures the acid resistance of bare rods. Testing the free length of the insulator is selected to avoid interference of the superimposed stresses in the crimping area.

Avenue 3 requires the use of new resin systems or the assurance that the presently used systems will not lead to organic acids by hydrolysis. A new test will have to be developed to prove it.

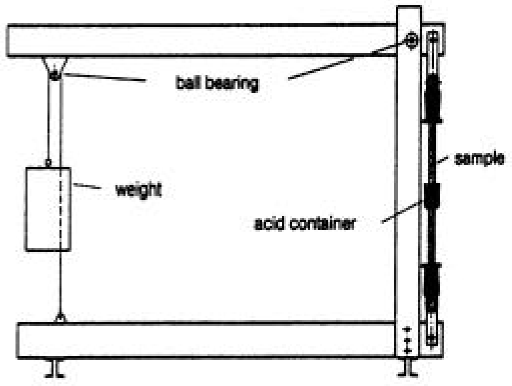

Figure 5-1: set-up for brittle fracture testing of bare rod

A comparison between bare rods and identical rods with silicone rubber sheath using the test set-up of Figure 5-1 revealed that the unprotected rods can be badly damaged by natural environmental stresses during long outdoor exposure (3.5 to 14 years) [12]. It is important to note that the results showed that the protected rods had no signs of damage. This indicates that a well protected rod with a suitable resin formulation has a low probability for brittle fracture failure. It is difficult to compare the results obtained with pure tension tests and those obtained with 3 or 4 point bending tests.

Beside the acid resistance, the electrical strength of the rod is an important factor. There are a number of corrosive-resistant glass grades, which have better acid resistance than standard E-glasses but have lower dielectric strength. This is due to the existence of capillaries in the fibres, which are attributed to a lower gas solubility of the glass melt [19] or seed content of the molten glass [20]. These grades are successfully used in pipes and similar applications. For the qualification of appropriate materials for rods used in composite insulators, the breakdown strength, water penetration and hydrolysis performance of the complete system must all be considered.

Presently, there is no indication that polymeric post insulators or hollow core insulators can suffer from brittle fracture. This seems to be reasonable because they are only partially stressed by tension. The end fittings are larger than those of suspension and tension insulators, so the radii incorporated are larger, which make the sealing easier. In addition, in the case of hollow core insulators, the tube consists of plies with different winding angle. Hence there is never a pure tension stress resulting in smaller specific values, this also reduces the probability of brittle fractures.

6 - Risk Assessment for existing Lines

The assessment of the risk for existing lines to be affected by brittle fractures is difficult because considerable financial implications can be involved in case of a wrong decision. Certain trends can be deducted from various service reports as shown on Figure 6-1 [2] and Figure 6-2 [12] :

- in case of systematic design faults the composite insulators suffer from brittle fractures after a relatively short time,
- inadequate seal with very slow water ingress can lead to problems after a longer service time, especially in case of low pollution levels.

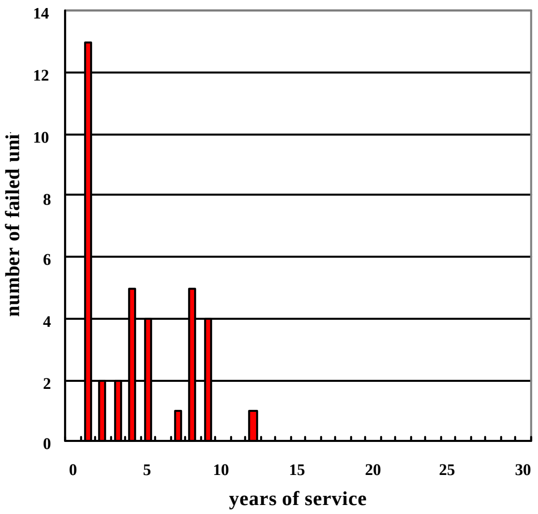

Fig. 6-1 : Brittle fractures in USA

Figure 6-1 shows the distribution of brittle fractures reported in the world with different insulator designs. More brittle fractures

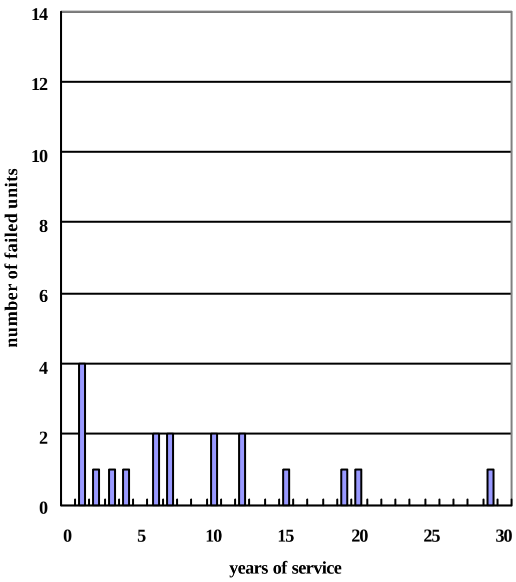

Fig. 6-2 : Brittle fractures of one type of insulator in various applications and different environmental conditions.

may still appear with time. Figure 6-2 reports on the behaviour of one insulator family (1st generation) the manufacture of which has been discontinued in 1983.

To decrease the risk of brittle fractures occurring in service the following can be recommended :

- in-service inspection of composite insulators to detect possible polymeric housing damage caused by frequent electrical discharge activity,
- specification of a sheath thickness of at least 3 mm,
- prevention of corona on hardware of the insulator at nominal voltage,
- visual control of the seals or the bonding between housing and end fitting,
- removal from service of insulators with exposed rod.

7- Conclusion

Composite insulators have a number of advantages over conventional insulators. This has lead to a significant increase of the number of units installed on HV lines. The phenomenon of brittle fractures, affecting a small number of insulators, can be attributed to the destruction of the glass fibre by an acid. The failure mechanism is complex but is always related to an ingress of moisture/water to the interface between polymeric housing and rod or to the rod. Three main measures are suggested to try to prevent brittle fractures. They are the prevention of moisture ingress or additionally, the use of acid resistant glass grades and/or non-acid producing resins. This paper attempted to show that the mechanism of brittle fracture, although complex, is now fairly well understood and that the manufacturers of composite insulators now have some solutions to still decrease the already low failure probability of their products.

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