455

Aspects for the Application of Composite Insulators to High Voltage (≥72kV) Apparatus

Working Group
A3.21

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WG A3.21

ASPECTS FOR THE APPLICATION OF COMPOSITE INSULATORS TO HIGH VOLTAGE (≥72kV) APPARATUS

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1 INTRODUCTION

The ceramic housing is a very solid, reliable and well proven solution. However the use of non ceramic insulators (mainly silicon rubber insulators: SRI) for the construction of station equipment is gaining momentum thanks to the potential advantages. Their technical and economic advantages are of particular significance in the EHV and UHV application range, because of the design flexibility, relatively light weight, withstand performance to internal pressure, seismic events, and high contamination and their ease of handling for manufacturing and installation. Last but not least, from the point of view of end-users, a very important feature of composite insulators is safety. Since they are not brittle there is virtually no risk of explosion with the associated projection of material as is the case for porcelain housing.

Experience of polymer housings started at industrial scale in the early 1980's. Since then the total number of hollow core insulators in service is about half a million in the voltage range above 145 kV (2006 data). The market is in excess of 50,000 insulators/year with a yearly growth rate in the order of 10-20%. Market penetration presently varies between about 10% for oil impregnated bushings through to well in excess of 50% for applications such as gas insulated & resin impregnated bushings, gas insulated instrument transformers, cable terminations. The penetration is higher in the higher voltage ranges and for applications where the safety is more critical and most of the UHV AC and DC application to date are applying composites.

Since there are now significant numbers of composite insulators which have been in service for a number of years it is appropriate to review their performance in the service environment. To this end, CIGRE WG A3.21 has undertaken a survey of experience and collected data from a wide range of source. This information has been reviewed and analysed and the results are presented in this Technical Brochure.

It is widely recognised that the performance of composite insulators is strongly related to aspects such as the selection of the material, the manufacturing process and the appropriateness of the electrical and mechanical design in relation to the specific application. As with any technology, the development and use of appropriate qualification procedures for composite insulators is a key factor in ensuring product quality and long term reliability.

With this in mind, it is notable that IEC Standards 61462 (2007) addresses the qualification of the housing itself but specifically excludes aspects such as the relationship between housing performance and the type of application, the qualification tests on the housing when assembled on the full apparatus, the assessment of the pollution performance and the assessment of the performance for DC application (in the absence of an agreed tracking test). Some of these aspects have been considered by WG A3.21 and the Technical Brochure presents information in the following related areas:

- The influence of the active parts (apparatus parts) inside the housing on the electric field on the surface taking into account the specific application (e.g. AC or DC) and consequently the influence on the short and long term electrical performance of the housing.
- The interaction between the housing and the active parts from the thermo-mechanical point of view and the need of special tests to assess the actual component performance (e.g. seismic performance, short circuit performance etc).
- The chemical interaction with the gas and fluids with special reference to the possible decomposition by-products of SF_6 and compatibility with oil and new synthetic fluids.

Other aspects such as maintenance, environmental impact, life costing and UHV applications are considered.

2 APPLICATIONS OF POLYMERIC MATERIALS TO THE EXTERNAL INSULATION OF APPARATUS AND COMPONENTS

2.1 Historical overview

Historically, porcelain has been the dominant material used for outdoor insulation on high voltage equipment. However, the development of polymeric materials for use as outdoor insulating material started for line insulators over forty years ago. About thirty years ago they were also introduced on high voltage equipment. Since then, material development and development in high voltage equipment has resulted in a number of different designs. As the technology is now widely accepted, more and more HV apparatus applications utilising the full performance of composite insulators are being introduced. Examples are surge arresters, disconnectors, bushings, cable terminations, instrument transformers, circuit-breakers etc. [2.1] to [2.6].

2.2 Application of composite insulators

Different kinds of technology are available for the manufacturing of composite insulators suitable for high voltage apparatus requirements. In principle, there are two different technologies used [2.1], [2.2], [2.3]:

a) Hollow composite insulators used as outdoor insulators in much the same way as porcelain (**Figure 2-1**.a). Typical apparatus where this technology is applied are gas or oil insulated equipment such as circuit-breakers, instrument transformers, bushings and also surge arresters especially in EHV applications.

b) Directly moulded solutions where the outdoor insulating material is applied directly onto the high voltage equipment. Typical apparatus where this technology is applied are surge arresters (**Figure 2-1**.b), cable terminations and dry type Resin Impregnated Paper (RIP) bushings.

As can be seen in figure 2.1.a) hollow composite insulators consist of three basic parts: end fittings for connection and sealing to other structures, an insulating tube to provide mechanical strength and a polymeric material serving as protection against the outdoor environment. Inside the tube electrical insulating media such as oil, SF_6, dry air, nitrogen and different types of foams may be used. In some cases such as circuit-breaker and bushing applications the insulators may be pressurised.

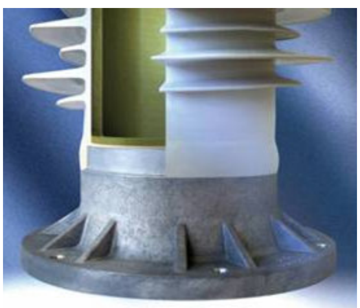
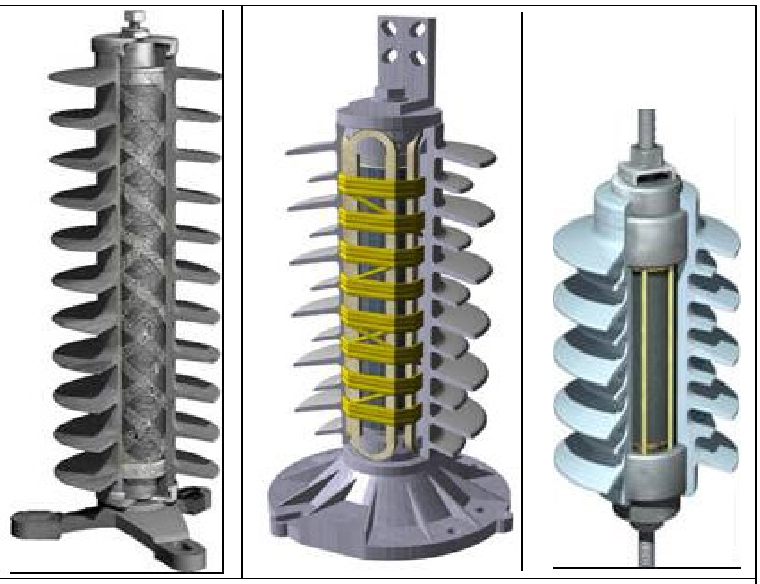
	
a) hollow composite insulators	b) directly moulded: housing directly applied onto the apparatus (examples of surge arresters)

Figure 2-1 Composite insulators for station equipment

As can be seen in Figure 2-1.b) the structure of surge arresters and of other special apparatus can be quite different. In some cases the metal oxide blocks serve as part of the mechanical structure with reinforcement provided by different wrap, loop or rod structures. In addition there can be a cage design to improve the short circuit performance.

A summary of the applications of composite insulators to station apparatus is made in Table 2-1, indicating the applicability of solution a) and b), the additional involvement of solid core insulation and the insulating media foreseen inside the hollow insulator for each application. Table 2-1 indicates that direct moulding is applied only for some apparatus. As an example of this application the case of the surge arrester is analysed in Appendix A-2. Since the most widely adopted solution is the hollow insulator, this technology will be taken into consideration as a reference in this document. Typical insulating media inside a hollow insulator are gas (SF_6, SF_6/CF_4, air, N_2), liquid (different types of oil) and solid (foam, gel). Examples of applications can be seen in Figure 2-2 to Figure 2-9.

Table 2-1: Applications of composite insulators to HV apparatus

Type of apparatus	Design	Directly moulded	Hollow core insulator	Solid core insulator	Insulation media
Station Post insulators	Figure 2-2	Yes	Yes, filled with gas /liquid or solid insulation	Yes	gas, solid, liquid
Circuit-breakers	Figure 2-3				
	Live tank	No	Yes	No	gas
	Dead tank (also GIS)	No	Yes, principally a bushing	No	gas
	Generator CB	No	Yes, principally a bushing	No	gas
Switches	Line switch	No	Yes		gas
	Ground switch	No	Yes		gas
Disconnectors		No	Yes	Yes	gas, solid, liquid
Surge arresters	Figure 2-5	Yes	Yes	No	gas, solid
Instrument transformers	Figure 2-6				
	CT	Yes	Yes	No	gas
	VT	Yes < 110 kV	Yes	No	gas, solid, liquid
	CVT	Yes < 110 kV	Yes	No	gas, solid, liquid
	Optical sensors	Yes	Yes	Yes	gas, solid, liquid
Bushings	Figure 2-4 and Figure 2-7				
	Wall bushings	Yes, RIP	Yes	No	gas, solid, liquid
	Transformer bushings	Yes, RIP	Yes	No	gas, solid, liquid
Combined equipment	Figure 2-8				
	Bushing and cable terminations with integrated Surge arrester	No	Yes	No	gas, solid
	Surge arrester used as post insulator	Yes	Yes	No	gas, solid
	Disconnector Circuit-breaker	Yes	Yes	Yes	gas
Cable terminations	Figure 2-7	Yes (pre-manufactured)	Yes	No	gas, solid, liquid

	
a) 500 kV DC station post insulator	**b) 420 kV AC station post insulator**

Figure 2-2: Composite post insulators

	
a) Composites on dead tank circuit-breaker	**b) Composites on live tankcircuit-breaker**

Figure 2-3: Composite insulators for circuit-breakers

	
Figure 2-4: Composite bushing for HV power transformer	*Figure 2-5:Composite insulator for surge arresters*

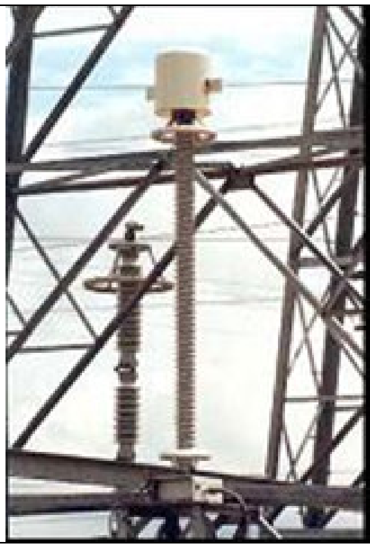
	
a) Composite for conventional instrument transformer	**b) Composite for optical current transformer (with fibre optics)**

Figure 2-6: Composite insulators for instrument transformers

		
a) 420 kV GIS bushing	**b) 220 kV cable termination**	**c) Bushings on a mobile transformer**

Figure 2-7: Composite insulators for bushings and cable terminations

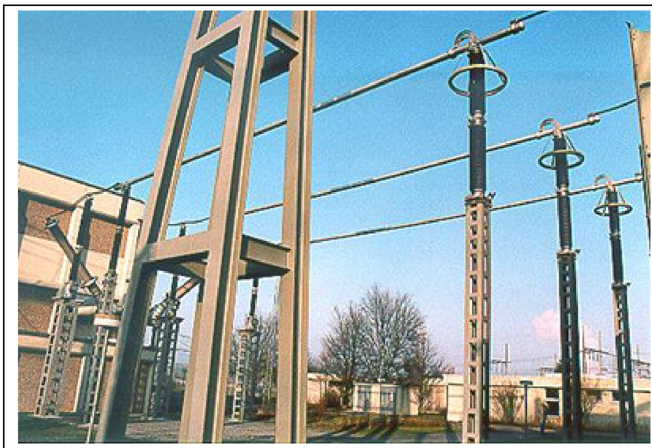
	
a) Hollow core housed arrester also used as a station post insulator [2.2]	**b) Disconnecting circuit-breaker (disconnector combined with circuit-breaker)**

Figure 2-8: Composte insulators for combined equipment

Figure 2-9: 550 kV Gas Insulated Substation

2.3 Manufacturing of insulators for HV equipment

2.3.1 Tube (core material)

The composite tube is the structural part in a hollow composite insulator. The tube material consists of stiff fibres embedded in a polymer matrix and is characterised by low weight and high stiffness and strength. The most common materials in composite insulators are glass fibres and epoxy due to their good electrical insulation and mechanical properties.

The properties of the composite are governed by the properties of the constituent materials, fibre architecture, volume fraction of fibres etc. This means that the properties of a composite material vary in different directions and can therefore be tailored for a specific application and load case. The tube is generally cylindrical or conical depending on the application and voltage level. The epoxy resin type can be adjusted to the temperature requirements, but generally the resin system has a glass transition temperature of about 130°C. Moisture absorption and diffusion of such resin must be kept as low as possible as most of these apparatus are designed for outdoor applications.

A very important and crucial variable for a successful tube design is the lay-up of the different fibre layers. The lay-up strongly influences the properties of a composite tube (Figure 2-10). Actually, axial reinforcement strengthens the tensile strength of the tube, the tensile elastic modulus and the bending strength as well. It is mainly used for suspension insulators.

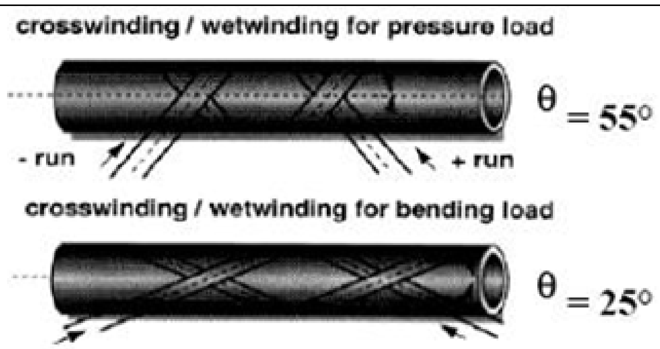


Figure 2-10: Examples of winding angles for wet winding production of tubes

Radial reinforcement improves the pressure strength. As an example the design which is employed for circuit-breakers is based on a compromise between axial and radial reinforcement. Indeed, a criss-crossed reinforcement optimises cantilever and pressure withstand. A finite element analysis highlighted that a winding angle of about +/- 55° is suitable for this application.

Filament winding is an efficient process for series production of tubes with high fibre content. The complete cycle for impregnation and placing the fibres onto a mandrel is fully automated giving low process variations. The void content impairs the performance of the material and is therefore a key parameter that has to be controlled and measured. The impregnation of the fibres is integrated in the winding operation which means that the complete forming process of the tube is closely controlled. A second step, in direct connection to the winding process is a curing phase for the composite material. This curing of the epoxy-matrix takes place in specially designed ovens with highly accurate control of temperature and time. The curing phase needs to follow an optimised temperature curve to minimise internal stresses and at the same time reach a fully cured state. Concerning the composite impregnation, although different manufacturing technologies can be found, mainly vacuum impregnation or wet winding are used for high voltage insulators.

The vacuum impregnation technology, allowing the manufacturing of low partial discharges composite, is currently used for operating under high electrical stress and hence vacuum impregnation is mainly used for applications with SF_6 as internal insulation. Moreover tubes manufactured from vacuum impregnation are characterised by a higher elasticity modulus and tensile strength. One reason for this is that winding angles close to 0° can be achieved by this technology.

The wet winding technology (Figure 2-11) is well adapted to composite for outdoor insulation where the electric stress is lower since the electric stress applied to the outdoor insulators is governed by the air insulating capability, which is lower than that of SF_6. Low void content (ca 1-2% by volume) is required in order to ensure proper function over the life span of the insulator.

The shapes of the tubes has evolved to include conical or tapered, bottle and of course cylindrical. Today it is possible to reach very large inner diameters and very long tubes (up to 9 m and beyond). Furthermore there is a selection of inner linings to assure protection of the glass fibres against corrosion from the decomposition products (e.g. HF and SF_4 caused by arcing in SF_6) and the heat created by arcs.

Figure 2-11: Wet winding of tubes for composite insulators

2.3.2 End fittings

The end fittings, also named flanges, combine with the tube to provide the load bearing function of the insulator. They also ensure tightness between the internal insulating media and the surrounding environment. The material used is generally an alloy of Al/Si/Mg to provide a high corrosion resistance. For extreme mechanical requirements stainless steel may be applied. A crucial issue is to correctly dimension the flange to tube transition. The flange is normally chemically bonded to the tube by an adhesive. It is common to combine the chemical bonding with a mechanical attachment such as crimping or shrinking. The end fittings must be designed in connection with the mechanical and dielectric constraints, and the mechanical sizing is dependent on the equipment design. For electrical reasons the most frequently used design is to coat part of the flange with the shed material (as can be seen in Figure 2-1a). The interface between end fittings and the tube is a critical aspect for long term performance and requires expertise and care.

2.3.3 Housing

For outdoor application, the core is covered by a housing protecting the tube from the environment and providing the necessary creepage distance to withstand electrical stress in air. This housing has no mechanical role.

Among the various materials already used for outdoor insulation, silicone rubber (SiR) has in the past ten years become the preferred material in HV and EHV applications. In particular, its hydrophobicity and its ability to recover hydrophobicity following over time are of major interest. Silicone rubber is a generic name commonly used to express the type of housing material used, which can be applied in different forms such as LSR (Liquid Silicone Rubber), RTV (Room Temperature Vulcanising silicone rubber) and HTV (High Temperature Vulcanising silicone rubber). Usually the process of producing the insulators sets the requirement for which type of rubber to use.

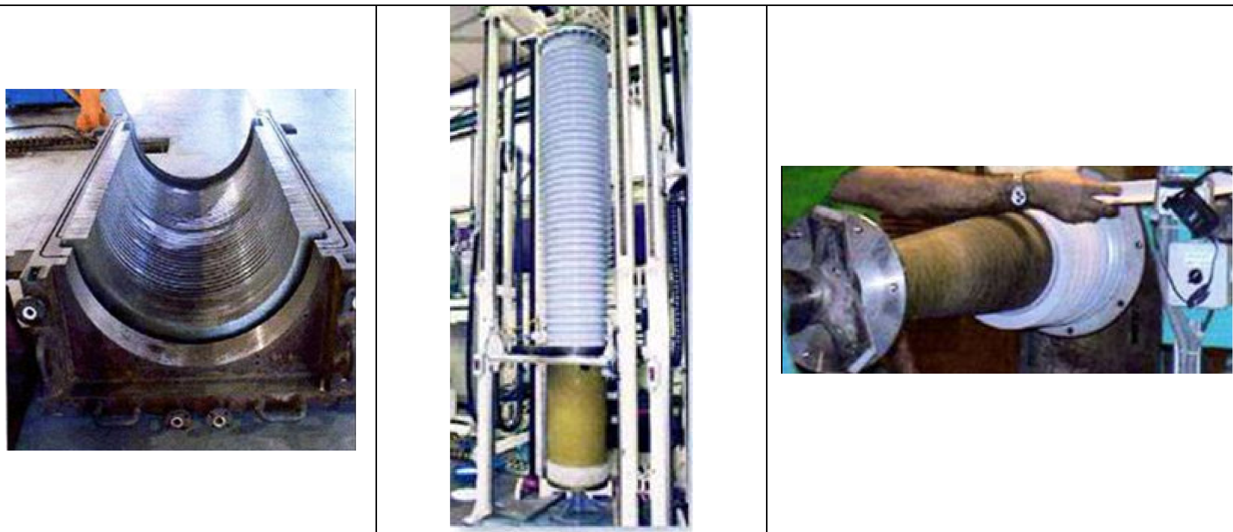
Silicone rubbers used as housing materials usually consist of a number of different additives for obtaining the desired properties. The silicone polymer, polydimethyl siloxane (PDMS), by itself is relatively weak when cross-linked, forming a brittle transparent rubber. Thus it is necessary to reinforce the polymer by adding very fine, high surface-area fillers. These fillers are usually surface-treated to become more chemically compatible with the silicone polymer. It should be noted that filler treatments as well as filler particle sizes are what tend to distinguish different silicone rubber formulations. The most common reinforcing fillers used are different types of silica. However, higher filler content tends to cause a slower recovery of hydrophobicity than lower filler content. Moreover pigments for obtaining a desired colour as well as silicone oils to aid processing, are added. Finally curing agents are added for vulcanization (cross linking).

High Temperature Vulcanising (HTV) silicone rubbers are mixtures of a siloxane polymer with high molar mass (long polymer chains) and relatively high amounts of inorganic fillers (up to 50% in weight), of which the major component is Alumina trihydrate (ATH). ATH is often added for improving tracking resistance. HTV rubbers are usually cured using peroxides, but other curing systems are increasingly used as well.

Liquid Silicone Rubbers (LSR) are two component addition-curing systems with low viscosity allowing them to be injected or pumped into moulds after an initial mixing step. Curing occurs at high temperatures. The lower viscosity is obtained using siloxane with lower molar mass, in combination with lower amounts of filler, compared to the HTV systems. Usually only reinforcing silica is used since the addition of large amounts of ATH would lead to a too high viscosity. The lower pressure used during injection puts lower demands on the moulds compared to the high pressure used for HTV materials.

Room Temperature Vulcanising (RTV) silicone compounds are used for some outdoor applications. The RTV-2 silicones (made of two components) have even lower viscosity than the LSR rubbers and are normally used for casting (pouring the silicone into moulds). These materials can be cross-linked at room temperature or higher by adding the second component. A drawback is that the percentages of the two components differ significantly from each other in contrast to LSR systems where the ratio is usually 50:50. Finally, RTV-1 silicones are one-component systems that are cured by reaction with moisture in the air and are often referred to as silicone glues.

The sheath and the sheds can be applied by injection of LSR, by extrusion of HTV, compression of HTV, casting of RTV or stacking of pre-vulcanised HTV silicone sheds (see Figure 2-12 for some examples). The majority of the insulators on the market are produced either through injection of LSR or extrusion of HTV. These different technologies are now in use since more than 20 years.



a) injection moulding	b) step moulding process	b) extrusion

Figure 2-12: Examples of housing forming techniques

2.3.4 Assembling a hollow core insulator

The three components have to be joined in order to complete the production of the insulator. The end fittings are commonly fitted to the tube before the application of the housing. There are different ways of fitting the flanges but normally an adhesive, heat and shrink process is involved. Great care has to be taken in the production when assembling the end fittings since the mechanical load is to a great extent taken up by them thus increasing the risk for leakage of insulating media if not properly performed.

Before applying the housing material, the surface of the tube has to be treated by a primer. This is to ensure proper adhesion between the housing material and the tube/end fitting. The application and treatment of this primer is normally decided by the different brands used. The primer is a silicone based component diluted with some form of solvent. The handling and treatment of the different surfaces is a critical part in the production process in order to have a stable process that ensures good adhesion between the different substrates.

2.4 Design requirements

The design of composite hollow core insulators have to take into account electrical, environmental, chemical and mechanical stresses. The main design stresses, depending on the application considered, are reported in Table 2-2.

Electrical stresses are often considered in relation to the environmental stresses, such as presence of pollution, rain, ice etc. The shed profile and the number of sheds must be chosen to allow good dielectric withstand under wet and polluted conditions taking into account the requirements and guidance of documents such as IEC60060-1, IEC60815-1 and IEC60815-3.

Chemical stresses need to be taken into account for specific components, such as circuit-breakers, which could be affected by the decomposition products of SF_6 and for oil insulated equipment where oil compatibility is vital.

As far as mechanical stresses are considered, the required tests should include external bending, torsion, compression and tensile loads, internal pressures and overpressures, such as those deriving from short circuit and seismic loads.

Beyond design requirements, the manufacturing process may affect and impair the performance of the insulators. Therefore, high attention should be paid to assure a continuous quality control of the production process and the products. As an example, Figure 2-13 [2.6] shows how the glass transition temperature of the composite tube may depend on the manufacturing process leading to tubes with exactly the same chemical composition having different characteristics.

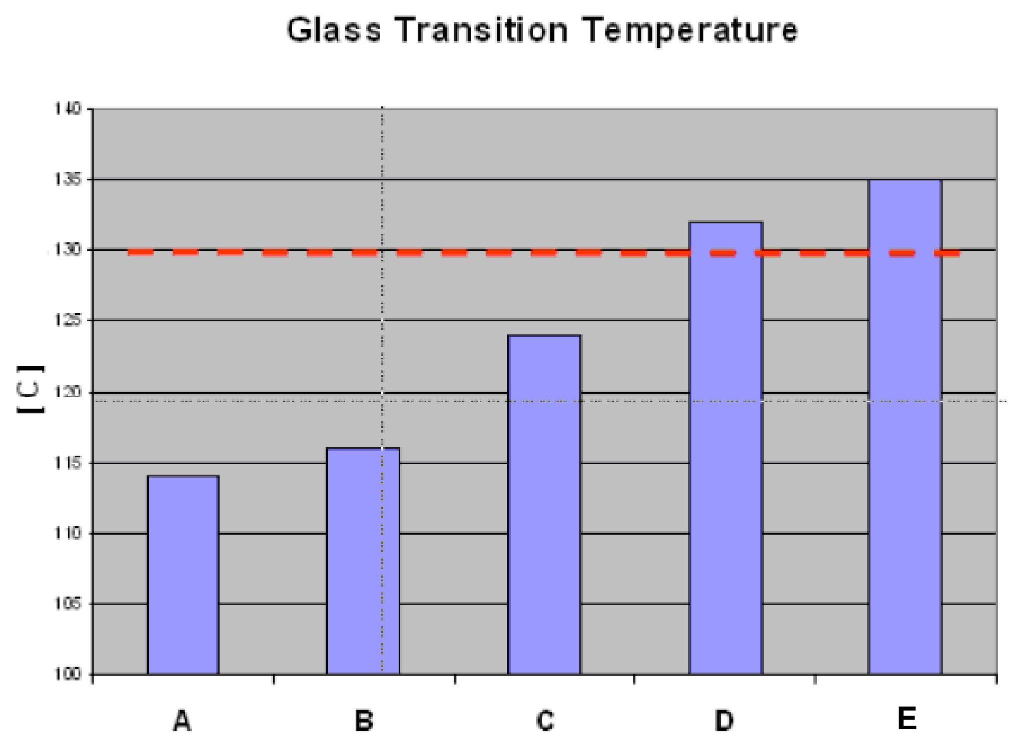


Figure 2-13: Glass transition temperature analysed on tubes of the same chemical composition from different suppliers

The design stresses are related to the specific application. A detailed analysis of this dependence and the consequences on design and testing will be the subject of the following chapters.

Table 2-3: Main design stresses for the various applications

Design stresses	**Electro Environmental**		**Chemical**	**Mechanical**		
	Electric field + pollution, rain	Thermal		External loads	Pressure (e.g. short circuit)	Seismic
Post insulators	X			X		X
Circuit-breakers	X	X	X	X	X	X
Switches	X	X	X	X	X	X
Disconnectors	X			X		X
Surge arresters	X	X	X	X	X	X
Instrument transformers	X	X	X	X	X	X
Bushings	X	X	X	X	X	X
Combined equipment	X	X	X	X	X	X
Optical fibres	X			X		X

2.5 Advantages and precautions

Composite insulators have many advantages as shown in Table 2-4. In particular, composite insulators have proven to be reliable even under exceptional events as earthquakes or internal/external faults as short circuit or vandalism. They also provide good insulation performance due to their silicone housing and the intrinsic hydrophobic characteristic of this material. Well designed composite insulators present limited ageing, fully complying with the required design life, and satisfactory performance, even in heavily polluted areas where no cleaning or special maintenance are necessary with important economic savings.

A further advantage is the flexibility of composite insulators in terms of mechanical and geometrical design to meet a wide range of requirements with short design cycle time. They facilitate innovation in terms of new solutions to known applications and have been widely employed where innovative solutions such as integration of devices have been developed.

Their technical and economic advantages are of particular significance in the EHV and UHV range, because of the design flexibility (single pieces of 10 m or more may be manufactured), relative low weight (10-30% of a corresponding porcelain insulator), ease of handling for manufacturing and installation and their ability to withstand stresses such as seismic events and high levels of pollution.

Last but not least, from the point of view of end-users, a very important feature of composite insulators is safety. Since they are not brittle there is virtually no risk of explosion with the associated projection of material as is the case for porcelain housing.

However, satisfactory performance of composite insulators is directly related to a good selection of the material, a good manufacturing process and as well good electrical and mechanical design. Environmental constraints such as temperature, presence of aggressive gases and so on should be also taken into account in the design phase. Qualification procedures can help to qualify the technology and the materials to assure the performance during the required life time of the insulator and these aspects are dealt with in detail in the following chapters.

Biological growth and bird attacks on composite insulators have been reported [2.7], [2.8] and a range of different type of fungi can grow on composite insulators leading to a reduction of the hydrophobicity [2.7]. However, even taking into account fungal growth, the overall performance of the insulator remains satisfactory. As regards bird attacks, this seems to be a problem related to transmission line insulators in some countries only.

Another question in this context is whether vapour could permeate directly through the sheds and walls of the housing (polymeric materials are generally slightly permeable for vapour) or through the bonding area between flanges and FRP tube. Investigations and service experience indicate that the amount of moisture ingress due to these mechanisms is below the quantities which can pass through a good sealing system. These quantities can easily be controlled by internal desiccants as is usual practice for much of the HV apparatus in the electric power system. Nevertheless research continues in an attempt to better understand these mechanisms and to derive minimum design requirements on composite hollow core insulators used for HV apparatus applications [2.9] [2.10].

Table 2-4: Composite insulators: advantages and precautions

	Electro Environmental	**Thermal**	**Chemical**	**Mechanical**	**Others**
Advantages	Safety	Not affected by thermal shock	Hydrophobicity	Safety	Low life cycle cost
	No cleaning, no maintenance			No explosion	One single piece up to UHV
	Design flexibility			Low weight	Manufacturing flexibility and short manufacturing time
	High performances under pollution			Less critical to vandalism	Easy handling and installation
				Predictable mechanical behaviour	Not fragile
Precautions	Design and material knowledge for long term reliability	Temperature limit of -55 / +110°C	Compatibility with SF_6 by-products and oil	Vapour permeation	Can be damaged by handling and installation
					Attack by animals during storage

2.6 References

[2.1] Y. Kieffel, V. Hermosillo, B. Mistiaen, R. Puyané,M. Hassanzade and J.L. Bessède, “Experience with hollow core composite insulators at AREVA T&D - Research and applications” INMR World Congress & Exhibition, Hong Kong, China, 2005

[2.2] R. Martin, “Innovative applications and opportunities for composite hollow core insulators” INMR World Congress&Exhibition, Rio de Janeiro, Brazil. 2007

[2.3] V. Hinrichsen, ”Latest Designs and Service Experience with Station-Class Polymer Housed Surge Arresters INMR World Congress&Exhibition, Marbella, Spain, 2003

[2.4] A. Strömbeck, Key Parameters for Affordable Design of Hollow Core Insulators, INMR World Congress&Exhibition, Hong Kong, China, 2005

[2.5] D. Windmar, H. Hillborg, Today’s operating performance and manufacturing processing requirements for silicone rubber in electrical components, INMR World Congress&Exhibition, Hong Kong, China, 2005

[2.6] D. Windmar, A. Holmberg, M. Lundborg: “Production and application of hollow composite insulators on HV apparatus” – World Congress & Exhibition on Insulators, Arresters & Bushings, Crete - 2009

[2.7] A, Dernfalk, Diagnostic methods for composite insulators with biological growth, PhD thesis, Department of Electric Power Engineering, Chalmers University of Technology, Gothenburg, Sweden, 2004

[2.8] I. Gutman, T. Ohnstad, L. Wallin, D. Windmar, U. Åkesson: “Field experience and test verification of HV composite apparatus insulators”, CIGRE-2008, A3-302

[2.9] N. Möhring, H.-G. Haupt, V. Hinrichsen, C. Berger: "Vapor Permeation and Mechanical Damage Limits of Composite Hollow Insulators", 14th International Symposium on HighVoltage Engineering (ISH), Beijing, August 25-29, 2005

[2.10] N. Möhring, H.-G. Haupt, V. Hinrichsen, C. Berger: "Wasserdampfpermeation in GFK Rohren", ETG-Fachtagung "Grenzflächen in elektrischen Isoliersystemen", Würzburg, 16./17.9.2008

3 SERVICE AND FIELD EXPERIENCE OF HIGH VOLTAGE EQUIPMENT WITH POLYMERIC HOUSING

3.1 General

Experience of polymer housings started at industrial scale in the early 1980's [3.1], [3.2]. Since then the total number of hollow core insulators in service is about half a million in the voltage range above 145kV (2006 data). The market is in excess of 50,000 insulators/year with a yearly growth rate in the order of 10-20%. If directly moulded apparatus at voltages greater than 60 kV are considered, e.g. for surge arresters, cable terminations and bushings, there are probably another million of units in service mainly for applications below 145 kV.

The main driving forces for using polymeric housing are: the safety and reduced total life cost in service due to the high mechanical strength (bending and internal pressure) and the superior silicone rubber performance in polluted environments in comparison to porcelain. The penetration is higher in the higher voltage range and for the applications where safety is more critical.
The penetration estimated by the WG from data provided by manufacturer for the year 2007 is reported in Table 3-1.

Table 3-1:Polymer housing penetration in % for HV apparatus

Polymer Penetration in HV Apparatus			
HV Apparatus Type	<170 kV	245 kV	>360 kV
Live Tank Circuit-breakers	<5-10%	<5-10%	<5-10%
Dead Tank Circuit-breakers Bushings	>30%	>30%	>70%
Gas Insulated Station Bushings	>30%	>50%	>50%
Combined Circuit-breakers Bushings	>90%	>90%	>90%
RIP Bushings (Wall/Transformer)	>50%	>50%	>50%
Gas Bushings (Wall/Transformer)	>50%	>50%	>50%
OIP Bushings (Wall/Transformer)	10-20%	10-20%	10-20%
Oil Instrument Transformers	10-20%	10-20%	10-20%
Gas Instrument Transformers	>50%	>50%	>50%
Cable terminations*	>50%	>60%	>80%
Surge Arresters *	>10%	>10%	>10%
*Polymer housing with hollow insulators only. If all directly moulded components are considered the polymer penetration is close to 100% for voltages <170 kV and 40-50% for >245 kV			

3.2 Service experience

The WG employed three main sources of service experience data:

- Data collected by WG members using a questionnaire distributed to power companies
- Publications including test station experience
- Data provided by manufacturers based on their delivery lists and publications

According to the IEC/TS 60815-1 [3.3], for service experience in naturally polluted conditions a period of satisfactory operation from five to ten years can be considered as acceptable and for test station experience a period of satisfactory operation from two to five years can be considered as acceptable. These indications can be used for the evaluation of service experience of polymeric insulators.

3.2.1 Power companies' experience.

A special questionnaire was developed by the working group trying to collect the data in a simple and standard way, see Table 3-2. Information was also collected through interviews with WG members.

Table 3-2: Questionnaire circulated

1. Type of equipment that uses composite insulators	Voltage classes, kV	Approximate number in service
1.1 Circuit-breakers		
1.2 Switches		
1.3 Cut-outs		
1.4 Surge arresters		
1.5 Instrument transformers		
1.6 Bushings		
1.7 Post insulators		
1.8 Combined equipment (disconnecting circuit-breaker, bushing including arrester, etc.)		
2. Type of equipment using composite insulators		
2.1 Circuit-breakers		
2.2 Switches		
2.3 Cut-outs		
2.4 Surge arresters		
2.5 Instrument transformers		
2.6 Bushings		
2.7 Post insulators		
2.8 Combined equipment		
3. Type of environment where the apparatus are installed		
3.1 Desert		
3.2 Coastal		
3.3 Industrial		
3.4 Agricultural		
3.5 Inland		
4. Level of pollution stress where the apparatus are installed		
4.1 Clean		
4.2 Polluted		
5. Any specific observations on apparatus composite insulators		
5.1 Visual corona?		
5.2 Loss of hydrophobicity?		
5.3 Any deterioration or damage (e.g. surface degradation, erosion, impurity coating, puncture, splitting, etc.?)		
5.4 Flashovers?		
5.5 Biological growth?		

Answers were obtained concerning the following power companies:

- Canadian power company (Hydro-Québec)
- Czech Transmission company (via WG member)
- Dutch power company (TenneT)
- German power company (via WG member)
- Japanese and partially world-wide power companies (via WG member)
- Swedish power company (Svenska Kraftnät)
- Norwegian power company Statnett (via WG member)
- Brazilian power and transmission company (Furnas Centrais Electricas) (Via WG member)

A summary of the obtained results is as follows:

- Canadian power company Hydro-Québec. Apparatus with composite housing started to be used in 1990 for distribution. Circuit-breakers, switches, surge arresters, bushings and post insulators are used for 25-69 kV with a maximum service record of 16-17 years. Circuit-breakers and surge arresters are used at 315 kV since year 2000 due to safety issues and for evaluation purposes. These apparatus are mostly applied in an inland environment with a few being exposed to an industrial environment. The specific creepage distance is normally 20-30 mm/kV phase to phase (i.e. 35-52 mm/kV phase to ground. [3.3]). No flashovers or visible corona have been observed but there has been some loss of hydrophobicity and some deterioration which has been limited to distribution class apparatus.
- Czech Transmission company. The experience with instrument transformers with silicone rubber housing is summarized in Table 3-3.

Table 3-3 Service experience with instrument transformers

Voltage level (kV)	Year of production	Number of IT	Percentage of inspected IT (%)	Percentage of IT with degradation (from inspected IT) (%)	Maximum service record (years)	Typical specific creepage distance, (mm/kV)
400	before 1997	73	46	47	16	30
220		31	20	50	12	
400	1997	42	36	13		
220		20	30	0		
400	after 1997	107	30	0		
220		31	10	0		

  About 300 polymer housed instrument transformers are installed in the voltage classes 220kV and 400kV with a typical specific creepage distance of 30 mm/kV phase to phase (about 52 mm/kV phase to ground). Some degradation has been seen on instrument transformers of older design installed before 1997; typically loss of hydrophobicity, hard surface layer, cracks and increasing hardness. Instrument transformers installed since 1997 appear to be performing well.
- Dutch power company TenneT. Apparatus with composite housing include about 195 single-phase circuit-breakers, switches, surge arresters, instrument transformers and bushings. The majority are installed at 380 kV with some surge arresters being installed at medium voltage. Maximum service record is 15 years (surge arresters and instrument transformers). These apparatus are used in the areas with coastal, industrial, agricultural and inland environment. The specific creepage distance is normally 25-31 mm/kV phase to phase (43-54 mm/kV phase to ground). Visual corona and some deterioration were observed on a few of the units.
- German power company. Apparatus with composite housing include about 230 surge arresters, instrument transformers and bushings in the 123-170-245-420 kV voltage classes. Maximum service record is 18 years (bushings). These apparatus are used in the areas with coastal, industrial, agricultural and inland environment. The specific creepage distance is normally 25 mm/kV phase to phase (43 mm/kV phase to ground). No any specific observations recorded except minor biological growth which is not influencing the insulator performance.
- Japanese and partially worldwide power companies. This is the result from 10 power companies.

- Station Surge arresters. These include about 245 apparatus in the 55-66-84-98-110-196-266 kV voltage classes. Maximum service record is 13 years. Creepage distances vary from 24 to 47 mm/kV phase to phase (42-81 mm/kV phase to ground) associated to the specific pollution severity as in Table 3-4. A good performance is reported: no visual corona or deterioration or any other types of events were reported as in Table 3-4.
- Circuit-breakers. These include about 45 apparatus in the voltage class from 154 to 550 kV. Maximum service record is 10 years. Creepage distances vary from 24 to 54 mm/kV phase to phase (42-93 mm/kV phase to ground). These apparatus are used in the areas with agricultural and inland environment with maximum ESDD level below 0.12 mg/cm^2 (42 apparatus are in the area with maximum ESDD 0.03 mg/cm^2). The performance has been good and only a few cases loss of hydrophobicity and biological growth are recorded.
- Bushings. These include 9 apparatus in the 300-500 kV voltage class. Maximum service record is 6 years. A creepage of 45 mm/kV phase to phase (78 mm/kV phase to ground) was used for 300 kV bushings. These apparatus are used in areas with coastal, industrial and inland environment with maximum ESDD level below 0.06 mg/cm^2. A good performance was observed, no visual corona or deterioration or any other types of events were reported.

Table 3-4: Data about station arresters from Japan

Voltage Class, kV	84	196	196	266	266	98	66	55,110
Creapage distannce, mm/kV	36.1	46.8	36	41.7	41.8	-	29	24
Approximate years in service	3	1-4	1-2	1-2	1-2	1	8	13
Number in service	3	42	21	99	51	3	1	24
Type of environment	No	No	No	No	No	No	No	No
Desert	No	No	No	No	No	No	No	No
Coastal	No	Yes	No	Yes	Yes	No	No	No
Industrial	No	No	No	No	No	No	No	No
Agricultural	No	No	No	No	No	No	No	No
Inland	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pollution (ESDD: mg/cm^2)								
approx. 0.01	No	No	Yes	No	Yes	Yes	No	Yes
<= 0.03	No	No	Yes	No	Yes	No	No	No
0.03 - 0.06	No	Yes	No	Yes	Yes	No	Yes	No
0.06 - 0.12	Yes	No	Yes	Yes	Yes	No	No	No
0.12 - 0.35	No	Yes	No	No	No	No	No	No
0.35 <	No	No	No	No	No	No	No	No
Any specific observations								
Visual corona?	No	No	No	No	No	No	No	No
Loss of hydrophobicity?	No	No	No	No	No	No	No	No
Deterioration/damage?	No	No	No	No	No	No	No	No
Flashovers?	No	No	No	No	No	No	No	No
Biological growth?	No	No	No	No	No	No	No	No

- Swedish power company Svenska Kraftnät. Apparatus with composite housing include about 150 circuit-breakers and disconnecting circuit-breakers and surge arresters in the 245-300-420 kV voltage class. Maximum service record is 5 years. These apparatus are used in areas with coastal, industrial, agricultural and inland environment. The specific creepage distance is normally 16-31 mm/kV phase to phase (28-54 mm/kV phase to ground). A good performance was found with no specific observations recorded. On this basis Svenska Kraftnät has decided to construct all new substations completely equipped with composite insulators.
- Norwegian power company Statnett. Apparatus with composite housing include about 80 live tank circuit-breakers at 245-300-420 kV and 150 units at 72,5-145 kV, 400 surge arresters at 132-400 kV and 12 disconnecting circuit-breakers. The specific creepage distance is normally 20-25 mm/kV phase to phase (35-43 mm/kV phase to ground). Maximum service record (for arresters) is 15 years. The service experience is positive, however, some biological growth has been observed in service.

- Brazil power and transmission company (Furnas Centrais Elétricas). Apparatus with composite housing started to be used in 1995 for protection of transformers tertiary. Twenty four 800 kV current transformers with silicone rubber housing are in service since 2000. Ten units of 800 kV surge arresters with silicone rubber housing are in service since 2007 and sixteen were installed in 2009. Two hundred and twelve surge arresters of 72.5 to 245 kV will be installed in the beginning of 2010. These apparatus are mostly applied in coastal, industrial and agricultural areas. The specific creepage distance is 20-30 mm/kV phase to phase. No flashovers or visible corona were observed. Good hydrophobicity (1-3 class). Some biological growth has been observed in service on 800 kV Current Transformers

As a conclusion, the reported service experience is positive, with minor degradation in only few cases observed. A summary of above data collection is presented in Table 3-5.

Table 3-5: Summary on service experience collected via power utilities

Source	Apparatus in total	Voltage class range, kV	Maximum service record, years	Typical specific creepage distance, mm/kV phase to phase	Service experience
Hydro-Québec	No data	25-315	17	20-30	In general positive experience. Some loss of hydrophobicity, some deterioration for distribution class only
Czech Transmission company	304	220-400	16	30	In general positive experience. Some deterioration only for apparatus installed before 1997
TenneT	195	50-380	15	25-31	In general positive experience. Some visual corona, some deterioration
German power company	230	123-420	18	25	In general positive experience. Some biological growth
Japanese and other power companies	298	55-550	13	24-47	In general positive experience. Some loss of hydrophobicity, biological growth
Svenska Kraftnät	150	245-420	5	16-25	Positive experience
Statnett	642	72,5-420	15	20-25	In general positive experience. Some biological growth
Furnas Cenrais Electricas	Surge arresters	13,8 to 800	50	20-30	No visual corona; No loss of hydrophobicity; No flashovers; Some biological growth
	Instrument transformers	800	24	20-30	

3.2.2 Manufacturers experience

A similar questionnaire to that shown in Table 3-2 was circulated to manufacturers in Japan.

The results, referring to experience of 100 arresters, 3 instrument transformers, 21 bushings and a number of circuit-breakers, indicate a generally good performance with no visual corona or deterioration or any other types of events being reported.

According to manufacturer’s experience, the majority of insulators supplied have specific creepage distance ranging from 25 to 31 mm/kV phase to phase (43-54 mm/kV phase to ground), although, depending on application & customer, specific creepage distances ranging from 16 to 50 mm/kV phase to phase (28-87 mm/kV phase to ground) have been delivered**.**

3.2.3 Experience from test stations: pollution performance

Whilst general service experience may be obtained from commercial installations, the information is insufficient for dimensioning purposes because directly comparable experience with insulators of different materials and dimensions are not usually available in service. The most efficient way to obtain information regarding optimal dimensioning is to carry out tests in specialized test stations where high-quality measurements and periodical inspections can be made. Based on this philosophy, a number of test stations were organized to test the long term performance of composite apparatus insulators in stations representing rather severe conditions. These included coastal (Dungeness and Kelso), inland (Ludvika) and semi-desert (Negev) locations and the results were reported in [3.4] to [3.11]. These results were later complemented by investigations of composite apparatus insulators removed from all above mentioned test stations and also from commercial installations. The details about the test objects, test sites and the measured pollution parameters are summarised below [3.5].

Table 3-6 Test sites and field test conditions

Test site	Climate	Environment	Pollution severity (IEC 60815)	Test objects	Exposure time [years]
Dungeness (UK)	Temperate	Coastal	Very Heavy	Arrester,circuit-breaker, bushing	2.8-7.7
Kelso (South Africa)	Subtropical	Coastal	Very Heavy	Arrester, bushing	2.3-3.5
Thailand	Tropical	Coastal/industrial	Very Heavy	Arrester	1.5
Negev (Israel)	Tropical	Semi-desert	Heavy	Arrester	5.5

Table 3-7: Test objects

Test object	Test site	Test voltage (ph-g) [kV]	Specific creepage distance (ph-ph) [mm/kV]
Arresters	Dungeness	84	20; 25; 31
	Kelso	58	12; 16; 23
	Thailand	156	32
	Negev	95	31; 39
Breaker Support insulator	Dungeness	84	27
		84	27
Bushings	Dungeness	84	25; 32; 34
		231	35
	Kelso	58	23

In general HV silicone rubber apparatus insulators, tested for a period from 2 to 8 years, all performed well. The apparatus insulators installed at Kelso and Dungeness test stations were investigated in greater detail as reported in [3.4], [3.7] [3.11].

With regard to ageing characteristics, the results of 2-8 years of field testing show that there is only slight deterioration for the apparatus insulators even with rather short creepage distance and in severe coastal environment. This is a much better performance than that of silicone rubber line insulators tested at the same site. The most important factors which contribute to this less rapid ageing are the lower magnitude and differently located maximum E-field in the vicinity of HV flanges and lower current density due to a large diameter of the insulators in comparison with line insulators.

The pollution performance of silicone rubber apparatus insulators was better than that of the porcelain insulators at the same site and the hydrophobicity at the end of the test period (2-8 years) remained significantly better than that of porcelain in all case (Table 3-8 from [3.6]).

Table 3-8 Hydrophobicity (wetability class according IEC TS 60273) measured at different sites

Site	Composite insulator	Porcelain insulator
Dungeness (coastal)	3-6	7
Kelso (coastal)	5-6	7
Ludvika (inland)	1-2	7
Negev (semi-desert)	1-3	7
Estonia (industrial)	3-4	7

One of the conclusions in [3.4] is that it may be possible for composite housings to be applied in coastal areas with a reduced creepage distance from that prescribed by IEC 60815 for porcelain and glass insulators [3.12]. A summary of the investigations performed over a 10 year period confirms, like service experience, that the modern composite insulators technology is to be considered as mature [3.6]. Based on these investigations, Scandinavian transmission utilities Svenska Kraftnät (Sweden) and Statnett (Norway) have recently established policies of using predominantly composite apparatus insulators in their network. Svenska Kraftnät has decided to standardise on composite housings for circuit-breakers, arresters, voltage and current transformers on the basis of better operational and personal security, marginal difference in price from porcelain alternative, positive service experience and environmental-friendly designs. Statnett has decided to use all arresters, voltage and current transformers only with composite housings and is considering use of composite circuit-breakers [3.6].

3.3 Other aspects of service experience

Apart from the good performances under pollution conditions as reported in the previous chapter (no pollution related flashover reported in the literature), other aspects of service experience are considered as follows:

3.3.1 Safety aspects

One of the main driving forces for choosing composite hollow insulators is safety. Failure of porcelain can be caused by external impact such as throwing of stones or shooting at the insulators or can be caused by internal pressurisation due to arcing or deterioration of internal components. Failure of pressurized porcelain insulators inevitably leads to the expulsion of shattered porcelain fragments which are hazardous to both people and other equipment. If the failure is due to a failure of internal insulation or parts leading to internal arcing, the substantial pressure rise and the effect of thermal shock upon the porcelain is likely to result in porcelain being projected over significant distances; up to 200m has been reported from Denmark [3.6].

No such cases have been reported for polymer insulators, a situation which can be explained by the difference in performance of composite insulators in comparison to porcelain insulators under external/internal fault conditions. **Figure 3-1** [3.13] shows insulators, or parts thereof, that have been subject to shooting tests in a laboratory environment. The composite insulator pressurized to 6 bar did not explode when shot and the only external indication was a puncture of the insulator which otherwise remained intact. Conversely, the porcelain insulator exploded and distributed large, sharp edged, pieces throughout the test cell. Similar comparative behaviour between the two insulator types is experienced during surge arrester internal damage (short-circuit) tests which are part of the standardised proving requirements for surge arresters in the IEC 60099-4 (short-circuit tests) [3.14].

Furthermore, earthquake experience has shown that composite insulators are much less likely to fail than porcelain.

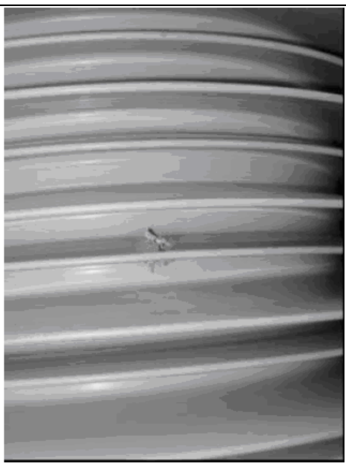
	
a) composite insulator: internal pressure vented though a hole in the housing without any shattering	b) porcelain insulator piece shattered several metres away after explosion

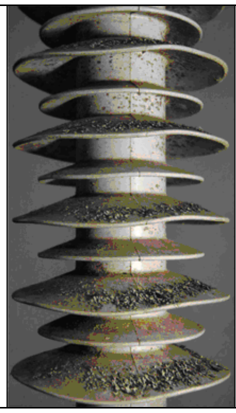
Figure 3-1: Example of results of shooting tests on composite and porcelain pressurised insulators [3.13]

3.3.2 Biological growth aspects

Polymer and even porcelain insulators can under certain circumstances be subjected to biological growth (algae, fungi and lichen) and this can theoretically influence both pollution performance and ageing characteristics of insulators. Concerns for polymer insulators include that the housing material might be consumed by the biological growth (as a food source) or that it might be possible that fungi penetrate the surface layer of the insulator without consuming the material.

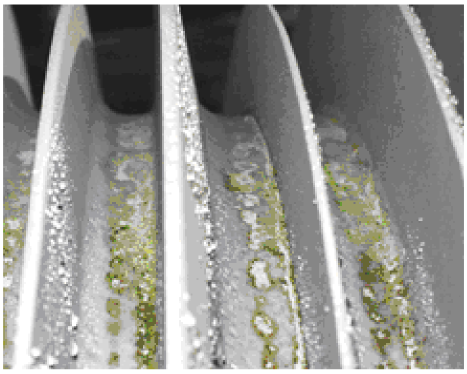
Different types of biological growth were found in various climates ranging from warm and humid in South Africa, Florida (USA) and Sri Lanka to relatively cold, but still humid, in Scandinavia, Japan and Germany. Some examples are shown in Figure 3-2.

A)



B)

C)



D)

Figure 3-2: Examples of biological growth observed in different parts of the world: A – Algae in Sweden [3.6]; B – Lichen in Norway; C – Algae in Japan [3.8]; D – Algae on horizontal insulator in Germany

According to present knowledge, biological growth is located only on the surface of the silicone rubber [3.15], [3.16] and in the worst cases reduces the hydrophobicity on the part of the insulator (usually the shaded part). The risk for flashover due to the biological growth is rather low [3.6] because in order to lead to flashover, the resistance of the pollution layer should be relatively low. However, biological growth normally occurs in relatively clean areas leading to a situation where either insulator will be hydrophilic, but clean, i.e. with high resistance, or it will be contaminated but free of biological growth and therefore be hydrophobic (due to recovery of hydrophobicity) with high resistance. Because biological growth seems to be a surface phenomenon, wiping or washing are considered to be an effective countermeasures.

3.3.3 Bird related issues

Up to now no bird related issues have been reported from service for polymer apparatus insulators installed in substations, while a few issues were reported for line insulators (e.g. those in Australia related to kakadoo, occurred however only before the energisation of the line [3.9]).

3.4 Conclusions

The penetration of polymeric housings for apparatus is increasing with market growth of the order of 10-20%.

The experience from service and test stations is generally positive for all silicone rubber clad apparatus and only minor degradation such as loss of hydrophobicity or biological growth has been reported in some cases.

The field & test station performance confirms that polymeric housings have a better pollution performance than porcelain and this might eventually lead to the possibility of reducing creepage distances of silicone rubber insulators from those used for glass and porcelain insulators. This possibility is recognised in IEC 60815-3 although no firm recommendations are given.

When considering the field experience other benefits should be taken into account, such as explosion proof and seismic performance.

3.5 References

[3.1] D. Windmar, H. Hillborg: “Today’s operating performance and manufacturing processing requirements for silicone rubber in electrical components”, World Congress & Exhibition on Insulators, Arresters & Bushings, Hong Kong, 27-30 November, 2005

[3.2] K.P. Ellis: ”Twenty Years of Field Experience: OIP Transformers and OIP Bushings Supplied with Silicone Rubber Insulators”, World Congress & Exhibition on Insulators, Arresters & Bushings, Rio de Janeiro, Brazil, 13-16 May, 2007

[3.3] IEC/TS 60815-1: ”Selection and dimensioning of high-voltage insulators for polluted conditions - Part 1: Definitions, information and general principles”, Edition 1.0, 2008-10

[3.4] I. Gutman, L. Stenström, D. Gustavsson, D. Windmar, W.L. Vosloo: “Optimized use of HV composite apparatus insulators: field experience from coastal and inland test stations”, CIGRE Session 2004, A3-104

[3.5] I. Gutman, H. Wieck, D. Windmar, L. Stenström, D. Gustavsson: “Pollution measurements to access the performance of naturally exposed silicone rubber composite insulators”, IEEJ Transactions on Fundamentals and Materials, Vol. 127, No. 9, 2007

[3.6] I. Gutman, T. Ohnstad, L. Wallin, D. Windmar, U. Åkesson: “Field experience and test verification of HV composite apparatus insulators”, CIGRE-2008, A3-302

[3.7] S. Narita, A. Sawada, H. Watanabe, B. Johnnerfelt, L. Stenström: “Design and testing of polymer-housed surge arresters with special emphasize on seismic stresses and selection of specific creepage in coastal areas”, CIGRÉ SC A3 & B3 Joint Colloquium, Tokyo, Japan, paper 108, September 2005

[3.8] Manabu Sakata, Morihida Kokofu: “Status of R&D for Polymer Insulators at TOHOKU Electric Power”, World Congress & Exhibition on Insulators, Arresters & Bushings, Hong Kong, 27-30 November 2005

[3.9] B. Pokarier: “Insulation Selection and maintenance philosophies of an Australian utility operating in an electricity market”, World Congress on Insulator Technologies for the Year 2000 and Beyond, Barcelona, Spain, 14-17 November 1999

[3.10] B. Richter, W. Schmidt, K. Kannus, K. Lahti, V. Hinrichsen, C. Neumann, W. Petrusch, K. Steinfeld: “Long Term Performance of Polymer Housed MO-Surge Arresters”, CIGRE-2004, A3-110

[3.11] V. Hinrichsen, W. Petrusch, B. Richter, K. Steinfeld: "Prüfung des Langzeitverhaltens von silikonisolierten Überspannungsableitern", ETG-Workshop "Silikonelastomere", Berlin, 20.3.2003, ETG-Fachbericht No .93, pp. 119-128

[3.12] IEC/TS 60815-2: “Selection and dimensioning of high-voltage insulators intended for use in polluted conditions – Part 2: Ceramic and glass insulators for AC systems”, Edition 1.0, 2008-10

[3.13] D. Windmar, A. Holmberg, M. Lundborg: “Production and application of hollow composite insulators on HV apparatus” – World Congress & Exhibition on Insulators, Arresters & Bushings, Crete - 2009

[3.14] IEC 60099-4, Ed. 2.1:2006: "Surge arresters – Part 4: Metal-oxide surge arresters without gaps for AC systems"

[3.15] A. Dernfalk: “Diagnostic Methods for Composite Insulators with Biological Growth”, PhD Thesis, Chalmers University of Technology, Gothenburg, Sweden, October 2004

[3.16] S. Wallström: “Biofilms on silicone rubber materials for outdoor high voltage insulation”, PhD Thesis, KTH, Stockholm, Sweden, 2005

4 PRESENT IEC STANDARDS AND THEIR APPLICABILITY TO APPARATUS AND COMPONENTS WITH POLYMERIC INSULATION

4.1 Introduction

As shown in Chapter 2, two main cases are to be considered:

- The general case adopting a hollow type insulator
- The specific case, as the case of many surge arrester solutions, where the housing is directly moulded on the test object.

4.2 Present Standards

IEC 61462-2007 “Composite hollow insulators –pressurized and unpressurized insulators for use in electrical equipment with rated voltage greater than 1000 V – definitions, test methods, acceptance criteria and design recommendations” [4.1] is the basic reference for the general case when hollow composite insulators are considered.

This international standard applies to composite hollow insulators consisting of a load bearing insulating tube made of resin impregnated fibres, a housing (outside the insulating tube) made of elastomeric material (for example silicone or ethylene-propylene) and metal fixing devices at the ends of the insulating tube. Composite hollow insulators as defined in the standard are intended for general use (un-pressurised) or for use with a permanent gas pressure (pressurised). They are intended for use in both outdoor and indoor electrical equipment operating on alternating current with a rated voltage greater than 1000 V and a frequency not greater than 100 Hz or for use in direct current equipment with a rated voltage greater than 1500 V.

IEC 61462 makes general cross reference to IEC 62217-2005 “Polymeric insulators for indoor and outdoor use with a nominal voltage >1 000 V –General definitions, test methods and acceptance criteria” [4.2], with the objective:

- to define the common terms used for polymeric insulators,
- to prescribe common test methods for design tests on polymeric insulators,
- to prescribe acceptance or failure criteria, if applicable,
- to give recommendations for polymeric insulator test standards or product standards, complemented by specific requirements as needed

IEC 61462 distinguishes between design tests and type tests because several general characteristics of a specific design and specific combinations of materials do not vary for different insulator types. In these cases results from design tests can be adopted for different insulator types. The tests foreseen are summarised below.

4.2.1 Design tests

These tests are intended to verify the suitability of the design, materials and manufacturing technology.
A composite hollow insulator design is defined by:

- materials and design of the tube, housing and manufacturing method,
- material of the end fittings, their design and method of attachment,
- layer thickness of the housing over the tube (including a sheath where used).

According to the Standard, one hollow insulator assembled on the production line shall be tested. The tube's internal diameter shall be at least 100 mm and the wall thickness at least 3 mm. The insulation length (metal-to-metal spacing) shall be at least three times the tube's internal diameter but not less than

800 mm. Both end fittings shall have the same method of attachment and sealing as on standard production insulators.

The following tests are specified:

Tests on interfaces and connections of end fittings, item 7.2 of the Standard
- Reference dry power frequency flashover test
- Thermal mechanical pre-stressing test
- Water immersion pre-stressing test
- Verification tests
- Visual examination
- Steep-front impulse high voltage test
- Dry power frequency voltage test
- Internal pressure test (This test is not applicable for composite hollow insulators designed for unpressurised service conditions).

Tests on shed and housing material, item 7.3 of the Standard
- Hardness test
- Accelerated weathering test
- Tracking and erosion test
- Flammability test

Tests on the tube material, item 7.4 of the Standard
- Dye penetration test
- Water diffusion test

When significant changes in the design occur, re-qualification shall be done as prescribed in the standard.

Examples of design tests are given in **Figure 4-1** to **Figure 4-3**

a)	*b)*	*c)*

Figure 4-1: Examples of design tests: Tests on interfaces and connections of end fittings: a) Dry power frequency voltage test; b)Thermal mechanical pre-stressing test, c)Steep-front impulse high voltage test

Figure 4-2: Example of design test. Tests on shed and housing material, item 7.3 of the Standard Tracking and erosion test (1000 hours salt fog test)

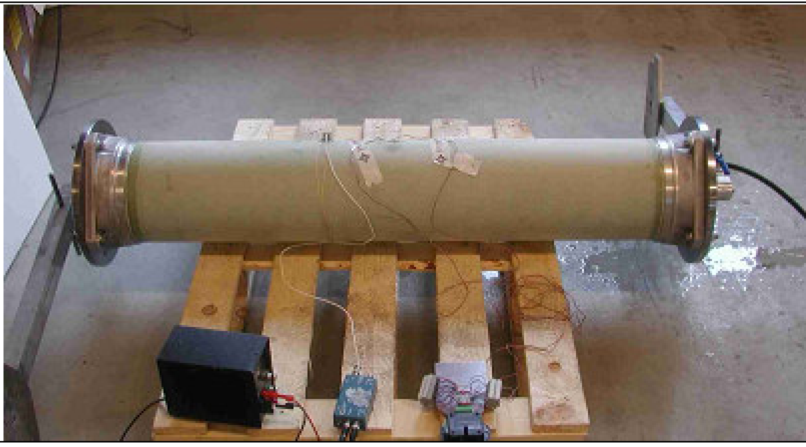
Figure 4-3: Example of design test. Tests on the tube material. Dye penetration test
(Note – the length of the test sample presented in this figure is much larger than required by the standard)

4.2.2 Type tests

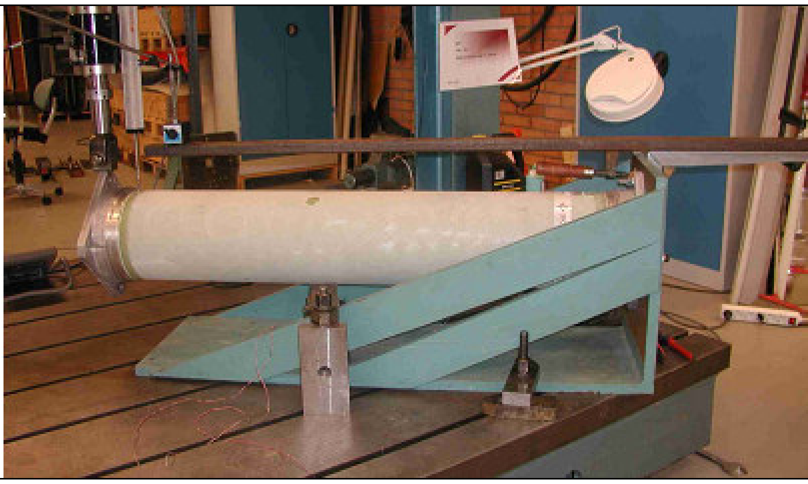
Only mechanical type tests are foreseen and they consist of:

- a pressure test, for pressurized insulators only (**Figure 4-4** a),
- a bending test (**Figure 4-4** b).

According to the Standards, the test specimens shall be either full length insulators or shorter but otherwise shall be identical insulators made on the production line. The length of the specimens (metal-to-metal spacing) shall be not less than 800 mm. The applied load shall be adjusted for insulator length to obtain the required stress. Both end fittings shall be the same as used on production line insulators. The insulator specimens used for these tests shall be with or without housing. Where the tests are made without housing, the thermal cycle of housing application shall be applied to the tube prior to testing.



a)



b)

Figure 4-4: Examples of type tests.a) pressure test, (for pressurized insulators only), b) bending test

4.3 Limitations of existing standards

The following aspects are not addressed by the existing standard:

- The housing performance may also depend on the equipment inside or outside the composite hollow insulators. Test methods not specified are to be considered for specific combinations of materials and specific applications and are left to the agreement between manufacturers and users.
- The practical use of composite hollow insulators covers both AC and DC applications however a specific tracking and erosion test procedure for DC applications as a design test has not yet been defined and accepted.
- Pollution tests according to IEC 60507 are not included in the standard as they are generally not applicable. Specific pollution tests for polymeric insulators are under consideration.
- The standard does not prescribe dielectric tests such as impulse voltage or power frequency voltage type tests, nor does it prescribe pollution tests because the withstand voltages are not characteristics of the hollow insulator itself, but of the apparatus of which it ultimately forms a part.
- All the design tests, apart from the thermal-mechanical test, are performed at normal ambient temperature. Extreme service temperatures may affect the mechanical behaviour of composite insulators. A general rule to define “extreme high or low” insulator temperatures is not available at this time and, for this reason, the supplier should always specify service temperature limitations. Whenever the insulators are subjected to very high or low temperatures for long periods of time it is advisable that both manufacturer and user agree on a mechanical test at higher or lower temperatures than that mentioned in this Standard.

In particular the following aspects are not dealt explicitly in the standards and will be analysed in the following chapters:

- The need for tests to assess the electric field interaction of the active parts inside the housing on the short and long term performance of the housing
- Mechanical interactions and the need for special tests to assess the actual component performance (example seismic performance, short circuit performance). As an example, short circuit testing on long insulators is a problem. In the past the lengths of porcelain housing units were limited and within the practical limits of testing. Polymeric housings can be much longer and do not always fall within the practical limits of test capabilities.
- The need for special tests to assess the thermal and chemical interaction of the internal parts
- Standards specify a production unit but for HV applications the sample insulator is too small and in many cases needs to be specially produced. If a production unit is used it may not conform to the standards because of the higher voltage rating and longer length of the insulators.

Some of these aspects are already taken into account by the product standards or by supplementary specifications. The following clause details some specific examples where additional/alternative tests are foreseen for surge arresters, circuit-breakers, current transformers, cable termination and bushings. Some cases are analysed to demonstrate the need for adaptation to suit specific applications; an aspect which is dealt with in greater detail in the later chapters dealing specifically with electrical, thermo-mechanical and chemical interactions.

4.4 Specific additional requirements in existing equipment standards for High Voltage apparatus

Equipment standards already consider additional requirements deemed necessary to take care of specific aspects of the use of composite insulators.

4.4.1 Standards/specifications for surge arresters with composite housing

The revision of the surge arrester standard [4.3a], [4.3b] follows an identical approach both for arresters using composite hollow core insulators and for designs where the housing is directly attached to the metal-oxide column. Therefore, all definitions and test procedures have to take into account that different requirements may apply. For this reason, for example, the mechanical definitions and test procedures of IEC 61462 have not been adopted for surge arresters.

The following highlights those clauses and particular aspects of the surge arrester requirements which are of relevance to the scope of this Technical Brochure.

Test of the bending moment: In the latest version of the surge arrester standard [4.3b], the moisture ingress test (consisting of a terminal torque pre-conditioning, a thermo-mechanical pre-conditioning and a water immersion test) has become the evaluation part of the bending test. IEC 60099-4 is the only standard that requires cyclic bending testing as a type test and the reason for this is explained in further detail in Chapter 7.

Weather aging test: This test corresponds to the "tracking and erosion tests" of IEC 62217 and IEC 61462. However, as discussed in chapter 5, very long surge arrester housings may be punctured due to the extreme radial field stresses and hence a weather aging test is required on the longest unit of a given design. Since this length may be greater than two metres in the case of polymeric housings the test can usually only be performed as a 1000 h salt fog test (named "Test series A" in the arrester standard). However, since a key feature of silicone rubber materials is their hydrophobicity, and more specifically their ability to recover hydrophobicity over time, a 1000h test without the incorporation of “recovery cycles” might be considered unduly onerous. To address this, a cyclic 5000 h test (named "Test series B" in the arrester standard) is allowed as an alternative option consisting of the following stresses applied in a cyclic manner: solar radiation simulation; artificial rain; dry heat; damp heat (near saturation); high dampness at room temperature (saturation shall be obtained); salt fog at low concentration. If this test can be run on the longest unit of the design, no further test has to be performed. If not, it should – on agreement between manufacturer and purchaser – be performed in addition to the 1000 h salt fog test on the longest. This test can be run on a shorter section of only a few kilovolts rated voltage.

A long term radial field stress test was discussed for several years, but consensus about a suitable test procedure by which to impose reasonable dielectric long term stress in reasonably short time was not found and the topic was closed without resolution

4.4.2 Standards/specifications for circuit-breakers with composite housing

The relevant standards for high voltage circuit-breaker are:

- IEC 62271-1: High-voltage switchgear and controlgear – Part 1: Common specifications [4.5]
- IEC 62271-100: High-voltage switchgear and controlgear – Part 100: Alternating current circuit-breakers" [4.6]
- IEC 62271-300, 2006, High voltage switchgear and controlgear – Part 300: Seismic qualification of alternating current circuit-breakers" [4.7]

They apply whether the circuit-breaker is equipped with ceramic insulators or composite insulators.

When replacing ceramic housing by composite housing on a circuit-breaker one should reconsider the following aspects:

Dielectric test: Generally speaking, for the same major dimensions the dielectric performance of composite and ceramic circuit-breaker housings is equivalent in dry conditions. It is recognised that a breaking chamber equipped with a composite housing can withstand higher voltages in wet condition and in polluted condition than a breaking chamber equipped with a ceramic housing, due the surface properties of the silicon rubber housing.

Composite housings have a lower relative permittivity (in the range of 3-4) compared to ceramic housing (range of 6-8) and therefore, the voltage distribution inside and outside the breaking chamber differs when a composite housing is used compared to a ceramic housing. This is to be taken into account in the insulation co-ordination design of the circuit-breaker.

Temperature rise due to continuous current: Composite housings have a lower thermal conductivity than ceramic housing meaning that temperature rise tests performed with ceramic housing cannot be considered valid for the case where the housing is exchanged for composite material. When using a composite housing for a breaking chamber, the maximum continuous current that can be carried out by the main contact system is reduced compared to when using ceramic chamber housing and specific tests should be performed to prove the current carrying capability with a composite housing.

Seismic tests (IEC 62271-300): Due to their lower weight and different mechanical properties, the application of composite housings significantly modifies the behaviour of a circuit-breaker during a seismic event. Seismic tests performed on a circuit-breaker equipped with ceramic insulators are no longer valid when changing to composite insulators and vice versa. However, simulation tools do exists: if a calibration is done based on a test on a circuit-breaker equipped with ceramic insulators, and if weights and properties of the composite housing are properly described, a new calculation can be performed that will give accurate results for a circuit-breaker equipped with composite housing

Static terminal load tests (IEC 62271-100): Due to their lower weight and different mechanical properties, composite housings used on a circuit-breaker significantly modify the behaviour of the circuit-breaker when applying mechanical loads at its terminals (loads derive from ice, wind and connected conductors). Terminal load tests performed on a circuit-breaker equipped with ceramic insulators are no longer valid when changing to composite insulators and vice versa. However, simulation tools do exists: if a calibration is done based on a test on a circuit-breaker equipped with ceramic insulators, and if the mechanical properties of the composite housing are properly described, a new calculation can be performed that will give accurate results for a circuit-breaker equipped with composite housing. The second edition of IEC 62271-100 contains the following text: "If the manufacturer can demonstrate by means of calculations that the circuit-breaker can withstand the specified stresses, then tests need not be performed". Terminal load tests are normally not performed and calculations are sufficient. Bending moments will not change as a result of terminal loads. Wind and ice load need to be reconsidered when changing from ceramic to composite insulators.

Making and breaking performance (IEC 62271-100): The making and breaking performance of a circuit-breaker is normally not affected when using composite chamber insulators instead of ceramic chamber insulators. However it should be verified that the by-products of the gas used for arc interruption do not interact with the inner surface of the housing and that this inner surface is not damaged by the hot gases produced during the arc interruption (see chapter 8 for more detailed information). The circuit-breaker standard does not specify any particular test to demonstrate the withstand capability of the insulator to such chemical attack however it incorporates a dielectric test as a voltage condition check after any type test. Such a dielectric test can be performed after the 100% asymmetrical short circuit type test, T100a, which is probably the most aggressive test duty specified in terms of generation of hot gas and arcing by-products. A further aspect to be considered is the electro-dynamic effect of the short circuit in the short-time current and peak withstand current test: The first peak of the short-circuit causes a bending moment on the post insulator due to the interaction of the phases. This needs to be considered for three-pole operated circuit-breakers with short phase distances although, again, this aspect can be verified through tests or calculation.

4.4.3 Standards/specifications for bushings

The bushing standard IEC60137 [4.8] is applicable for all bushings above 1000V intended for alternating voltage. Earlier editions only included requirements for hollow ceramic insulators but from edition 6 (2008)applications with polymeric insulators are also addressed.

The general approach adopted in the bushing standard is to refer to IEC61462 regarding properties of the composite insulator itself such as issues related to adhesion of housing on the tube and flanges. When designing a polymeric insulator for a new application, parameters such a MML (maximum mechanical load) and MSP (maximum service pressure) are defined as target values to be fulfilled for the insulator itself. From a mechanical point of view the insulator may support the internal parts, meaning that this aspect should be included when defining the MML and MSP of the insulator, or the internal parts may support the insulator. The bushing is then type tested according to the bushing standard to verify that the completed product i.e., the performance of the external insulation and the influence of the inner parts.

IEC60137 includes requirements for insulators (both porcelain and composite) by specifying tests for all bushing types and by specifying further, pressure related, tests for gas filled or gas insulated bushings. Reference to IEC 61462 is made under clause 8 (Type tests) and clause 9 (Routine tests). Clause 8 states that "the test is performed on the insulating envelope in accordance to IE61462 or 61233 where appropriate" however it is not explicit whether IEC60137 is referring to the pressure and tightness test under type test or under routine test in IEC61462. Clause 9 specifies that the insulator alone shall be tested according to IEC61462 before the routine pressure and tightness test on the complete bushing.

In principle, the standard refers to all types of bushings however its applicability where the outdoor insulation material is directly moulded on the RIP may require additional attention since the referenced IEC 61642 does not refer to this specific case. In clause 7 of IEC60137 it is mentioned that "All tests shall be carried out in accordance with the relevant IEC publication referred to in the particular clause. Tests on insulating envelopes of ceramic material shall be carried out in accordance with IEC62155. Tests on insulators of composite material shall be carried out in accordance with IEC61462 and IEC62217". One can interpret this as it also would be valid for cases where the outdoor insulating material is directly moulded on the RIP core. However, it is not clearly stated and can thus be interpreted in different manners.

Requirements that remain unclear and need more attention are, for example, material test on the outdoor insulation as well as aging test like tracking and erosion (1000h salt fog test) and test on interfaces and connections of end fittings as specified for composite insulators in IEC61462.

4.4.4 Instrument transformers

IEC 60044 parts 1 through 8 deals with instrument transformers such as current, inductive voltage, capacitor voltage, electronic voltage and electronic current transformers. IEC 60044 does not mention any special requirements when changing from porcelain to composite insulator and the standard makes no reference to IEC61642.

4.4.5 Special applications

Composite insulators are applied also to multi function equipment, such as bushing + surge arresters, circuit-breakers + disconnectors + instrument transformers etc. These applications are not yet fully taken into account by Standards and may require specific attention.

4.5 Conclusions

IEC 61462 covers hollow insulators but may not always be sufficient to cover tests on entire equipment and the case of the composite housings directly moulded on the equipment. Specific tests are thus necessary depending on the application considered and further analysis of these aspects is presented in the following chapters.

4.6 References

[4.1] IEC 61462-2007 "Composite hollow insulators –pressurized and unpressurized insulators for use in electrical equipment with rated voltage greater than 1 000 V – definitions, test methods, acceptance criteria and design recommendations

[4.2] IEC 62217-2005 "Polymeric insulators for indoor and outdoor use with a nominal voltage >1 000 V –General definitions, test methods and acceptance criteria"

[4.3a] IEC 60099-4 Ed. 2.1- 2006 "Surge arresters – Part 4: Metal-oxide surge arresters without gaps for AC systems"

[4.3b] IEC 60099-4 Ed. 2.2 "Surge arresters – Part 4: Metal-oxide surge arresters without gaps for AC systems" (identical to [3a] plus Amendment 37/354/FDIS)

[4.4] IEC 60044 1 to 8, Standards covering instrument transformers such as current, inductive voltage, capacitor voltage, electronic voltage and electronic current transformers

[4.5] IEC 62271-1 - 2007: "High-voltage switchgear and controlgear – Part 1: Common specifications

[4.6] IEC 62271-100 - 2008: High-voltage switchgear and controlgear – Part 100: Alternating current circuit-breakers (

[4.7] IEC 62271-300-2006: High voltage switchgear and controlgear – Part 300: Seismic qualification of alternating current circuit-breakers"

[4.8] IEC 60137 - 2008: Insulated bushings for alternating voltages above 1000 V

5 EFFECT OF THE ACTIVE PARTS UPON THE ELECTRIC FIELD

5.1 Introduction

Composite insulators have to be designed taking careful account of the numerous electrical field interactions that can occur. The designer has to ensure that the applied electrical field will not cause discharge, insulator puncture, partial discharges or excessive insulator ageing. The accurate evaluation of the electric fields and of their impact on discharge of pre-discharge phenomena is complex but critical to long term performance of composite insulators. Considering the general case of a hollow insulator with inner active parts, many parallel and series combinations of materials need to be addressed. The main elements can be summarised as follows:

- The external insulation. Generally air insulation is present outside the housing. The insulator is terminated with metallic flanges. Shielding electrodes will be present to reduce the field gradients at the top of the insulator and to improve the voltage distribution along the insulator. For transformer bushings one part of the bushing (the top part) is in air and the other (the bottom part) in oil (generally).
- The insulator housing, generally made of silicone, in the outdoor part.
- The fibre glass tube
- The inner component (s), which may vary significantly depending on the application. In particular electrodes and insulation materials of various kinds such as oil, SF_6, air, solid insulation may be present. This internal insulation system may, itself, be complex involving many insulating materials.

5.2 Design constraints

Excessively high electrical field applied to a composite insulator can have various consequences [5.1]. Partial discharge may occur within voids inside the solid materials, around impurities or at the interfaces housing/end-fitting of the insulator. These discharges can damage the interfaces and, if of sufficiently long duration, can lead to insulator failure [5.2]. However it is to be pointed out that the maximum admissible electrical field value in the material and at these interfaces depends on the material and technology used and can only be determined by the manufacturer of the insulator.

Electric fields can be especially critical at triple points. A triple point is defined as a location where a metallic part, an insulating part and gas are joining (**Figure 5-1**). The geometry around this point is generally made of small radii components which lead to high dielectric stresses at the triple point. The geometry of the triple point has to be carefully designed to ensure that that the electric field on the metallic part and at the surface of the insulating part does not exceed the design criteria, depending on the insulation involved. Furthermore, even if the value of the field does not exceed the design criteria, it should be verified that the maximum total field (axial component + radial component) on the shield does not point towards the surface of the insulating part. If such a case happens, the profile of the shield should be reshaped (**Figure 5-2**).

Wet insulators may suffer from “water drop corona” at the surface of the insulator. Water drops on the surface of the housing, due to their shape and location, create locally enhanced electric fields such that corona will appear around a water drop or between adjacent water drops. This corona can temporarily reduce the hydrophobicity of silicone rubber housings. Various investigations have been made into this aspect [5.3], [5.10], [5.11] and have concluded that corona activity can be initiated on the silicone rubber surface above an electric field strength of 0.35 … 0.7 kV/mm (tangential direction) and 1 kV/mm (normal direction), respectively.

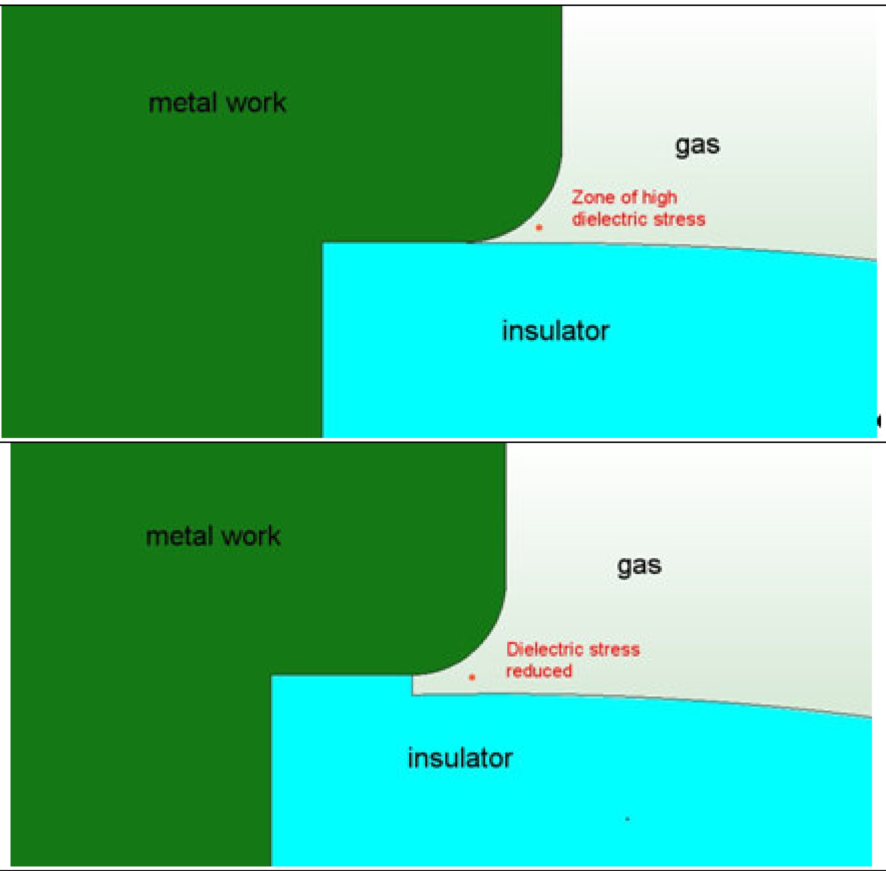


Figure 5-1: Typical triple point situation

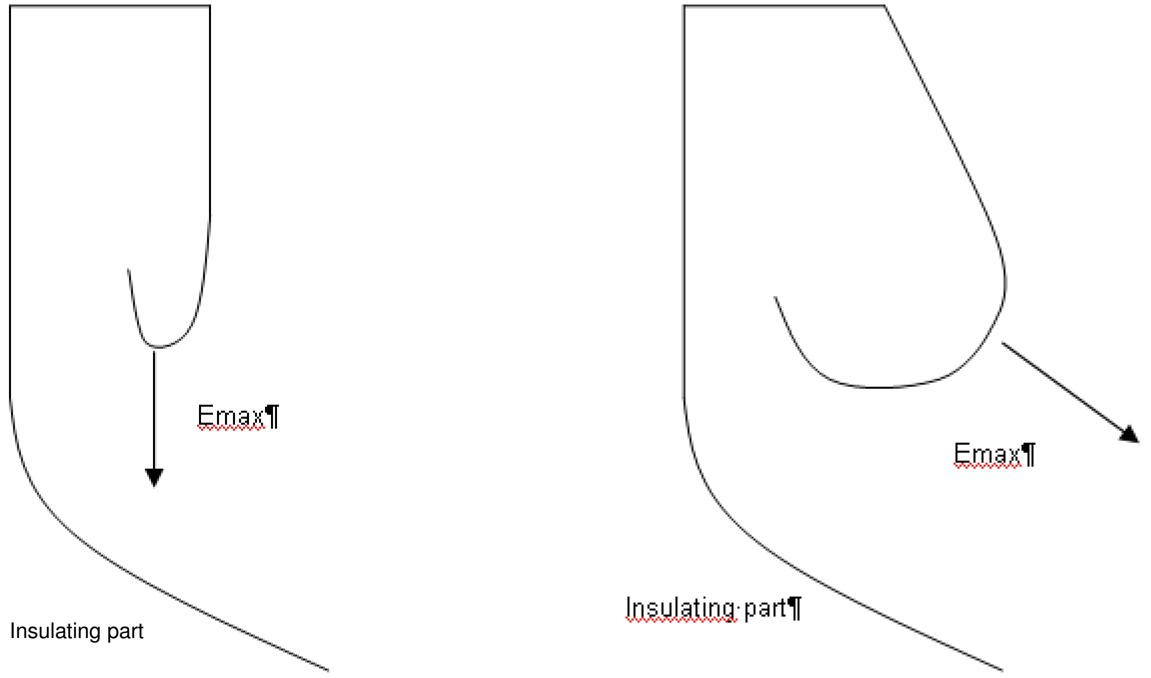


Figure 5-2: Electric field on electrodes in the vicinity of insulating part

In addition to the radio (RIV) and TV interference problems, the presence of electrical discharges close to the surface of the housing can also lead to some degradation of the material.

It is important to note that, as the insulators become polluted, the electrical field distribution will change and critical field values can occur locally. In the case of hydrophilic materials, or during temporary loss of hydrophobicity, wetting of the pollution layer will result in a leakage current and may induce electrical discharges activity at the surface of the insulator (dry band arcing). The E-field along the insulator will then change continuously with the appearance of these dry bands and the local E-field can no longer be easily determined by calculation. This aspect can be controlled at the design phase by the proper selection of :

- materials (material which preserves hydrophobicity)
- profile with a specific creepage distance suitable for the installation site
- voltage per unit arcing distance

all of which help to limit this behaviour.

For long insulators, such as those used for EHV/UHV arresters or bushings the uneven voltage distribution along the insulator may cause high transversal stresses toward the inner active parts. This aspect should be carefully analysed from the point of view of insulation co-ordination of the external/internal insulation systems. In **Figure 5-3** the phenomenon is illustrated with reference to surge arresters. The potential of the high-voltage terminal or of the ground terminal may be shifted along the housing up to a point where a flashover to the other terminal would occur. At the same time, the internal metal oxide stack ensures an even axial voltage distribution. Thus extremely high potential differences may occur between the external layer and the internal parts, possibly leading to internal partial discharges in case of designs with an internal gas volume and puncture of the insulator.

5.3 Electric field under A.C, DC and transient voltages

The electric field is strictly related to the permittivities and resistivities of the specific insulation involved [5.6]. In particular the field distribution under transient voltage (including permanent AC voltages) is governed by the permittivity ε while the field distribution under DC voltage is governed by the insulation resistivity ρ. A correct evaluation of the electric field can be made only if the resistivity and permittivity values of all the materials involved are well understood. Typical data about permittivities and resistivities of the different materials taken from different sources is reported in Table 5-1. The data are indicative, since for many insulations and insulation systems the actual values depend on many factors, such as the actual composition of the material and the fillers.

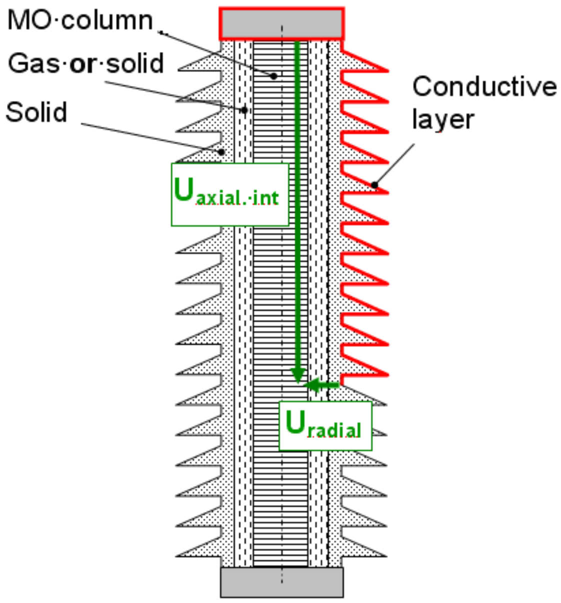


Figure 5-3: Radial field stress of a surge arrester under polluted conditions

Table 5-1- Typical values of ε and ρ

Material	relative permittivity ε	resistivity ρ
	(p.u.)	(Ω*m)
Air	**1**	**very high***
SF6	**1**	**very high***
Oil	**2,2- 2,7**	**10^{10}-10^{14}**
oil impregnated paper	**3,5**	**10^{12}-10^{15}**
porcelain	**5-6,5**	**10^{10}-10^{12}**
Fiberglass tube	**4-5**	**10^{12}-10^{14}**
Silicone	**2,8-4**	**10^{12}-10^{14}**

Permittivities are, in the range of application considered, practically only a property of the material. Thus, once the material is determined, the electric field can be determined. The permittivity values range for most of the insulation from 1 to 5. The values for porcelain, fibreglass and silicone are rather close, such that the field distribution of porcelain housing and composite housing having the same design would be rather close under transient voltage conditions. Even the insulating material inside the housing (e.g. oil, SF_6, foam) has a limited influence, as shown in **Figure 5-4** which reports the electric field gradients on the first sheds of a housing for the three cases of ε=1 (representing air or SF_6 as a fluid), ε=3 (representing a fluid insulation as a filler) and ε=800 (representing the extreme case of the "inner filler" made by zinc oxide blocks). The variation of the electric field passing from ε=1 to ε=3 is rather limited (two upper curves). A significant beneficial influence is present only for the case of the arrester simulation (lowest curve): εr = 800.

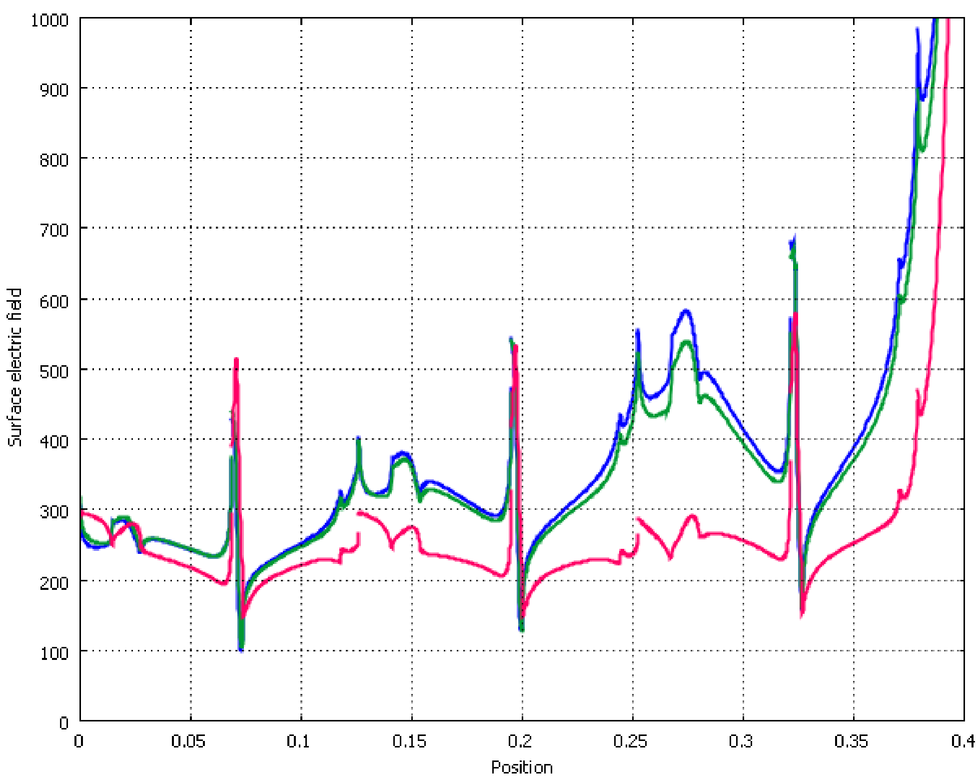
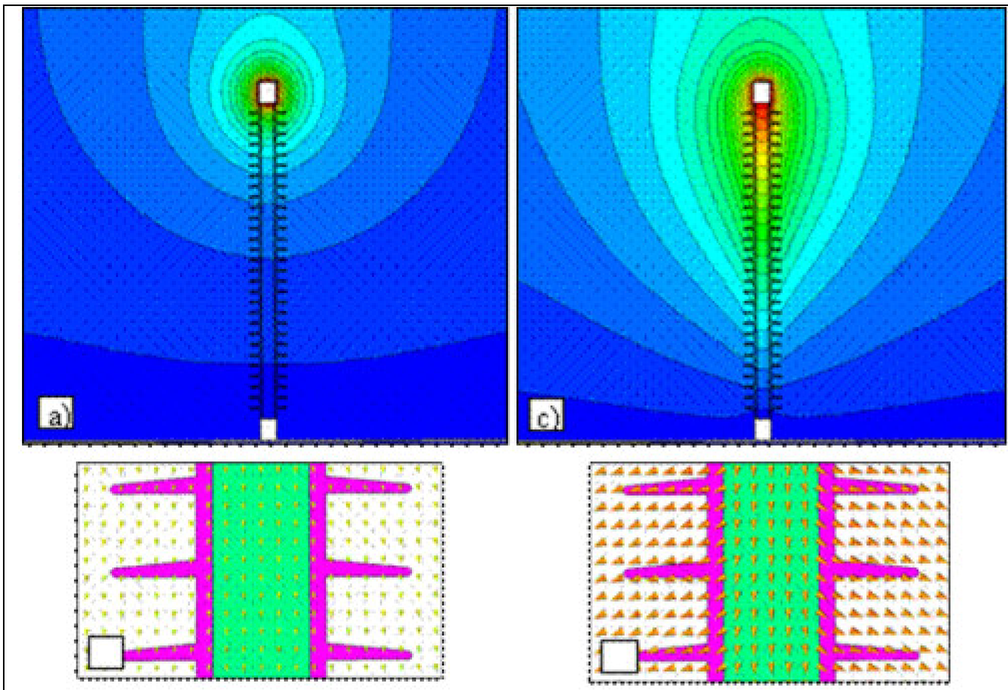


Figure 5-4: Electric field on the first sheds of a composite housing under ac voltage as a function of the permittivity of the inner insulating material
blue:εi=1, green:εi=3, red:εi=800

Metal-oxide columns represent a particular case since the zinc oxide blocks are characterised by a relative equivalent permittivity εr ≈ 800 (ranging from of 200 to 1000). **Figure 5-5** shows in comparison the potential and the field distribution of a post insulator, where εr = 4, and a surge arrester, modelled as the same insulator, but with εr = 800.



a)	*b)*

Figure 5-5: Results of a numerical electric field simulation on an insulator configuration of 1700 mm height and 60 mm core diameter at different assumed permittivities of the core:
a) ε_r = 4 potential distribution and field distribution at 800 mm height
b) ε_r = 800 potential distribution and field distribution at 800 mm height

From these Figures the influence of such high permittivity on the electric field stress may be clearly seen.

The resistivity values of the various materials have a much larger spread. In principle the resistivity of air and SF_6 at the design gradients (which are much lower than the flashover ones), is infinite. In practice their resisitivity is governed by stray parameters, such as the presence of ions, humidity etc. The resistivity of liquid and solid materials is significantly influenced by the electric field, temperature and humidity, leading to variations of orders of magnitude. Thus the dependence of the resistivity on electric field and environmental parameters should be taken into account when evaluating the electric field under DC

For DC application it should be taken into account that the DC state is reached through a transient state as shown by the example in Figure 5-6 [5.8]. Electrical charges are moved by the stationary electric field and recombine again after switching off the DC voltage, according to the time constant ρ ε. With paper-oil insulation the discharging time lies in the range of hours, whilst for composite insulators and gases periods measured in days can be considered.

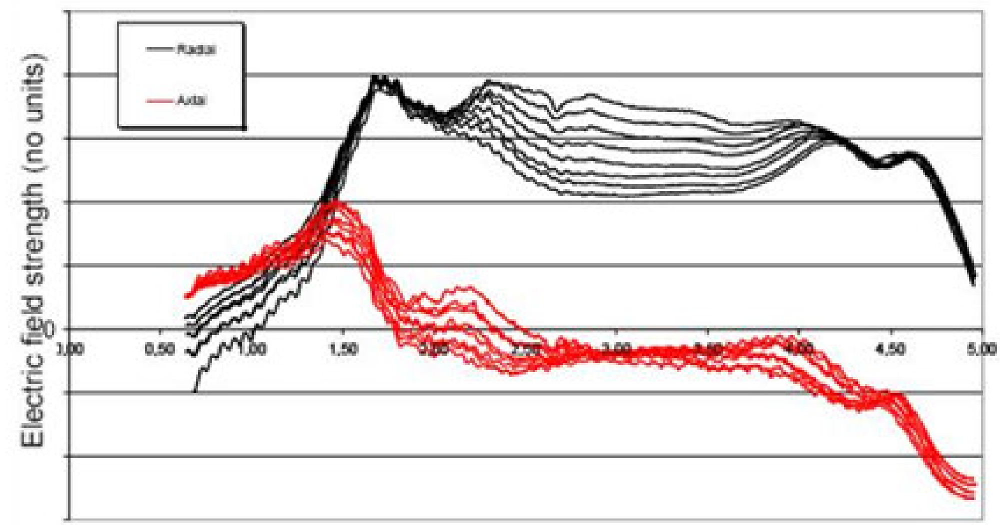
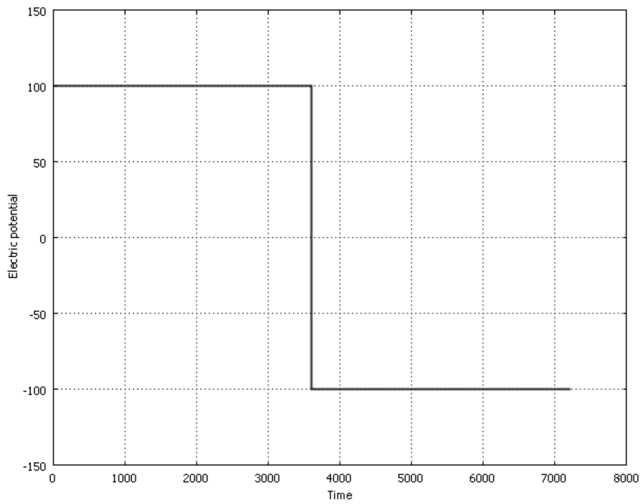


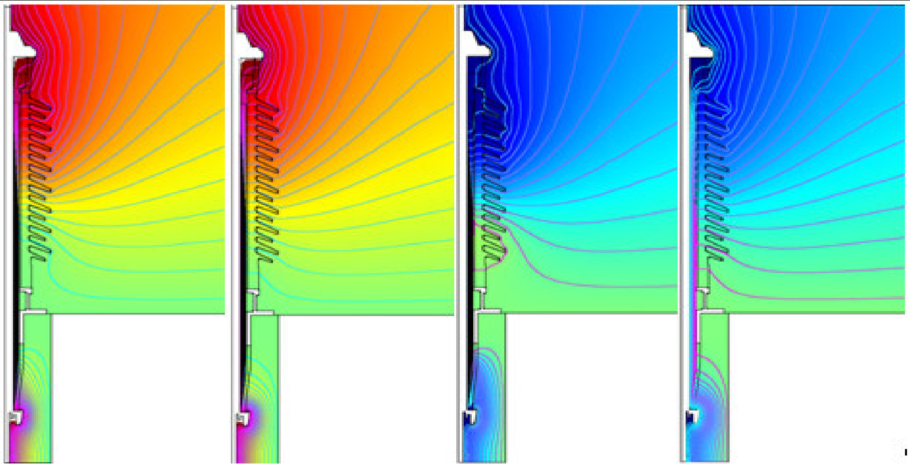
Figure 5-6: Axial and radial electric field along 500 kV bushing energized at 500 kV and then grounded. The different curves refer to different times after grounding (time sweep 1 minute). Electric field in arbitrary units. X axis: position along the bushing

Whenever a transient occurs, e.g. during a polarity reversal, both ε and ρ play a role. While in principle permittivities and resistivities should always be considered, the distribution is dominated by the permittivities during transients and resistivities in the static condition, leading to remarkably different voltage (and electric field) distribution. The full evolution of the electric field during transient conditions should be taken into account in design in order to identify the critical conditions for the different insulation involved. An example is shown in **Error! Reference source not found.** where the consequence of a transient on the potential distribution on a bushing is illustrated. The voltage is firstly raised to 100%, then maintained continuous for 3500 s, then decreased suddenly to -100% and then maintained for 7000 s.

Trapped charges following non linear phenomena (e.g. deriving from corona) can further complicate this situation.

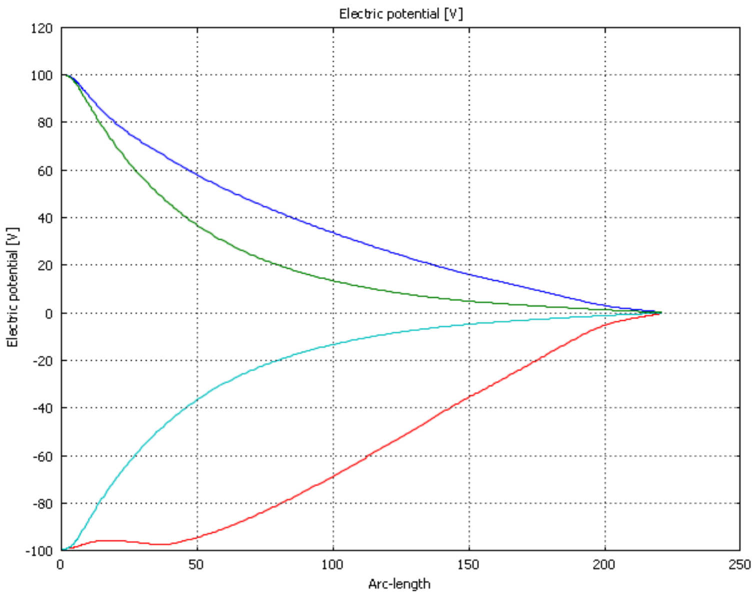


a) *applied transient*

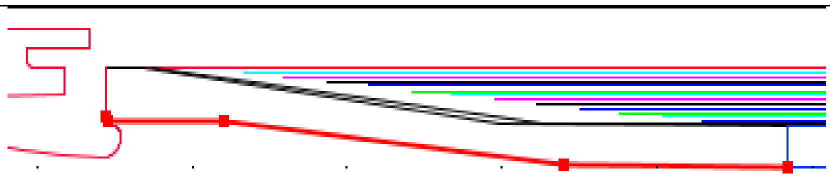


t=100 s *t=3500 s* *t=3600 s* *t=7000 s*

“Capacitive” distribution; “Resistive” distribution; ”mixed” distribution;“resistive” distribution



b) voltage distribution along the axis of the bushing



c) voltage distribution along the surface of the bushing immersed in oil : from the uppest to the lowest: 100s; 3500 s, 7000 s, 3600 s

Figure 5-7: Example of the variation of the voltage distribution for a bushing following a polarity reversal.

5.4 Examples of calculation and design optimisation for electric field control

5.4.1 Influence of inner electrodes on the electric fields (AC case)

An insulating tube is subjected to differing stresses according to whether it is used as a housing for an interrupter chamber, a supporting column, a bushing or a surge arrester housing. The differences in these configurations come from the field distribution induced by the location of metallic parts. As an example Figure 5-7 illustrates the electric field along the external diameter of a circuit-breaker chamber housing: the field distortion in the middle of the chamber where the active parts are located can be clearly seen.

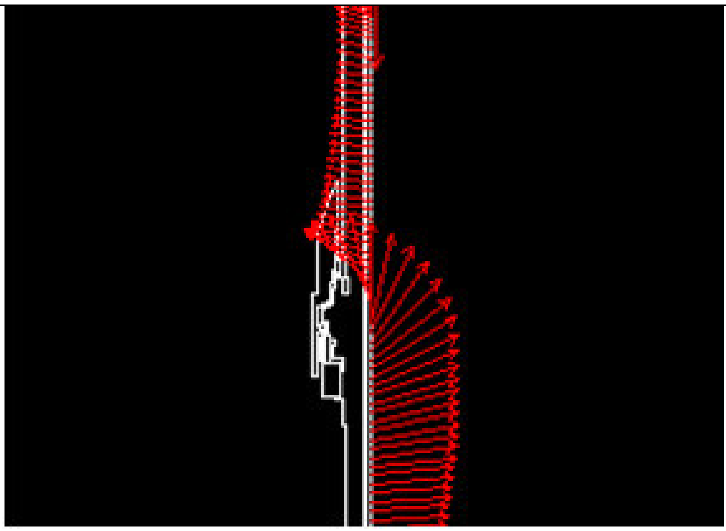
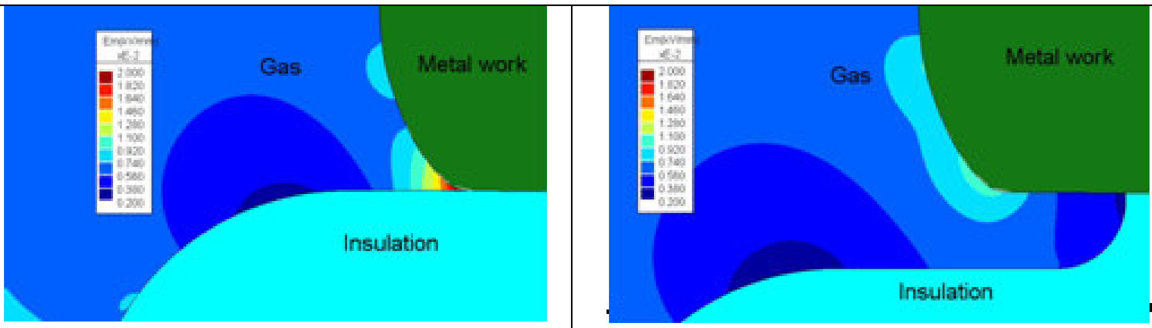


Figure 5-7: Circuit-breaker chamber: field distortion by internal parts

The containment of the field within the allowable values can be made by different approaches, e.g. acting on the housing diameter.

5.4.2 Electric field at triple points (AC case)

A real case of a 420 kV gas filled bushing is shown in **Figure 5-8**. The electric field at triple points may be critical both for the internal and for the external insulation. In the example case, the internal triple point at the glass/silicone and metal interface was the trigger of an external flashover. Externally this was not the point where the highest stress was determined by computation. A design change of the triple point area solved the problem

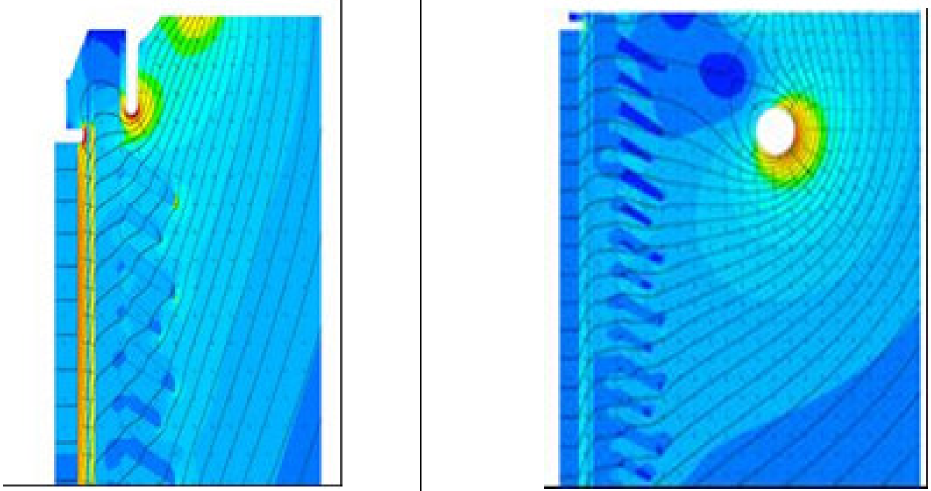


a)	b)

Figure 5-8: Triple point with a wrong design (a) and with a modified safe design (b)

5.4.3 Electric field control by shielding electrodes (AC case)

The case of a surge arrester with rated voltage of 140 kV is considered, mounted on a portal H=2m [5.10].



a)	b)

Figure 5-9: Influence of shielding electrodes .
a) without grading ring
b) with grading ring

The influence of the gap between resistor blocks and tube is illustrated in Figure 5-9 [5.10]. Interface gaps in the range 3mm to 10 mm did not result in satisfactory performance without the addition of a shielding ring. The use of a ring electrode reduces the maximum gradient in the interface allowing a reduction of the interface gap to 3 mm.

Depending on the arrester design the surface gradients can be very high such that corona occurs on the sheds in the presence of water drops. Again the adoption of a grading ring provides beneficial results for the surface gradients and thus for the performance in presence of water droplets, as shown in Figure 5-10 [5.9]

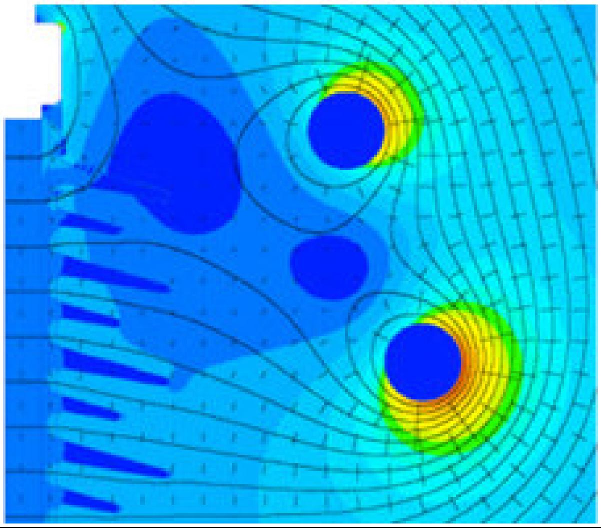


Figure 5-10: Influence of shielding electrodes on the electric field on the insulator surface.

This examples demonstrates that, once the target design electric field values are fixed, the designer can limit the gradient within the fixed values for any application, e.g. by the adoption of shielding electrodes.

5.4.4 Field control by active parts

The presence of inner parts can also improve the electric field along the housing.

The case of a 525 kV housing made of two 245 kV units mounted one on top of the other is considered as an example.

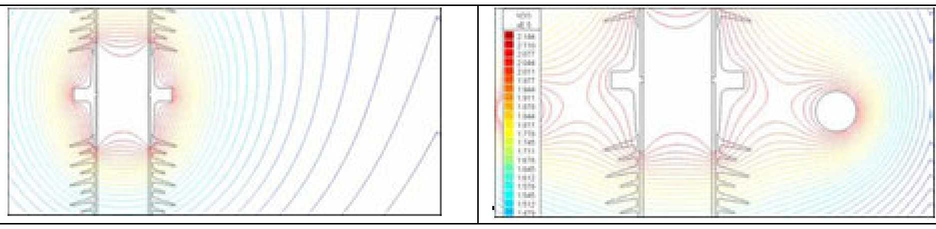


Figure 5-11: 525 kV housing without inner electrode

A shield electrode is necessary to control the electric field in the intermediate flange if the empty housing is considered (**Figure 5-11**) while no shielding electrode would be necessary in the case of a capacitive voltage transformer, due to field control provided by the inner part (**Figure 5-12**).

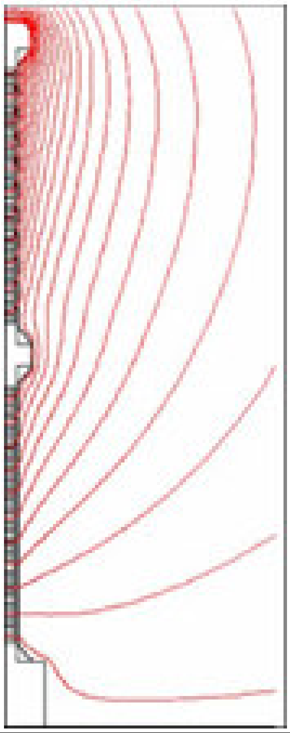


Figure 5-12: 525 kV capacitive voltage transformer with the same housing of Figure 5-11

An interesting solution for field control could be to use "combined apparatus" to control the field. In the example in **Figure 5-13** reference is made to a combined capacitive voltage transformer (CVT) and surge arrester. The voltage distribution is additionally controlled by the capacitive voltage transformer due high self capacitance of single element leading to a satisfactory field distribution even in the absence of shielding electrodes.

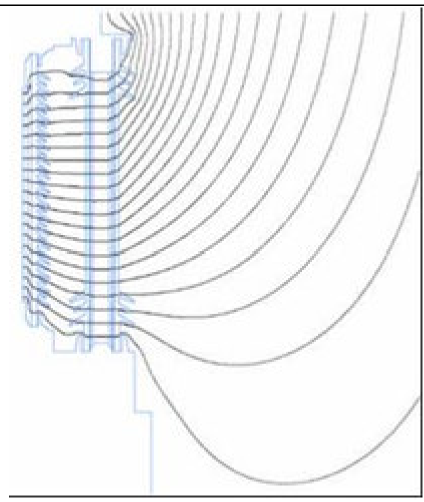


Figure 5-13: Electric field distribution for a combined CVT- arrester solution

5.4.5 Field control by non linear coating

An interesting approach is that of the partial coating of composite housing by non linear materials such as ZnO [5.10]. The use of non linear coating is suggested in [5.10] to control the field distribution such that a more compact gas insulated bushing would be possible without the need of inner electrodes to control the electric field.

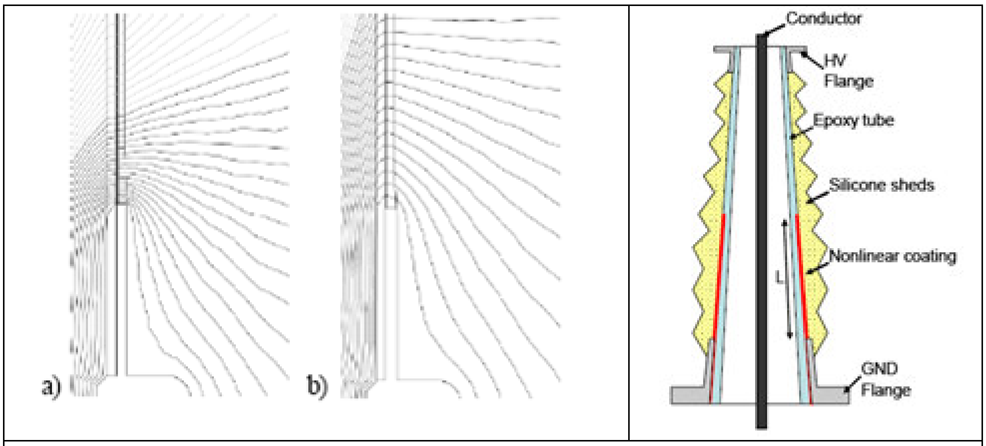


Figure 5-14: Electric field control in a gas insulated bushing by non linear coating
a) electric field without coating; b) electric field with coating

5.5 Conclusions

- The containment of the electric field within design targets is essential to assure a reliable performance of composite housing.
- Inner electrodes may change significantly the electric field meaning that compliance of the electric field with the required design values should be verified by accurate simulation of both the insulator and any inner active parts.
- The electric field under AC conditions is dominated by permittivities whilst in DC it is dominated by resistivities. However the DC condition is reached through a transient meaning that permittivities still play a role in determining the field stresses. The electric field distribution may differ remarkably under the different stresses.
- For the evaluation of the electric field the permittivities and resistivities of the materials must be accurately determined in addition to the accurate representation of the test object. The evaluation of the electric field for DC apparatus is particularly complex due to the dependence of resistivities on the electric field and environmental parameters.
- Once good models and criteria are available, the role of the designer is to evaluate the electric field in order to identify the solution(s) which adequately control the filed gradient within the target values e.g. by adopting suitable shielding electrodes.

5.6 References

[5.1] CIGRE Working Group B2.03 “Use of corona rings to control the electrical field along transmission line composite insulators” Cigre Brochure 284

[5.2] R. Mailfert, M. Thories, D. Riviere, L. Pergamin “ Effect of the superposition of electric mechanical and environmental stresses on the fatigue behaviour of composite insulating materials” CIGRE 1978 paper 15-10

[5.3] A.J. Phillips, D.J. Childs, H.M. Schneider, “Ageing of non-ceramic insulators due to corona from water drops” IEEE – PES – 236 PWRD 011-1997

[5.4] CIGRE TF 33.04.07 “Natural and artificial ageing and pollution testing of polymeric insulators” CIGRE Technical Brochure 143

[5.5] Cigre WG D1-14 “Material properties for non ceramic indoor insulation” Cigre Technical Brochure 255

[5.6] CIGRE WG 12.02 “Voltage tests on transformers and smoothing reactors for HVDC transmission” Electra N 46

[5.7] A.G. Sellars, S. J. Macgregor “The design of dielectric barriers for HVDC bushings” 1998 Printed and published by IEE

[5.8] B.O. Stenestam, R. Hartings "Challenges and tests performed in the development of UHV AC and 800 kV UHV DC bushings"

[5.9] M. Sehovac, P. Bertolotto "Application of Zinc oxide Arresters in the HV Network" INMR World Congress- Rio de Janeiro 2007

[5.10] L. Donzel, M. Hagemeister "Non linear field control of HV bushings" ISH 2007 Lubjiana

[5.11] T. Braunsberger, M. kurrat "Cyclic water drop corona on silicone rubber samples" – 15th ISH, Ljubljana, 2007

[5.12] V.M.Moreno, R.S. Gorur "Effect of long term corona on non-ceramic outdoor insulator housing materials" – IEEE Trans. On DEIS – 2001

[5.13] B.Boettcher, G. Malin, R. Strobl, "Stress control system for composite insulators based on ZnO-Technology", Transmission and Distribution Conference and Exposition, IEEE/PES, Vol. 2, Atlanta, 2001

[5.14] Strobl, R.; Haverkamp, W.; Malin, G.; Fitzgerald, F., "Medium voltage terminations using an advanced stress control technology", Transmission and Distribution Conference and Exposition, IEEE/PES, Vol. 2, Atlanta, 2001

6 INFLUENCE OF EQUIPMENT INTERNAL ACTIVE PARTS ON THE SHORT AND LONG TERM ELECTRICAL PERFORMANCE IN VARIOUS ENVIRONMENTS

6.1 Introduction

One of the aspects of major interest in the application of polymeric insulator housings is their electrical insulation performance which may be affected by the presence of internal active parts. This chapter considers this aspect in two sections. The first section considers and analyses the electrical performance of polymeric housing under short-term tests and includes both reference condition (i.e. comparison of polymeric housing with porcelain housing without internal active parts) and the influence of active parts.

The second section analyses the same performance under long term conditions, again covering both reference condition without internal active parts and the influence of active parts.

6.2 Electrical performances under short term tests

6.2.1 Performance under contaminated conditions: comparison polymer/porcelain housings

To date standardised pollution tests for polymeric insulators are not available. However, utilities and manufacturers need to evaluate the performance of insulators under polluted conditions since this is an important input for the dimensioning if no service experience is available. To be able to have such input, two different approaches have been followed by international research. Firstly the methods standardised for ceramic insulators were applied and eventually adapted to take into account the specific features of polymeric insulators (high hydrophobicity). Two standard tests for ceramic insulators are the salt fog test and solid layer test. Secondly, new pollution test methods were developed, trying to better simulate actual service conditions.

A summary of these methods is given [6.1]. The first approach is considered by Cigre to be more applicable for future standardisation and a standard pollution test is under consideration by Cigre WG C4.03.03. Some of the results based on standard and non-standard test methods applied for polymeric insulators are presented and analysed below.

6.2.1.1 Standard Salt Fog test for polymeric insulators

During the standard salt fog test, the insulator is thoroughly wetted by the projected salt fog. On hydrophilic (porcelain) insulators, the wetting will spread out to form a continuous conductive layer and the heating effect of the leakage current evaporates the water to leave a salt layer behind. However, this does not happen on hydrophobic (silicone rubber) insulators, where the salt water that lands on its surface will bead and run-off without leaving a pollution deposit, see examples in **Figure 6-1**

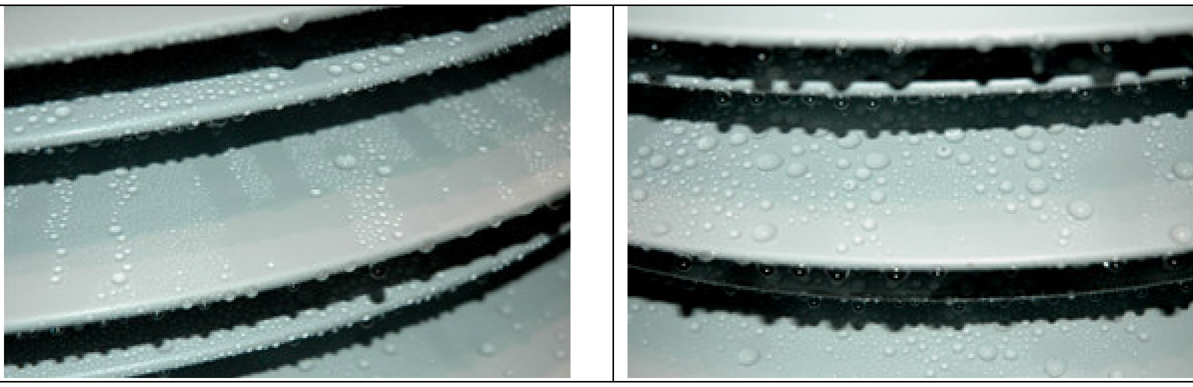


Figure 6-1: Examples of wetting patterns after salt fog tests at 160 kg/m3 on silicone rubber housing. The pictures show the surface before the test (left) and after three subsequent tests (right). The surface of the silicone rubber insulator is still highly hydrophobic

The investigations performed on 800 kV silicone rubber bushing indicated that the application of salt fog tests on new insulators without any pre-conditioning to temporarily reduce hydrophobicity leads to very high and unrealistic performance [6.2]. Other similar results were obtained in Sweden for a number of silicone rubber apparatus insulators in the range 420-550 kV including bushings and circuit-breakers. These were tested at salinities in the range of 40-160 kg/m^3 and withstood the tests without a single flashover and with very low leakage currents. This test is thus not applicable for comparison of porcelain insulators and polymeric insulators made of materials which exhibit hydrophobicity and the capability to transfer hydrophobicity to the layer of pollution (HTM materials according to [6.3]).

6.2.1.2 Salt fog test with the rapid procedure

More representative results in comparison with porcelain insulators may be obtained with the so called rapid procedure [6.1], [6.4], [6.5] due to insulator conditioning. A typical sequence of the test procedure is shown in **Figure 6-2**, where the flashover voltage is reported as a function of the number of voltage application. The flashover voltage (FOV) may be calculated as the mean FOV after stable FOV values have been reached. It was found that following the application of this procedure, the wetability class (WC) [6.6] which was close to 1 before the tests was, on average, reduced to values of about 4-5 at the end of the tests. This hydrophobicity level corresponds to what was observed after several years in service [6.7], [6.30]. Examples of tests carried out with a salinity ranging between 10 and 80 kg/m^3 are reported below.

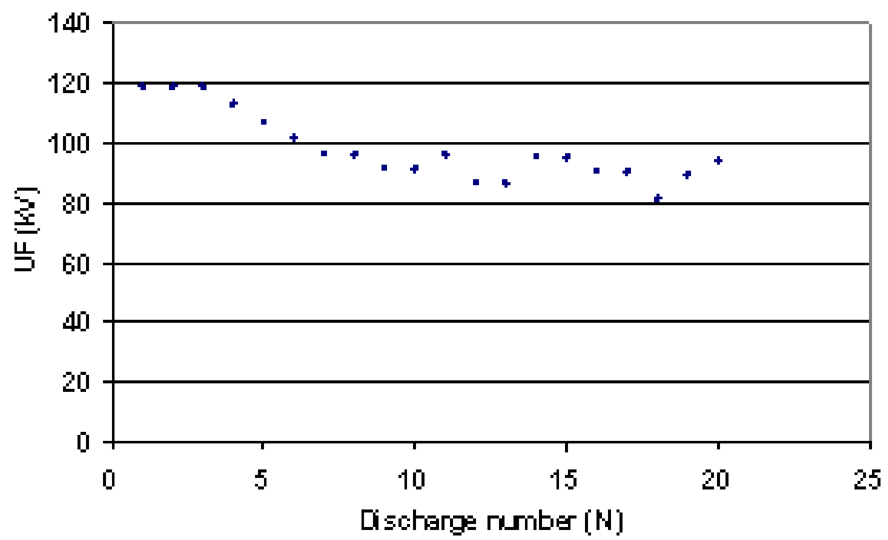


Figure 6-2: Typical sequence of a salt fog pollution test according to the rapid procedure

The characteristics of the insulators tested (all with helical profile) are shown in Table 6-1 [6.4]. Test objects from A to E were empty housings while objects E' and E" included inner electrodes of two different lengths. In Table 6-1, reference is made to the diameter of the larger shed.

Table 6-1: Characteristics of the insulators tested

test obj.	Length	Arching dist.	Diam.	Creep. factor	profile	shed spac.	shed overh.	inner electrode length
	(mm)	(mm)	(mm)	p.u.		(mm)	(mm)	(mm)
A	1290	1200	250	3,02	standard	35	50	
B	1290	1200	250	3,87	alternate	60	70	
C	1100	1000	332	2,90	standard	35	45	
D	1150	1000	490	3,30	alternate	60	60	
E	1200	1000	537	2,90	standard	35	45	
E'	1200	1000	537	2,90	standard	35	45	400
E"	1200	1000	537	2,90	standard	35	45	600

The flashover performance of composite housings of diameter 250-350 mm only are shown in Fig. 6-3 and compared with earlier results for porcelain housings of similar diameter. For better visualisation of the results the flashover specific creepage distance for both composite and hollow insulators is normalised as follows [6.4]:

- The flashover specific creepage distance is normalised using the expression for cap-and-pin insulators given by the following equation: lF (cap and pin)=16,5 $S^{0,22}$ (mm/kV, kg/m^3) [6.4]
- The ratio between the flashover specific creepage distance of composite and porcelain housings is presented versus creepage factor (ratio between creepage distance and arcing distance)

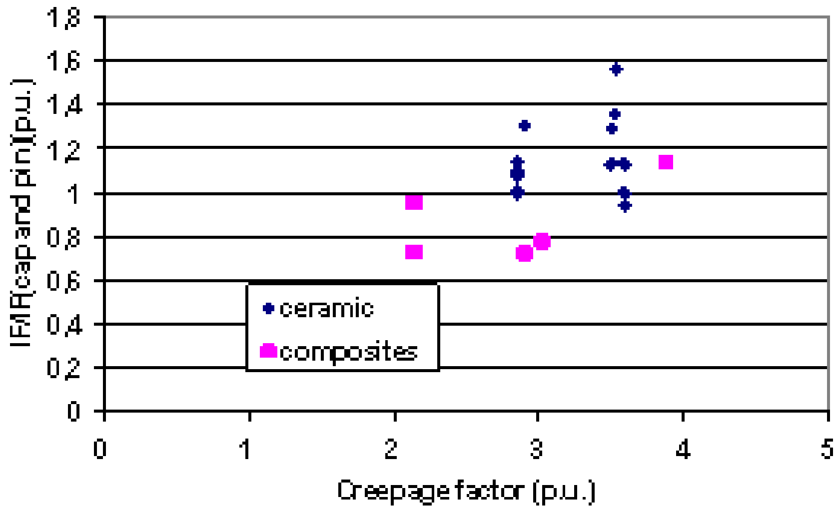


Figure 6-3: Ratio specific creepage distance to that of cap and pin insulators versus creepage factor

The results presented in **Figure 6-3** indicate generally better performance of composite insulators in comparison to porcelain, even after partial reduction of hydrophobicity by consecutive flashovers, which are the result of the rapid test procedure.

The influence of diameter on pollution flashover performance is shown in **Figure 6-4** for insulators with creepage factors of about 3.

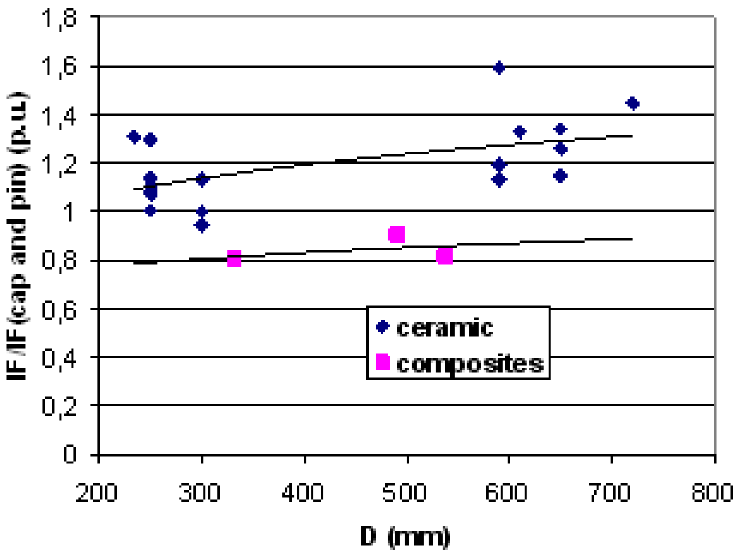


Figure 6-4: Influence of the insulator diameter (diameter of the larger shed) on the specific creepage distance

The results presented in **Figure 6-4** confirm the superior pollution performance of polymeric insulators in comparison to porcelain and also indicate a lower dependence of the pollution performance of polymeric insulators on insulator diameter (even with partially reduced hydrophobicity).

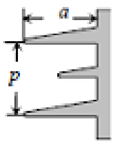
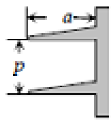
The above findings are confirmed by similar results on line composite insulators [6.8], [6.9].

6.2.1.3 Modified Solid Layer test

In [6.10], [6.11] it is stated that, for a standard solid layer test, is impossible to obtain a uniform and stable pollution layer on silicone rubber insulators using standard requirements of IEC 60507. The result is usually an unacceptably large spread in flashover results and thus, some pre-conditioning procedure should be performed.

An example of comparative results for polymer/porcelain housings with the modified solid layer procedures are given below [6.12] to [6.15]. Tests were conducted using the insulators of Table 6-2. The specimens were pre-conditioned and then contaminated by sprinkling powdered kaolin over the wetted surface. The insulators were then washed and left to dry [6.12] leading to a further uniform contamination layer on hydrophobic polymer insulator surface. The tests were performed with two non-standard wetting procedures: heavy wetting fog (13-15 g/m^3) and rain with intensity 4 mm/min produced by IEC nozzles for salt fog test.

Table 6-2 Insulators tested

S. No.*	Shed Configuration	Core Diameter, d mm	Max. Shed Diameter, mm	Average Diameter, $\overline{D}$ mm	Leakage Distance, L mm	Effective Height, H mm	a/p	l/p***
TL1		26	106	54.5	1880	685	40(25)/60	2.9
Bg1		292	372	320	1880	685	40(25)/65	2.7
Bg2		383	463	410	1880	685		
LP1**		54	144	86	2031	640	45(30)/60	3.2
SP1		74	172	109.7	2055	630	49(32.5)/60	3.4
TL2		26	126	64	1480	600	50/50	2.8
SP2		73	173	111	1480	600		
SP3		98	182	131.5	1800	600	42/37.5	3
Bg3		290	406	315	2170	885	58/70	2.5

* TL: Transmission Line Insulator, Bg: Bushing Shell, LP: Line Post Insulator, SP: Station Post Insulator

** Shed upper-surface is flat for the specimen S.No.LP1, whereas it is slightly inclined for the other specimens.

*** l: Leakge distance per shed pitch "p"

The influence of the insulator average diameter on the specific creepage distance is shown in **Figure 6-5** for insulators with alternating sheds (Alt. sheds) and standard profile (Str.sheds). The influence of diameter seems rather low especially in case of the alternating shed profile.

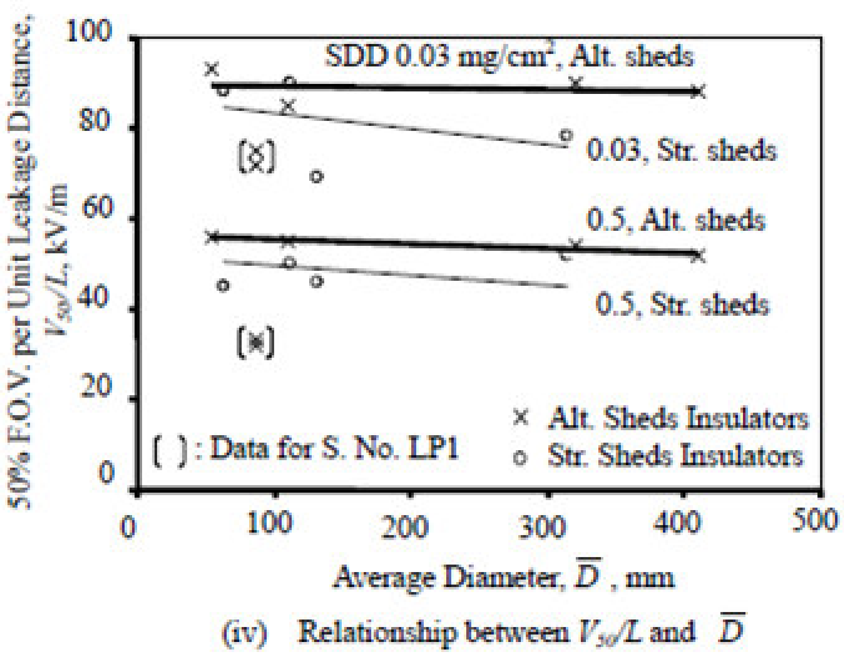


Figure 6-5: Modified solid layer tests with wetting by non-standard rain (adapted from [6.15]).Leakage distance per unit is presented as a function of average insulator diameter for two typical profiles, standard and alternating

Comparison of the pollution performance of polymeric and porcelain insulators under the modified solid layer tests with both non-standard rain wetting and heavy fog wetting is presented in **Figure 6-6**. The heavy fog tests results are also compared with the same tests earlier performed for porcelain insulators.

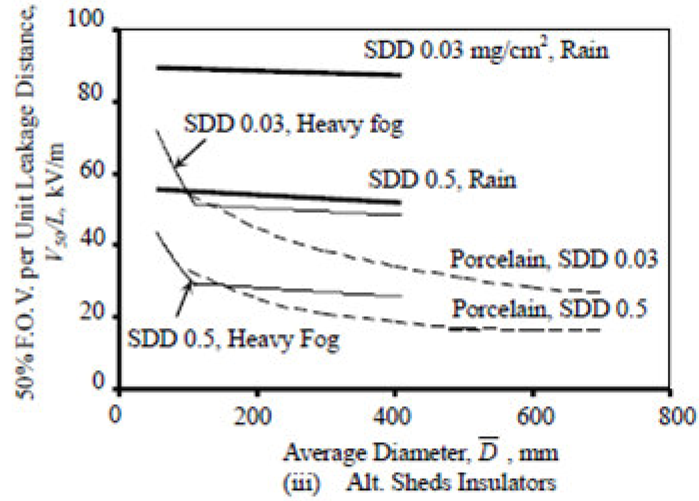


Figure 6-6: Modified Solid Layer tests with wetting by non-standard rain and heavy fog (adapted from [6.15]). Leakage distance per unit as a function of average insulator diameter for alternating profiles.

Again the influence of the average diameter is much less for polymeric insulators on the basis of a direct comparison under heavy fog for insulators with average diameter larger than 100 mm. Polymeric insulators have also superior performance in the same diameter range in comparison to porcelain.

6.2.1.4 Suggestions for the setting up of a standard pollution test procedure for polymeric insulators

The proposed method comprises three steps: (1) Pre-conditioning; (2) Application of the pollution layer; and (3) Flashover or withstand test.

Pre-conditioning is performed, as an example, by applying a dry inert material in powder form to the insulator surface e.g. by brush. In this case, with hydrophobicity level close to hydrophilic (WC 7), similar results as on porcelain are expected. However the hydrophobic properties recover very rapidly, as shown in **Figure 6-7** from [6.11], indicating significant difference in leakage currents after 6 days of recovery for polymeric apparatus insulator.

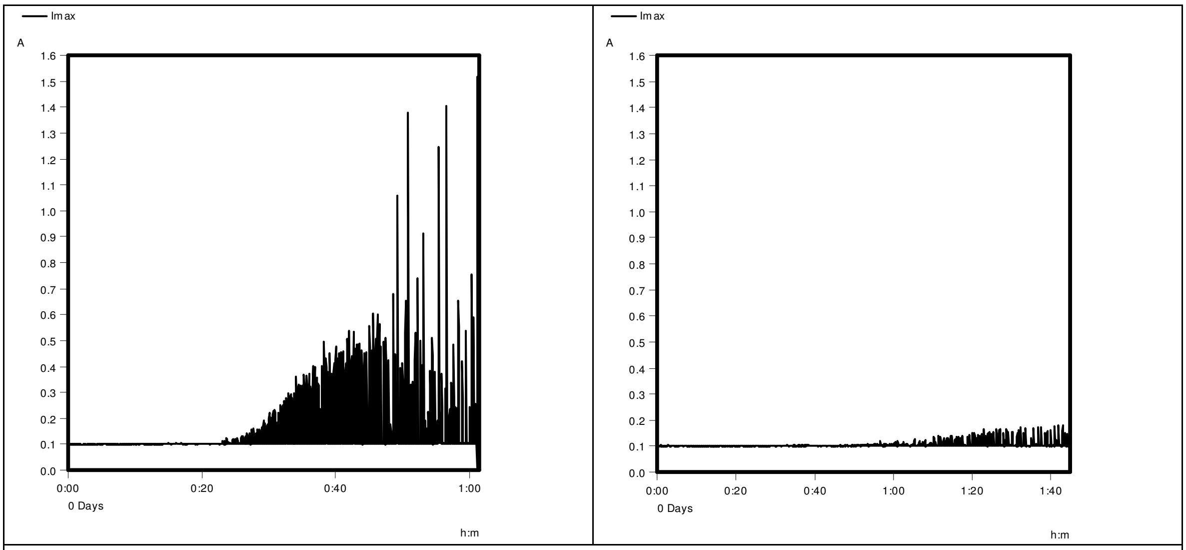


Figure 6-7: Leakage current during modified Solid Layer test on silicone rubber apparatus insulator. Left: without recovery; right: after 6 days of recovery.

In reality, as shown in Chapter 3, the hydrophobicity for silicone rubber insulators is generally maintained within the range WC 1 and WC 5 according to IEC 62073 (i.e. at the intermediate level in comparison with WC 7) even after significant service exposure. Thus it can be expected that the actual pollution performance of composite insulators will remain significantly higher than that for porcelain during the service life.

Methods to quantify the ability of an insulator to recover its hydrophobicity are under consideration in both CIGRE and IEC working groups. In CIGRE guidelines [6.19] it is suggested that the insulator can be tested under various intermediate states (from hydrophilic to hydrophobic) by increasing the recovery time between pollution applications and testing. This approach is echoed in IEC 60815-3 [6.20], which states, "For solid layer tests, the testing of HTM (Hydrophobicity Transfer Material) insulators may require investigation of the performance in both hydrophilic and hydrophobic states".

More recent experiments performed in Sweden on silicone rubber material samples [6.16] and full scale insulators [6.17] indicated that the approach with relatively short recovery time for about 2 days is feasible. The increase in resistance of polluted and wetted insulators after 2 days of recovery is about 3 times, see Figure 7 [6.16]. This would result in about 25% increase of flashover voltage, i.e. the rather short recovery period will effectively influence the pollution flashover performance. An important note is that the hydrophobicity measured in terms of wetability class of the polluted layer is still low. However, low molecular weight (LMW) components from the silicone rubber penetrate the pollution layer leading to the significant increase of the resistance.

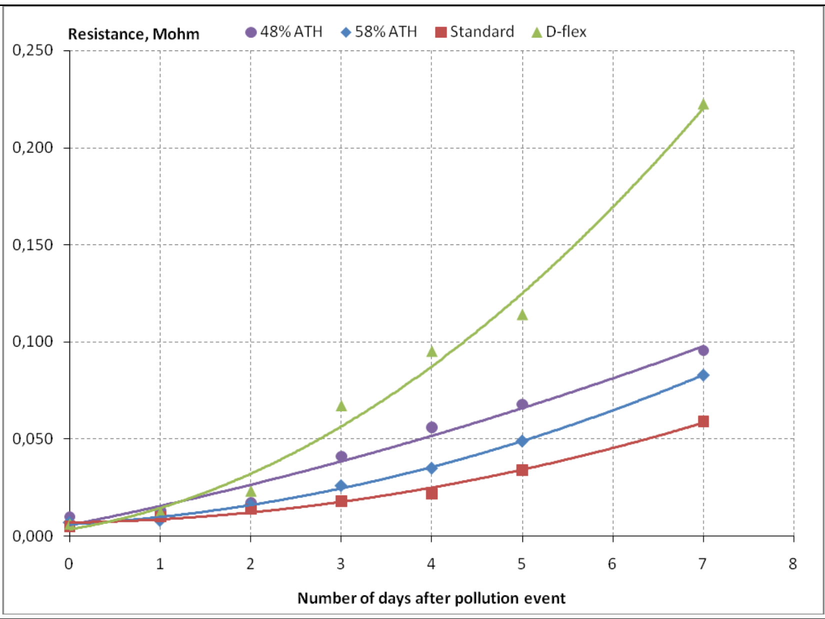


Figure 6-8: Resistance over elapsed time for silicone rubber samples polluted in standard slurry of 40 g/l of kaolin (adapted from [6.27]).

A recent pollution test with short recovery time (2 days) [6.17] was performed on line composite insulators using the Rapid Clean Fog procedure [6.5] to verify the above presented results. Two different silicone rubber insulators were selected since, based on general insulator knowledge, it could be expected that the different filler contents of the materials would result in different response with respect to recovery of hydrophobicity. The results, presented in Table 6-3 [6.18] confirmed that two days recovery is enough for a clear increase in flashover voltage.

Table 6-3: $U_{50\%}$ of line insulators tested with and without 2 days of recovery.

Insulator	SDD (mg/cm^2)	$U_{50\%}$ (kV)
Less filler	0,40 (no recovery)	350
	0,45 (2 days of recovery)	430
More filler	0,085 (no recovery)	256
	0,085 (2 days of recovery)	278

Due to the lack of standard methods, further work is ongoing at present in CIGRE WG C4.03.03 to propose and later on standardise such procedure via IEC. The most recent activities comprise a round robin test on pollution test method on composite insulators in twelve laboratories world-wide: China (3), Czech Republic, France, Italy, Japan (3), Sweden, UK, and USA.

6.2.1.5 Selection of polymeric insulation for polluted areas according to present IEC [6.20]

In CIGRE Guidelines [6.19] it is stated that *"The pollution flashover performance of some polymeric materials - especially silicone rubber - is generally superior to that of glass or porcelain."* However, pending the definitions of new methodologies and based on the uncertainties reported above, IEC adopted a design criterion for composite insulators [6.20] which is closely aligned with that for ceramic insulators. The advantages of composite insulators over ceramic (and glass) in terms of "better pollution performance" are recognized, concluding that a reduced creepage distance could and can be used for such insulators in many cases. However the document suggests that, taking into account the need to avoid any impact on the insulator lifetime, in many other cases it could be advisable to conservatively recommend the same creepage distance as for porcelain and glass insulators [6.20], [6.21], according to the curves in **Figure 6-9**. In addition the document [6.20] recommends increasing of the creepage distance beyond the standard values in the areas with extreme pollution.

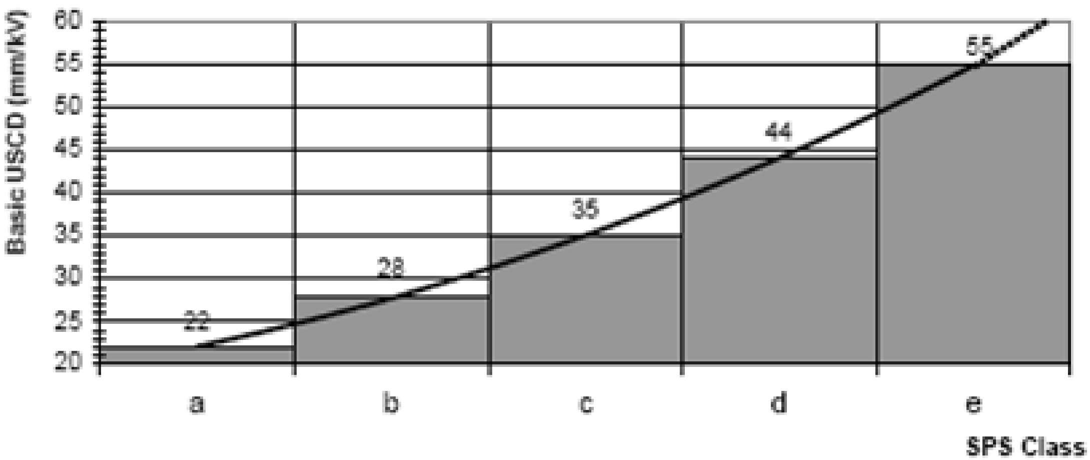


Figure 6-9: AC specific creepage distances specified in [6.11] (USCD referred to the phase to ground voltage)

The above curve refers to AC voltage and work is still going on within IEC to establish similar data for DC. Preliminary information from CIGRE WG C4.03.03 indicates that the required creepage distance for DC is about the same as for AC at low pollution levels but can be significantly higher at high pollution levels. However, as for AC, based on investigations on line insulators, DC composite insulators indicate a better pollution performance than porcelain insulators in new condition. Some reduction is performance has been noted after aging however a performance margin of some 20-30% over porcelain is maintained after ageing in laboratory or in the field for long time [6.22]-[6.24].

The curves in **Figure 6-9** are applicable to line insulators and to station insulators of rather small diameter. The extension of the results to housings (even without internal active part), requires, according to the Standards [6.20]-[6.21], to take into account the influence of the insulator diameter, see **Figure 6-10** from [6.20].

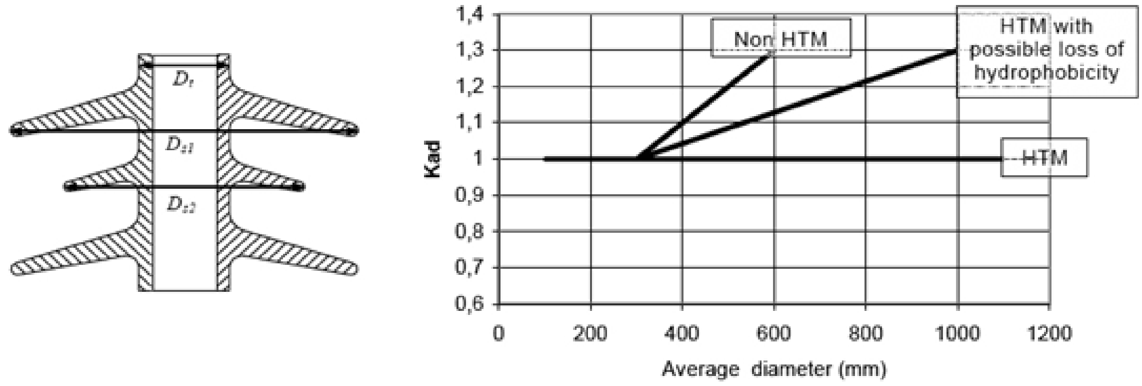


Figure 6-10:AC necessary increase of the creepage distance as a function of insulator diameter

According to the standard [6.20], the curve for the so-called "Non HTM" (non hydrophobicity transfer material) is exactly the same as for glass and porcelain, as shown in Fig. 6-10. The situation will be different in case of HTM material or material with temporarily lost hydrophobicity. The major difficulty for the designer is the choice the proper curve for insulators, which will preserve intermediate hydrophobicity values.

On the basis of design practice, service experience and tests results the design criteria for composites may need to be revised in future to take full advantage of their better pollution performance and the lower influence of the diameter on the pollution performance.

6.2.2 Performance under AC in dry and wet conditions: comparison polymer/porcelain housings

Comparative AC tests of polymer/porcelain under dry and wet conditions [6.4] were performed according to the procedure detailed in [6.26]. The test has been carried out by raising the voltage up to flashover with the flashover voltage being evaluated as the average of five consecutive voltage applications. The results obtained in dry condition are close to those for porcelain insulators (about 400 kV/m for the insulators considered) [6.27], [6.28]. The results in wet conditions in comparison to dry condition are shown in **Figure 6-11** as a function of the insulator diameter. The Figure indicates that the influence of wetting is much lower for polymer than for porcelain when new. The influence of the insulator diameter is also lower for polymer.

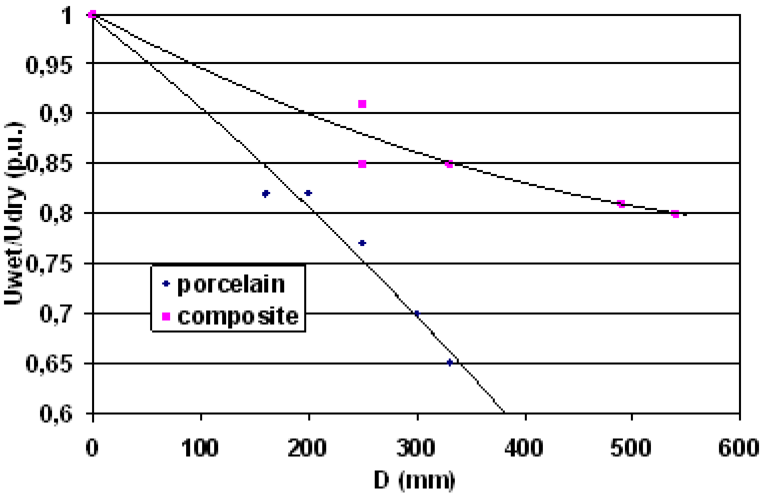


Figure 6-11: AC tests. Ratio of the flashover voltage under wet to that under dry condition versus the insulator external diameter. Comparison of polymer/porcelain.

The better performance of composite may be explained by difference in wetting due to hydrophobicity properties of polymer. Repetition of the tests may show a slight decrease in flashover voltage for polymer insulators but, according to [6.4] this is not more than 3%.

6.2.3 Performance under switching impulse (SI) in dry and wet conditions: comparison polymer/porcelain housings

Tests were performed with positive polarity and according to the up-and-down procedure with the application of 30 shots [6.4]. No reduction of the flashover voltage after repeated tests was observed probably because the energy of the discharges is much lower than in the case of AC tests.

The results obtained in dry condition are close to those for porcelain insulators [6.27]-[6.29]. The results in wet conditions in comparison to dry condition are shown in **Figure 6-12** as a function of the insulator diameter. **Figure 6-12** indicates that the influence of wetting is much lower for polymer than for porcelain when new. The influence of the insulator diameter is also lower for polymer.

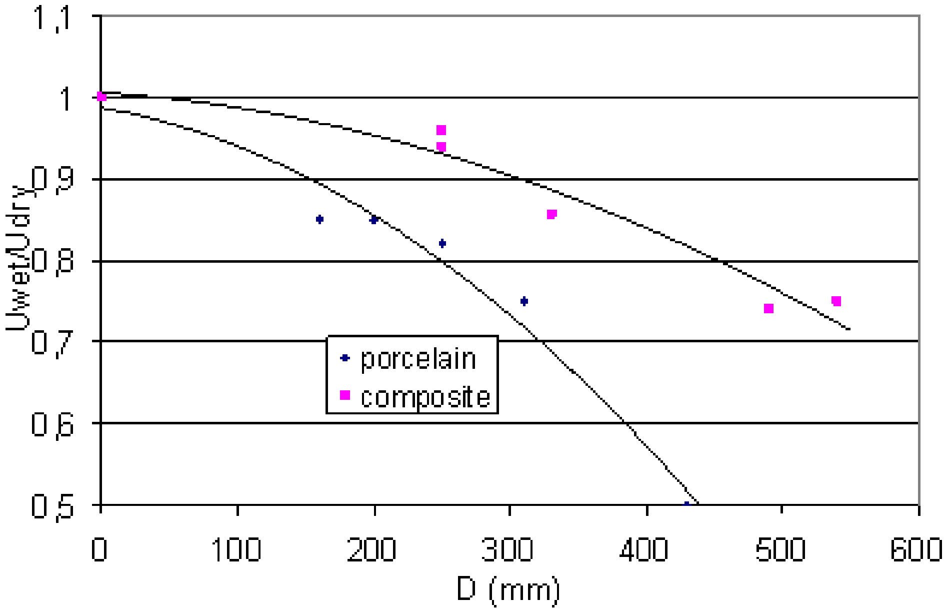


Figure 6-12: SI tests. Ratio of the flashover voltage under wet to that under dry condition versus the insulator external diameter. Comparison of composite and ceramic data.

6.2.4 *Insulators with internal active part*

6.2.4.1 Standard procedure of Salt Fog test

As stated in Section 6.2.1.1, investigations performed on various apparatus insulators, and more recently on an 800 kV silicone rubber bushing, have shown that the application of salt fog tests on new insulators without any preconditioning to temporarily reduce their hydrophobicity leads to very high and unrealistic performance [6.2]. Similar results were obtained in Sweden for a number of silicone rubber apparatus insulators in the range 420-550 kV including bushings and circuit-breakers.

6.2.4.2 Salt Fog test (Rapid procedure)

Test have been performed using the procedure described in Section 6.2.1.2 with a test object of insulator E of Table 6-1 and both with and without internal electrodes as shown in **Figure 6-13** [6.4]

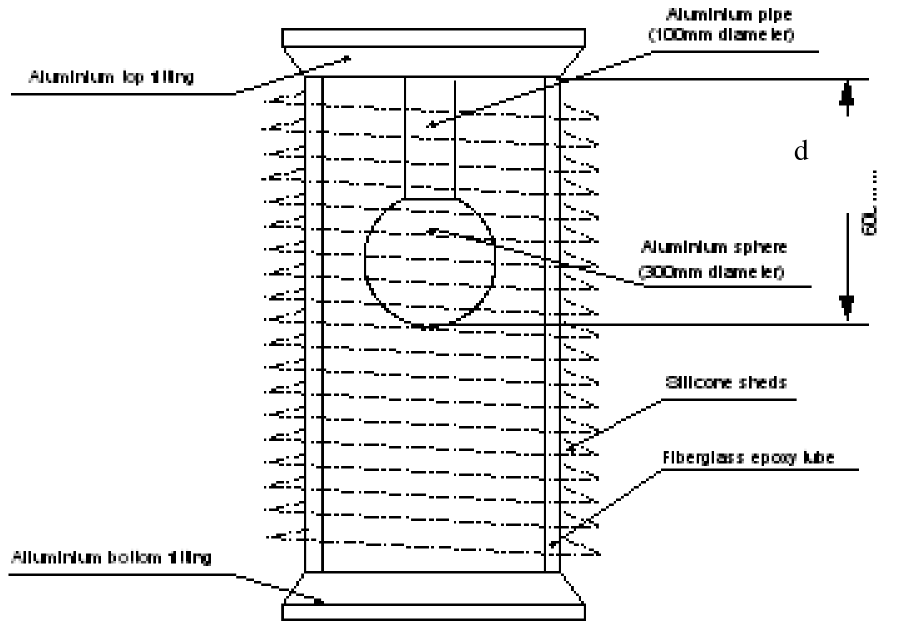


Figure 6-13: Test object with inner electrodes

The electric fields with and without the inner electrodes, evaluated for a clean insulator, are reported in **Figure 6-14**.

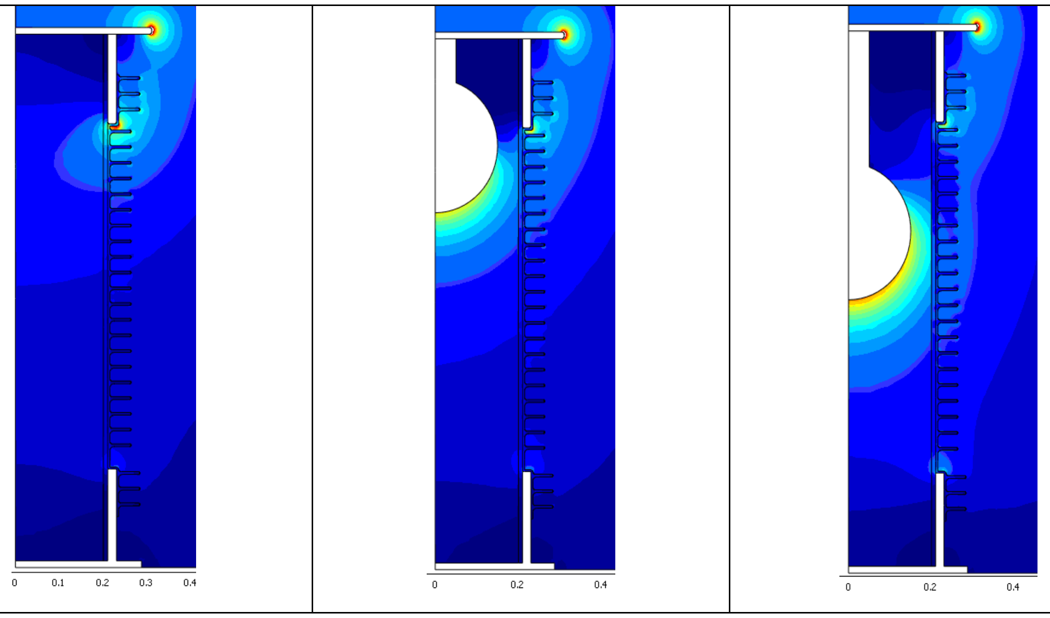


Figure 6-14: Electric field distribution for insulators E, E' and E" in Table 6- 1

The comparison of results obtained with the rapid salt fog method on the insulators of Table 6-1 is shown in **Figure 6-15** using the same normalization principle as in Section 6.2.1.2. The influence of the inner electrode appears limited and within the natural deviation of the test results (±5%).

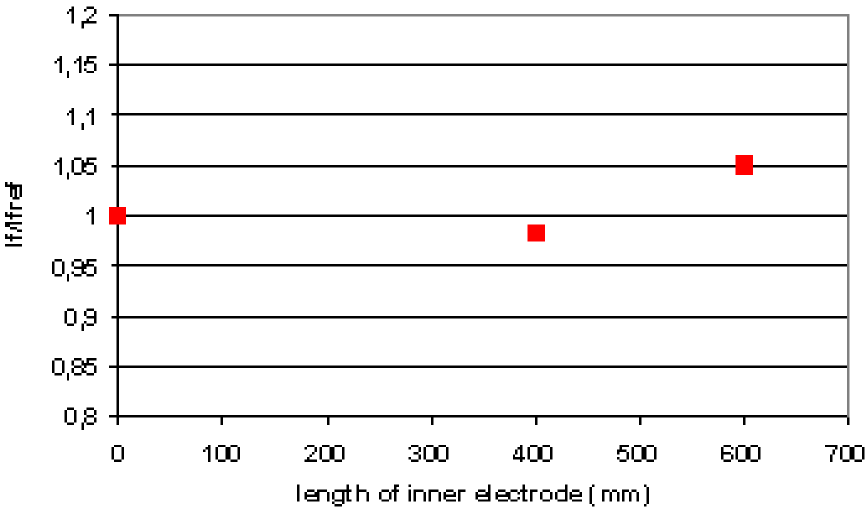


Figure 6-15: Influence of the length of the inner electrode on the specific creepage distance

6.2.4.3 Modified Solid Layer tests

Tests on a hollow insulator with and without inner electrodes were performed according to a modified solid layer procedure [6.12], i.e. with pre-conditioning and using heavy fog wetting (13 g/m^3). It is clear from Figure 6-16 that the presence of the internal electrodes has a significant influence upon the E-field distribution. Tests were made at SDD levels 0.03 mg/cm^2 and 0.5 mg/cm^2 [6.25].

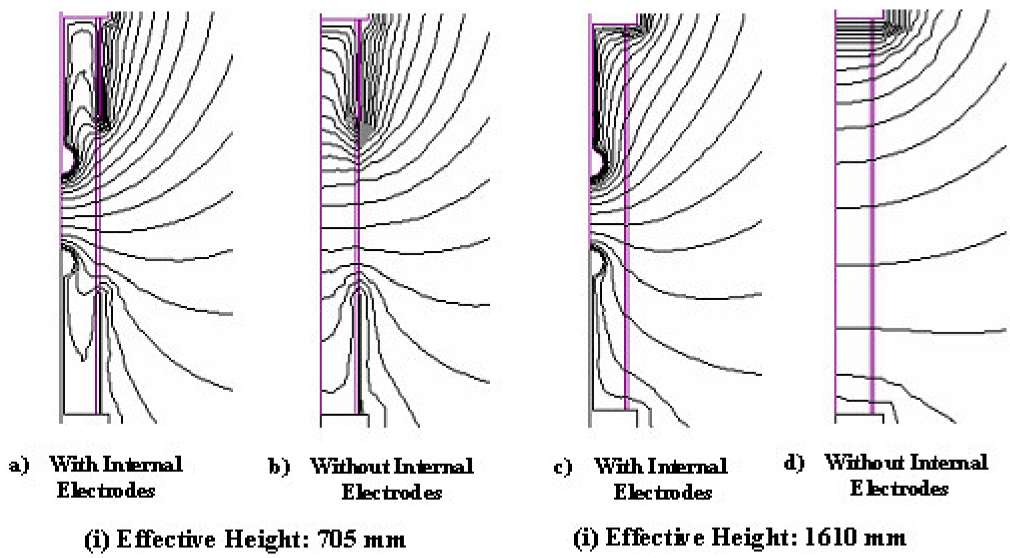


Figure 6-16: Calculated potential distribution with and without inner electrodes.

The presence of the internal electrodes had no significant effect upon the flashover voltages as shown in **Figure 6-17**. The only noted difference between the two cases is that the leakage current for the test objects with internal electrodes is approximately doubled in comparison to the insulators without electrodes. This is most probably attributable to the increased capacitance between the two electrodes.

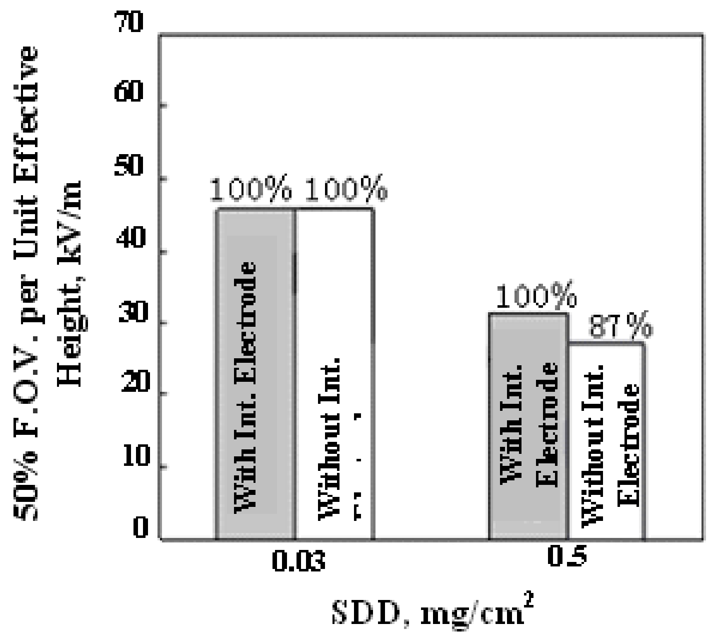


Figure 6-17: Flashover voltage with/without internal active parts.

6.2.4.4 AC dry and wet tests

The results obtained during AC dry and wet tests with/without inner electrodes (refer to Table 6-1 samples named E and E") are presented below in **Figure 6-18** for total electrode lengths of 400 mm and 600 mm [6.4]. $U_{reference}$ is the flashover voltage of the housing without inner electrodes.

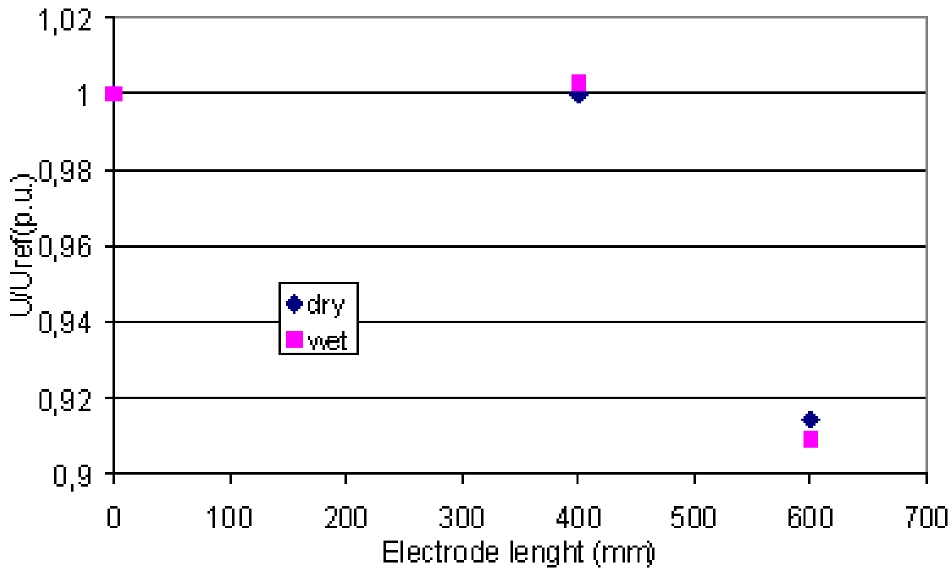


Figure 6-18: AC dry and wet tests. Ratio of the flashover voltage with inner electrode and without inner electrode (reference) as a function of the total electrode length

While the influence of the inner electrode appears to be negligible at 400 mm, the influence is appreciable both in dry and wet conditions with an electrode having a length of 600 mm.

6.2.4.5 SI dry and wet tests

The influence of the inner electrode on the strength during dry and wet SI tests both with and without inner electrodes (refer to Table 6-1 samples named E and E") are presented below in **Figure 6-19** for total electrode lengths of 400 mm and 600 mm [6.4]. U_{ref} is the flashover voltage of the housing without inner electrodes.

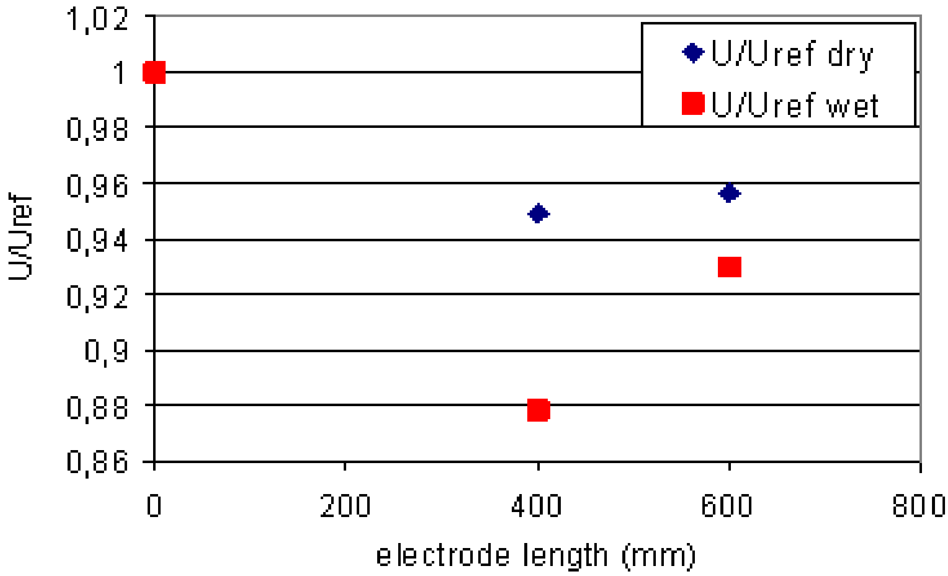


Figure 6-19: SI tests. Ratio of the flashover voltage with inner electrode and without inner electrode (reference) as a function of the total electrode length

Again, a significant influence of the inner electrode can be clearly seen.

6.2.4.6 Performance during AC tests incorporating ice and snow

Performance under conditions of ice or snow accretion, especially partially conducting layers which are typical for countries such as Japan and Norway, can be considered as similar to pollution performance and this type of environment should be taken into account for the dimensioning where such condition exist. The results of tests on complete circuit-breakers having both porcelain and silicone rubber housings are presented in [6.30]. **Figure 6-20** (adapted from [6.30]) presents an example of ice flashover stress per insulation height as a function of dripping water conductivity (water, collected under the insulator in special jars). The figure shows that there is no difference in ice flashover stress for either silicone rubber or porcelain insulators when they are completely covered with ice (bridging close to 100%). For partial accretion e.g. during short ice storms, silicone rubber may be slightly better due to the lower leakage currents in comparison to porcelain as reported in [6.30]. Where ice may be a dimensioning parameter for vertically installed insulators, snow may also be a dimensioning parameter for horizontally installed insulators. The flashover stress during heavy storms (e.g. about 90 cm snow depth as experienced in Norway) is similar to the flashover stress during ice accretion, i.e. about 100-110 kV/m [6.31]. Calculations performed in commercially available program for pollution, ice and snow conditions correlate well with service experience [6.31].

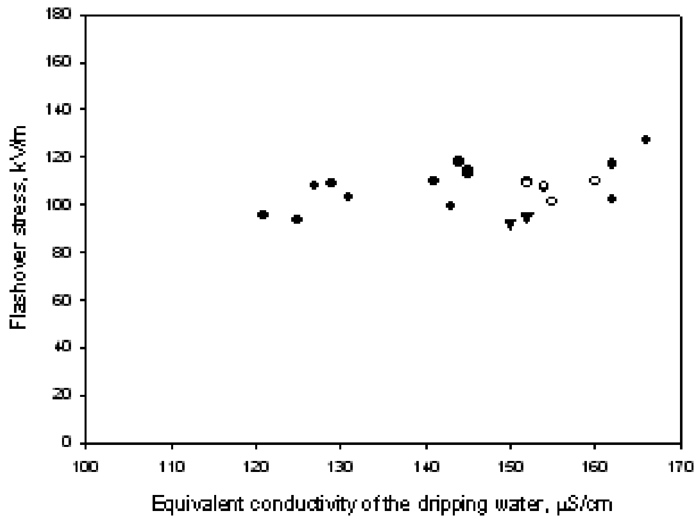


Figure 6-20: Comparative ice flashover stresses per insulation height of silicone rubber and porcelain circuit-breakers (dark circles = silicone rubber; triangles and white circles = porcelain).

Conductive ice or snow may be distributed non-uniformly along insulators and hence may interact in various ways with internal active parts of an apparatus insulator. The most critical situation in terms of voltage stress for a circuit-breaker is the synchronizing period during the connection of a generator to the system. In this case, the voltage across the circuit-breaker chamber(s) in the open position can, for a short period of time, reach 2.5 times the normal operating phase-to-ground voltage. A circuit-breaker of Y-configuration in Norway has recently flashed over and exploded during synchronizing under conditions of 90 cm snowfall [6.30], [6.31]. On this basis, ice and snow tests should be performed only full-scale because the interaction of the inner E-field distribution and specific surface E-field distribution governed by slightly conductive ice or snow can be crucial for each specific type of equipment.

6.3 Electrical performance under long term tests

6.3.1 *Without internal parts*

A summary of long term laboratory ageing tests according to a CIGRE review [6.1] is shown below in Table 6-4. Unfortunately most of the information refers to line insulators and very limited data is available for hollow and apparatus insulators.

The most important issue since this CIGRE review was published is that at present no standardised accelerated ageing tests exist or are under development. It is stated in IEC 62217 that "*The tracking and erosion tests given in this standard are considered as screening tests intended to reject materials, or designs, which are inadequate. These tests are not intended to predict long term performance for insulator designs under cumulative service stresses*." This is the general trend with no accelerated ageing tests being under development at present and no attempts to standardize the existing ones. In IEC 62217 three methods for tracking and erosion tests for polymeric insulators are described. These are the 1000 hour salt fog test, the wheel test and the multiple stress 5000 hour test. According to the standard, one of the above should be applied for verification of the resistance of an insulator design to the stress of electrical discharge activity. Two of those tests (excluding the wheel test) are also included in the standard IEC 60099 for arresters. Finally, it must be observed that a standardised tracking test is not available for DC applications and development of such a test seems rather important.

Table 6-4 Summary of laboratory ageing tests

Test Procedure	Voltage level	Specific creepage distance, l_k/U * mm/kV_{l-e}	mm/kV_{Um}	Additional stresses	Periods without additional stresses	Salinity during pollution period	Solar-radiation simulation (kW/m^2)	Evaluation criteria
CEA Tracking Wheel Test [90] 1: constant rotation 1000 hours 2: stepped rotation 1600 hours	medium voltage	28,6	16,5	salt water spray salt water	none none	0,22 kg/m^3 1,4 kg/m^3	- -	no tracking, no erosion to the core, no puncture of sheds or housing
IEC 1000 hours test [16]	medium voltage	34,6	20	fog generated from salt water	none	10 kg/m^3	-	3 overcurrent trips for each specimen acceptable, damage
CEA salt-fog procedure [91]	medium voltage	$\frac{l_k}{1,1 \times U_m / \sqrt{3}}$	$\frac{l_k}{1,1 \times U_m}$	fog generated from salt water on cement coated insulators	some	0,3 - 3 kg/m^3	-	damage, number of ageing periods without flashover
CIGRE 5000 hours test [16,62]	full scale ≤ 245/√3 kV	$\frac{l_k}{\leq U_m / \sqrt{3}}$	$\frac{l_k}{\leq U_m}$	fog generated from salt water, rain, humidification, heating, UV	none	7 kg/m^3	~ 0,9	3 overcurrent trips for each specimen acceptable, damage
ENEL 5000 hours test [28,66]	full scale ≤ 540/√3 kV	$\frac{l_k}{\leq 540 / \sqrt{3}}$	$\frac{l_k}{\leq 540}$	fog generated from salt water, rain, humidification, drying, UV, heating.	some	80 kg/m^3	1,5	Specified pollution performance after at least 3000 hours, damage after 5000 hours
EPRI Summer/Winter cycle test [5]	full scale ≤ 138/√3 kV	$\frac{l_k}{\leq 138 / \sqrt{3}}$	$\frac{l_k}{\leq 138}$	fog generated from salt water, rain, humidification, heating, UV	none	2,5 kg/m^3	0,01, measured at the wave length 350 nm with 10 nm band width	number of summer/winter cycles simulating years of service
EPRI Special desert-climate cycle [92]	full scale ≤ 500/ √3 kV	$\frac{l_k}{\leq 500 / \sqrt{3}}$	$\frac{l_k}{\leq 500}$	salt mist, clean rain, clean mist, UV, mechanical load	some	1 kg/m^3	0,01, measured at the wave length 350 nm with 10 nm band width	number of cycles simulating years of service
FGH 5000 hours test	- 100 kV d.c.	$\frac{l_k}{\leq 100}$	$\frac{l_k}{\leq 100}$	fog generated from salt water, rain, UV	some	7 - 10 kg/m^3	~ 1,5	specified pollution performance after 5000 hours

6.3.2 With internal parts

The influence of inner electrodes on long term performance was analysed in [6.25]. The same housing as tested in short-term pollution conditions was tested with and without inner electrodes. The configuration with internal electrodes is shown in **Figure 6-21** and the relevant field distribution is given in **Figure 6-22**. A voltage of 160 kV was applied continuously for 30 cycles, each cycle being 1 day and including salt fog, steam fog, rain and UV radiation. No significant effect of internal electrodes on accumulation of contamination and surface hydrophobicity was verified. However, the leakage current for the object with internal electrodes was about twice that without electrodes; an effect which can be attributed to the influence of capacitance between the electrodes.

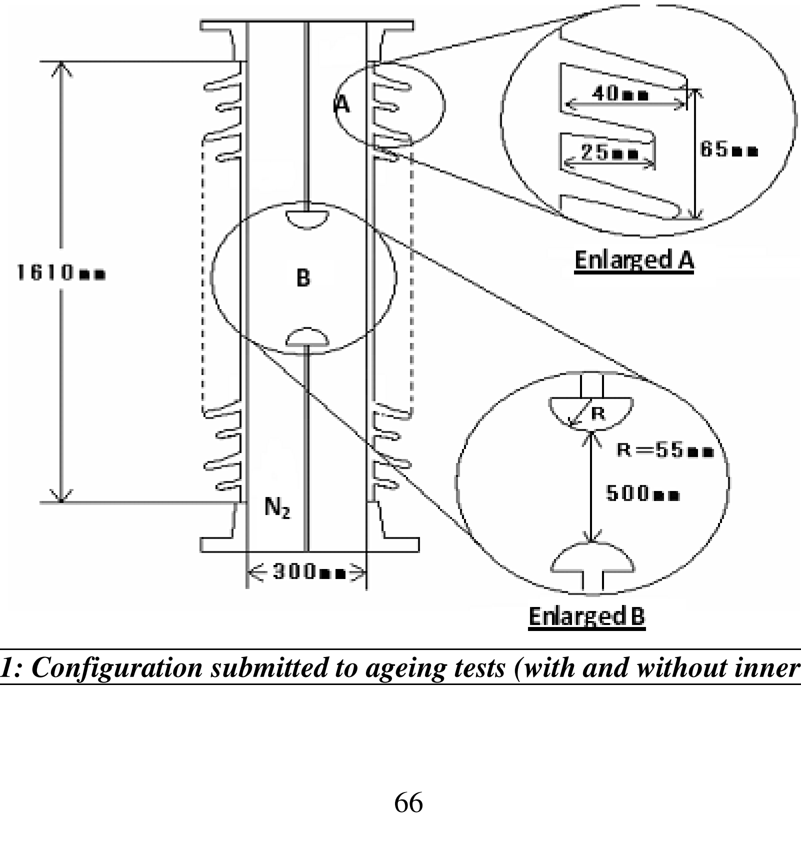
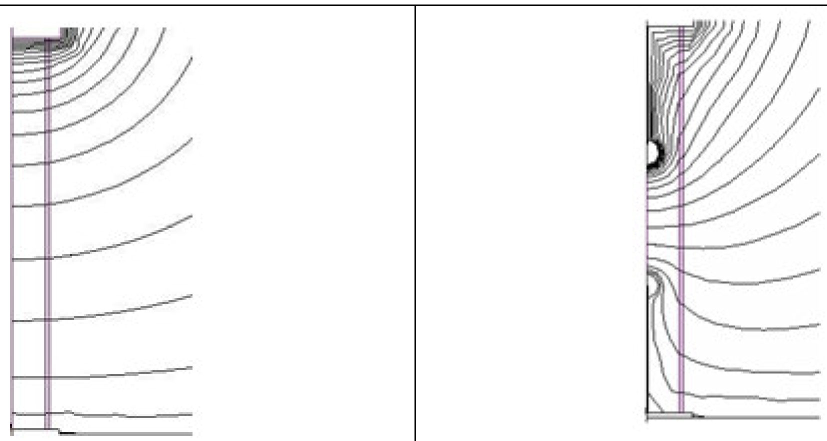


Figure 6-21: Configuration submitted to ageing tests (with and without inner electrodes)



a) Without internal electrodes | b) with internal electrodes

Figure 6-22: E-field calculation for the objects submitted to ageing tests (with and without inner electrodes)

The results reported above are in good agreement with the results from 1000 hour salt fog tracking and erosion tests at a salinity of 1 kg/m^3 on CVT, surge arrester and hollow insulators [6.32]. All of the insulators were close in geometrical parameters and Figure 6-23 (adapted from [6.32]) shows that the leakage current was much higher on CVT due to the strong influence of inner structure. Nevertheless, no difference in deterioration has been observed between the samples.

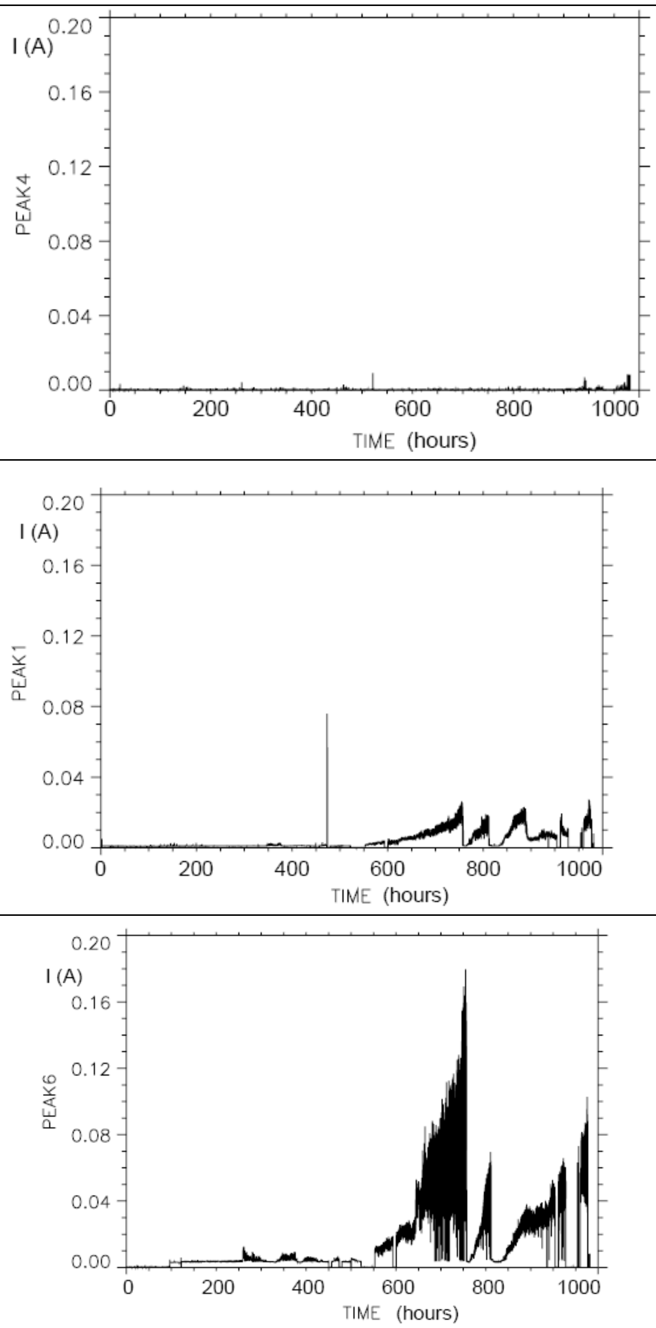


Figure 6-23: Leakage currents in 1000 hours salt fog test for the apparatus with different internal active parts: top – hollow insulator; middle – arrester; bottom – CVT.

Modern tracking and erosion test methods are intended to test long term behaviour of solid insulation of composite HV components by avoiding flashovers during the tests. On the basis of tests performed, the preliminary conclusion can be drawn that, as far as the housing is concerned, tests on empty housing are generally representative of the case when the housing are applied to apparatus, provided that the gradients on the surface are maintained below the design value for the housing.

The influence of internal parts becomes more evident for more compact designs. Having demonstrated the influence of the internal active part on leakage current development and recognizing the trend towards smaller, more compact designs of electrical apparatus, one could predict a greater need to consider the influence of the active parts in the design of the housings in future. In the extreme, housing puncture may occur due to incorrect co-ordination of the internal/external insulation and the weather ageing test procedure for arresters which is incorporated into according to amendment 2 to IEC 60099-4 already considers this situation.

The influence of the active parts on leakage current development and surface behaviour was clearly demonstrated during the long term testing at Dungeness test station in UK [6.33]. The highest accumulated charge was observed on the chamber of a circuit-breaker and continuous discharge activity was observed, possibly linked with the high surface field generated by the presence of the internal electrodes. These continuous discharges led to colour changes (see **Figure 6-24**, A) and even reduced the hydrophobicity from WC 2-3 to WC 5 in the middle of the chamber, where the open electrodes were located. At the same location, for the same type of insulators configured as support or hollow insulators without internal structure, a much lower accumulated charge is observed than on porcelain insulator with higher creepage distance [6.33]. Similar colour changes were observed on a model of a circuit-breaker tested in an industrial environment in Germany (see **Figure 6-24**, B) [6.34]. This model was tested with extremely high electrical field strength on the surface of some sheds in the middle of the insulator (up to 14 kV/cm) for 30,000 hours. No flashover occurred during the test and no erosion was found but it is clearly visible in the figure that the insulator sheds in the high field region were heavily blackened. The hydrophobicity of the heavily blackened sheds was totally lost with a very slow hydrophobicity recovery over several weeks. The test results indicated that the hydrophobicity of the silicone itself was not degraded, but that the hydrophobicity transfer was broken down by the high electrical field strength. Even under these locally extreme high electrical stresses, which were applied for a long time, no flashover was indicated and no traces of erosion were found. The sheds outside the zone of very high electrical fields were in a good condition without strong loss of hydrophobicity.

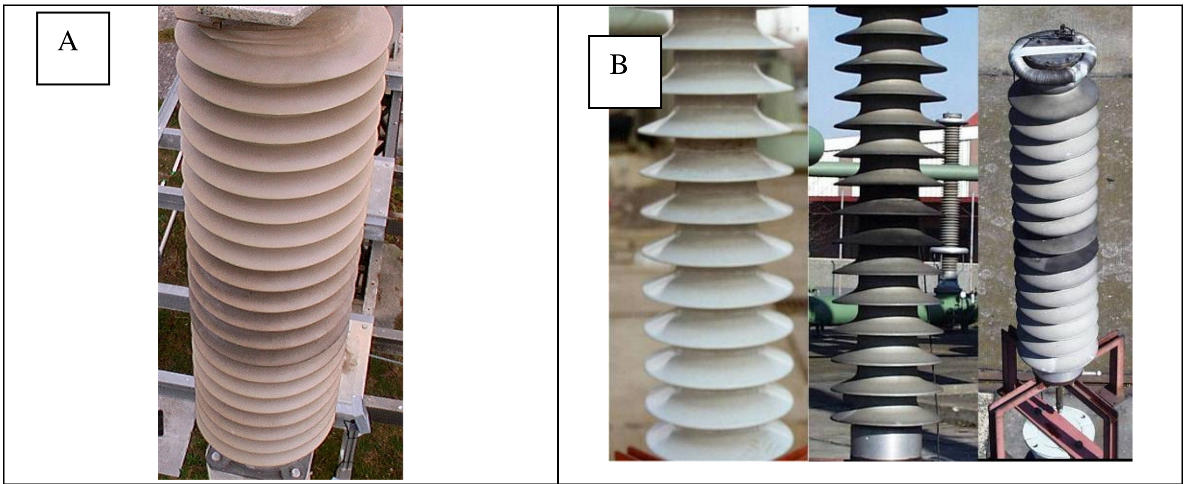


Figure 6-24: Circuit-breaker in open position tested in long term field tests in UK and Germany: A – Dungeness test station in UK; B – (before test, after 6 years, after 11 years) test station in Germany.

6.4 Conclusions

6.4.1 Performance under short-term tests

Comparing the performance of polymeric housings with porcelain ones the following can be indicated:

- *AC-SI wet tests.* The flashover voltage of polymeric insulators shows less reduction from the reference dry value under wet (rain) conditions than porcelain. The reduction of flashover voltage with increasing diameter is also less pronounced for polymeric insulators.
- *AC pollution tests*. Polymeric insulators have better performance than porcelain insulators for the same profiles (about 20-30%). Reduction of flashover voltage with increase of diameter is also less for polymeric insulators.

Comparing the performance of polymeric housings with and without inner electrodes:

- The influence of the inner electrodes may be significant for AC-SI dry and wet tests. Tests on complete equipment are therefore recommended;
- The influence of the inner electrodes is limited during pollution testing. Tests on simple housings are representative of, and could be extended to, the complete equipment.

6.4.2 Performance under long term tests

- Considering only the performance of the of the housing, tests on empty housings are generally representative of the behaviour of complete equipment provided that the electric field gradient at the surface of the equipment is below the design value for the housing.
- Internal electrodes may lead to higher leakage currents at the polymer surface during long term tests. The influence of the inner electrodes can become more evident for more compact designs.

6.5 References

[6.1] CIGRE Task Force 33.04.07: “Natural and artificial ageing and pollution testing of polymeric insulators”, Cigre Brochure 142, 1999

[6.2] C.S. Engelbrecht; R. Hartings; H. Tunell; B. Engström; H. Janssen; R. Hennings: “Pollution Tests for Coastal Conditions on an 800-kV Composite Bushing”, IEEE Transactions on Power Delivery, Vol. 18, No. 3, July 2003

[6.3] IEC/TS 60815-1: ”Selection and dimensioning of high-voltage insulators for polluted conditions - Part 3: Polymer insulators for AC systems”, Edition 1.0, 2008-10

[6.4] P. Cardano, M. de Nigris, A. Pigini, G. Rocchetti: “Dielectric performance of composite housing” ISH 2009

[6.5] P. Lambeth: “Variable-voltage application for insulator pollution tests”, IEEE Trans. on Power Delivery, Vol. 3, No. 4, Oct., 1988.

[6.6] “IEC TS 60073 - Guidance on the measurement of wettability of insulator surfaces,” Int. Electrotech. Comm. Geneva, Switzerland. 2003.

[6.7] Sklenicka V., Zeman I. : “Utilization and service experience with composite insulators in Czech power system.” Proceedings of World Congress & Exhibition on Insulators, Arresters & Bushings Shanghai, November 2001.

[6.8] A S. Bossi, A. Pigini, R. Reali, G.P. Fini, A. Porrino, Channakeshava, N. Vasudev, M. Ramamoorty “ Study of the performance o composite insulators in polluted conditions” CIGRE Report 33-104-1994

[6.9] G.P. Fini, G. Marrone, F. Gallucci, A. Pigini “Field experience and laboratory ageing tests on composite insulators for overhead lines” L’Energia Elettrica n. 7-8, vol. LXI, 1984

[6.10] I. Gutman, X.D. Liang, B. Luo, Z.Y. Su, E.Solomonik, W.L. Vosloo: “Evaluation of OHL performance based on environmental stresses and pollution laboratory testing of composite insulators”, CIGRE-2008, C4-112

[6.11] A. De La O, R.S. Gorur, J. Chang: “AC clean fog tests on non-ceramic insulating materials and a comparison with porcelain”, IEEE Transactions on Power Delivery, Vol. 9, No. 4, October 1994, p.p. 2000-2008

[6.12] K. Naito, R. Matsuoka, K. Izumi, K. Takasu: “Performance of Composite Insulators under Polluted Conditions”, CIGRE-1996, 33-301, 1996

[6.13] K. Ikeda, M. Ito, T. Sanpei, R. Matsuoka, K. Kondo, S. Ito: “Evaluation methods of contamination flashover voltages of hydrophobic polymer insulators”, 13th ISH-2003, Netherlands, 2003

[6.14] B. K. Gautam, S. Matsumura, K. Sakanishi, T. Kawaguchi, R. Matsuoka, M. Ito: “Effect of Core Diameter of Cylindrical Polymer Insulators on Contamination Flashover Voltage-Part I, Submitted to English Special Edition “Power and Energy System Technology of 21st Century” of IEEJ Trans. on Power and Energy.

[6.15] B. K. Gautam, S. Matsumura, K. Sakanishi, T. Kawaguchi, R. Matsuoka, M. Ito: “Effect of Core Diameter of Cylindrical Polymer Insulators on Contamination Flashover Voltage-Part II,

Submitted to English Special Edition "Power and Energy System Technology of 21st Century" of IEEJ Trans. on Power and Energy.
[6.16] I. Gutman, A. Dernfalk, A. Nefedov, and J. Seifert, "Pollution test methods for composite insulators: simulation of coastal environment and recovery of hydrophobicity", accepted for publication at 16th ISH-2009, Cape Town, South Africa, 24-28 August, 2009.
[6.17] S. Berlijn, K. Halsan, I. Gutman, and A. Dernfalk, "Assessing Ten Years of Service Experience with Composite Line Insulators at HVDC", World Congress & Exhibition on Insulators, Arresters & Bushings, Crete, 11-13 May, 2009.
[6.18] I. Gutman, A. Dernfalk: "Pollution tests for polymeric insulators", IEEE Transactions on DEI, to be published in 2010
[6.19] CIGRE Taskforce C4-13-01: "Polluted Insulators: Guidelines for selection and dimensioning. Part 1: General principles and the AC case" 2005
[6.20] IEC 60815-3 "Selection and dimensioning of high-voltage insulators for polluted conditions - Part 3: Polymer insulators for AC systems"
[6.21] IEC60815-2-Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 2: Ceramic and glass insulators for AC systems
[6.22] A. Pigini, AC Britten, C. Engelbrecht "Development of guidelines for the selection of insulators with respect to pollution for EHV- UHV DC: state of the art and research needs"
[6.23] A. Pigini "Pollution Requirements for Ultra High Voltage AC and DC systems" 2007 World Congress& Exhibition on insulators, arresters and bushings- Rio de Janeiro 2007
[6.24] A S. Bossi, A. Pigini, R. Reali, G.P. Fini, A. Porrino, Channakeshava, N. Vasudev, M. Ramamoorty " Study of the performance o composite insulators in polluted conditions" CIGRE Report 33-104-1994
[6.25] R. Matsuoka "Effect of Internal Electrodes on Contamination Flashover Voltage and Ageing Deterioration of Polymer Bushing Shells" CIGRE A3.21 (07)… IWD
[6.26] CIGRE WG 33.03 "Guidelines for the evaluation of the dielectric strength of external insulation" Cigre brochure N 72 1992
[6.27] IEC 60168 Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1000 V" 1996
[6.28] CIGRE TF 33.03.03 "Switching Impulse performance of post insulators" Electra n 109 1986
[6.29] WG 33.07 " Guidelines for the evaluation of the dielectric strength of external insulation" Cigre brochure 72 -1992
[6.30] H. Wieck, I. Gutman, T. Ohnstad: "Availability of Generator circuit-breakers under Snow, Ice and Pollution during Connecting to a Line", IWAIS-2007, Yokohama, Japan, 9-12 October, 2007, paper 6-2
[6.31] H. Wieck, I. Gutman, T. Ohnstad: "Flashover performance of a T-shaped circuit-breaker under snow conditions", IWAIS-2005, Montréal, Canada, 12-16 June, 2005, p.p. 315-319
[6.32] D. Windmar, H. Hillborg: "Today's operating performance and manufacturing processing requirements for silicone rubber in electrical components", World Congress & Exhibition on Insulators, Arresters & Bushings, Hong Kong, 27-30 November, 2005
[6.33] I. Gutman, L. Stenström, D. Gustavsson, D. Windmar, W.L. Vosloo: "Optimized use of HV composite apparatus insulators: field experience from coastal and inland test stations", CIGRE Session 2004, A3-104
[6.34] K. Juhre: "Interaction between composite insulators and the electrical field" – CIGRE Session 2006, SC A3 PS1 Q11

7 MECHANICAL AND THERMAL INTERACTION

7.1 Introduction

The purposes of this chapter are:

- to summarize the state of the art about standardization for composite housing related to mechanical and thermal issues
- to identify additional tests necessary to qualify composite housings taking into account the specific applications of the housing and the interaction with the inner parts of the equipment
- to recommend additional qualification activity to be carried out by housing manufacturers in the design and manufacturing phase

Finally appendices A-7.1 and A-7.2 give examples of the interactions and consequent testing needs in the case composites are applied to the specific case of surge arresters.

7.2 Mechanical and thermal aspects in the standards for composite insulators

The analysis of mechanical and thermal aspects is made assuming IEC 61462 as reference [7.1]. The Standard refers to housings to be used on apparatus and does not refer to direct moulded solutions where the outdoor insulating material is applied directly onto the high voltage equipment (see as an example the annex for the specific case of surge arresters). The main aspects of the Standard are summarized below for reference.

7.2.1 Mechanical aspects

Two main tests are specified in the Standard [7.1]:

- the mechanical bending test;
- the internal pressure tests for pressurized housing.

The following mechanical loads are defined in the Standard for the **mechanical bending tests:**

- **maximum mechanical load (MML)**: highest mechanical load which is expected to be applied to the hollow insulator in service and in the equipment in which it is used, thus to be specified by the equipment manufacturer
- **specified mechanical load (SML):** load specified by the manufacturer that is used in the mechanical tests. The SML forms the basis of the selection of composite hollow insulators with regard to external loads. The load is normally to be applied by bending at normal ambient temperature

The following definitions apply to the pressure tests

- **maximum service pressure (MSP):** difference between the maximum absolute internal pressure, when the equipment (of which the hollow insulator is a part) is carrying its rated normal current at maximum operational temperature and the normal outside pressure. MSP is the "design pressure" and is specified by the equipment manufacturer. It is equivalent to the “design pressure” as used for ceramic hollow insulators [7.2]. Solar radiation shall be taken into account when it has a significant effect on the pressure. In some special cases (for example circuit-breakers) the transient pressure rise occurring during breaking operation must be taken into account.
- **specified internal pressure (SIP)**: internal pressure specified by the manufacturer which is verified during a type test at normal ambient temperature

And the following parameters are defined to assess the condition of the housing after testing:

- **damage limit of the tube under mechanical stress**: the limit below which mechanical loads (pressure, bending load) can be applied, at normal ambient temperature, without micro damage to the composite tube. This means that following the application of such loads the tube is in a reversible elastic phase. If the damage limit of the tube is exceeded, the tube is in an irreversible plastic phase, which means permanent damage to the tube.

- **deflection under bending load**: displacement of a point on an insulator, measured perpendicularly to its axis, under the effect of a load applied perpendicularly to this axis
- **failing load (FL):** maximum load that can be reached when the insulator is tested under the prescribed conditions. It is stressed that damage to the core is likely to occur at loads lower than the insulator failing loads.
- **residual deflection**: difference between the initial deflection of a hollow insulator prior to bending load application, and the final deflection after release of the load.

The relations among the various parameters are illustrated in **Figure 7-1** and **Figure 7-2** from [7.1]

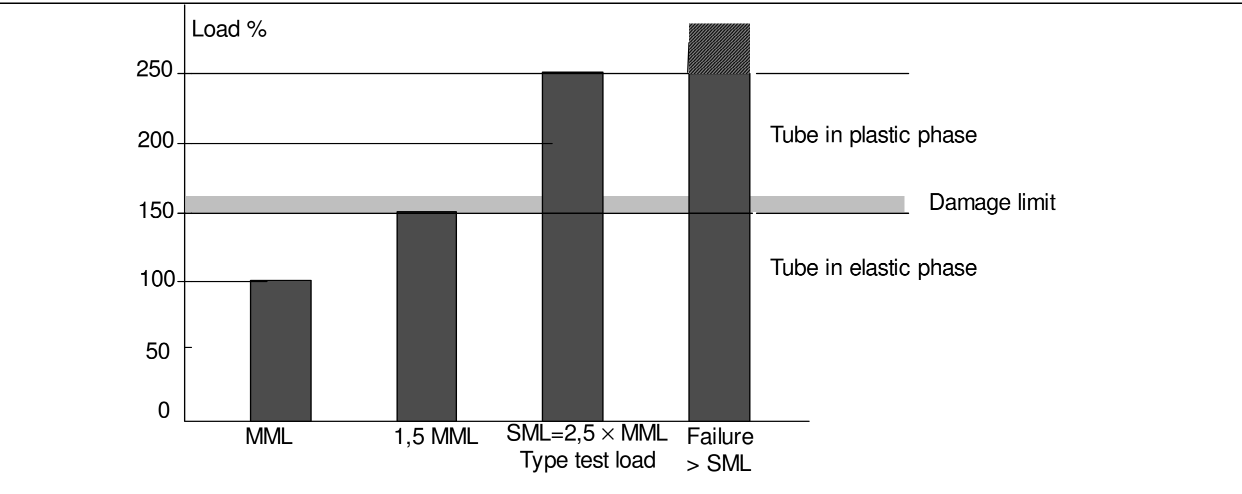


Figure 7-1: Relationships of the reference mechanical loads

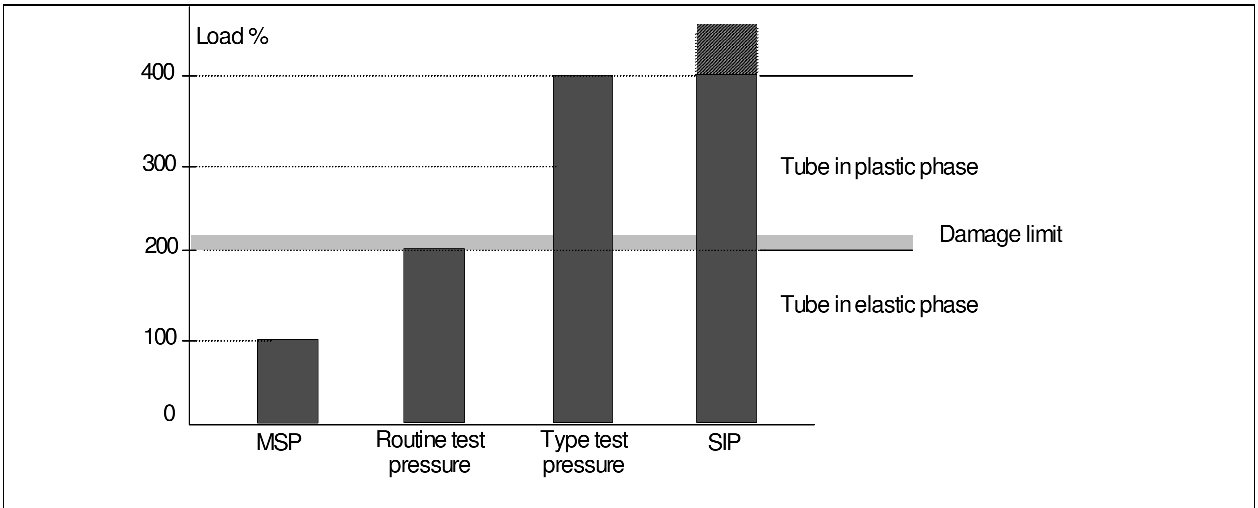


Figure 7-2: Relationship of reference pressures.

The Standard prescribes design, type, sample and routine tests.

- In **design tests** a thermo-mechanical pre-stressing test is foreseen with the application of a mechanical load equal to 0,5 SML applied in 4 directions with two cycles of heating and cooling (duration between 24 and 48 hours) with a temperature excursion of at least 85K and with the cold period with a temperature not lower than -50 °C. It is clearly stated in the Standard that the temperature and loads are not intended to represent service conditions, but to produce specific reproducible stresses in the interface of the insulator.
  For pressurized housings internal pressure tests are carried out to verify the leakage with gas at MSP with a very limited permissible leakage and with water up to SIP with no failure and no leakage. The maximum permissible leakage in the Standards at MSP is 0.5 % per year. The performance of the

tube itself is furthermore verified through specific tests (Dye penetration test or Water diffusion test, according IEC 61462 and according to IEC 62217).

- In **Type tests,** bending tests are made by applying subsequently a bending load equal to MML, 1.5 MML, SML = 2.5 MML and eventually increasing the load up to failure. The maximum deflection and residual deflection at 1 time and 1.5 times MML should not exceed the values defined by the manufacturer and agreed with the user. At SML no fracture or pull out of the tube should occur. As far as pressure tests are concerned (for pressurized housings only) the pressure should be increased subsequently to 2 MSP, 4 MSP and eventually to SIP (if SIP < 4SMP) with no damage at 2 times and 4 times SMP and with strain conditions within specified levels.
- **Sample tests** are carried out applying loads up to 1.5 MML and 2 MSP (for pressurized housings) for bending and pressure tests respectively. No damage should occur to the insulator, and the deformation should be within the limits specified by the manufacturer.
- **Routine tests** are performed applying loads up to MML and 2 MSP (for pressurized housings). Furthermore, tightness tests are foreseen. Definitions of Tightness, Testing Method and Acceptance Criteria are not specified in the IEC 61462 and have to be agreed with electrical equipment manufacturer and end-users.

7.2.2 Thermal aspects

As far as thermal aspects are concerned IEC 61462 makes reference to IEC 62217 [7.3] which considers the ambient temperature range +40°C to -40°C.

More specifically IEC 61462 defines:

- The specified temperature: highest and/or lowest temperature permissible for the composite hollow insulator.
- The insulator temperature range: the Standard states that the highest and lowest temperature permissible for the composite hollow insulator are to be specified by the insulator manufacturer and related to the design and to the specific application.

All of the mechanical tests are prescribed by the Standards at normal ambient temperature with the exception of the thermal mechanical pre-stressing test for which the specimen is sequentially submitted to a mechanical load in four directions and thermal variations (85 K variation and Min -50 °C). However, in this case, the Standard specifies that "*The temperatures and loads in this test are not intended to represent service conditions; they are designed to produce specific reproducible stresses in the interfaces of the insulator*."

The Standard adds that extreme service temperatures may affect the mechanical behaviour of composite insulators. However a general rule to define "extreme high or low" insulator temperatures is not given. For this reason the supplier should always specify service temperature limitations. Whenever the insulators are subjected to very high or low temperatures for long periods of time, the Standard recommends that both manufacturer and user agree on a mechanical test at higher or lower temperatures than that mentioned in the Standard. However, no specific indications are given.

7.3 Specific aspects depending on the different applications of composite insulators

The mechanical and thermal interactions affecting the insulator behaviour during its life in the HV electrical apparatus are not taken fully into consideration in the IEC 61462 and are left to agreements between housing manufacturer and equipment manufacturer, as clearly stated in the introduction of the Standard itself. These tests are usually defined in the Standard for apparatus application and/or end-users specifications. The testing procedures indicated by IEC 61462 are intended as minimum requirements which should be integrated into specific requirements by end-users' or by equipment manufacturers' Standards/specifications.

The thermo-mechanical stresses are to be determined by the apparatus manufacturers, depending on end-user specifications and the design and function of the apparatus. They have to be taken into consideration in the definition of insulator mechanical and thermal requirements superseding, if necessary, the indications given in IEC 61462 and IEC 62217. The service temperature, the pressure (SIP) and bending (SML) requirements as well as the definition of tightness may be different depending on the application.

Finally, it has to be mentioned that an insulator may be considered as appropriate for intended use only after the equipment of which it is a part has satisfactorily passed the type tests called for by the particular standards with which the equipment must comply. Specific tests may be needed to verify the performance for specific apparatus applications, such as the verification of the short circuit performance, mechanical tests at Tmax and Tmin, ageing tests under pressure and mechanical endurance tests, possibly accompanied by verification tests, such as leakage tests (e.g. SF_6 leaks) and failing load tests. A more detailed review of some of the specific aspects to be taken into account as a function of the application considered is reported in the following. As an example, the solutions adopted for surge arresters to take into account the specific apparatus requirements are reported in Appendix A-7.1.

7.3.1 Mechanical aspects

Annex B of IEC 61462 "*General recommendations for design and construction*" gives information and guidance on interactions to be taken into consideration for the insulator design and testing (§B.2 IEC 61462 Guidance for the maximum service pressure §B.5 IEC 61462 Guidance for mechanical loads required by Equipment Manufacturer). It is stated that "*The Equipment Manufacturer specifies the mechanical loads for the composite hollow insulator on the basis of weighted stresses arising from various service loads*". Attention is drawn to the fact that the relative importance of each of these loads for composite hollow insulators may be different from that assigned to the same load on equivalent ceramic hollow insulators as suggested in IEC 62155.

However, while IEC 62155 prescribes different safety factors for derivation of the test load depending on the continuity of the load, the derivation of MML and SML from the same information is not defined in IEC 61462 and this aspect may deserve further analysis. In particular it should be discussed if a specified long term load and specified short-term load should be introduced for specific applications, as already adopted, as an example, for porcelain housed arresters and proposed for composite housed arresters (see appendix A-7.1).

The testing procedures in IEC 61462 prescribe static loads and tests at ambient temperature (a part the thermal-mechanical pre-stressing design test with temperature variation of 85K and minimum Temperature -50°C). These tests might not be sufficient to assure the quality of the housing when used for specific applications, as reported as an example in the appendix for surge arresters (Appendix A-2). A cyclic test considering the features of most equipment designs may be more representative for real service stresses than a static bending test. Equipments are subjected to a number of different mechanical loads in service and the direction and amplitude of the loads vary. A static bending test may not be representative for all realistic loads in service and for all apparatus type.

Housings and equipment are more or less flexible and subjecting the equipments to maximum continuous load specified by the manufacturer in a cyclic way may result in significant deflection which in turn may affect the moisture ingress/gas leakage probability and/or jeopardise the overall mechanical performance. Furthermore, the maximum short-term load that can be applied without breaking may be significantly reduced after the housing/equipment has been subjected to a continuous load in a cyclic manner. A specified short-term load verified on new housing/equipment not previously subjected to any test, therefore, may give a too optimistic value.

For equipments with a strong interaction between inner active parts and the housing, such as housing directly moulded on the apparatus, all mechanical tests have to be performed on complete equipment, not only on empty housings.

Furthermore, the following additional aspects need consideration:

- The equipment manufacturer design requirements and end users specifications may have an impact on the damage limit values, requiring a modification of the insulator design with values higher than those specified by §4 and Table B.2 of IEC 61462.

- Specific Standards or National Safety regulations (e.g. ISPESL in Italy) may require verification of the mechanical characteristics at high temperature of the FRP (fibreglass resin reinforced tube) or of the complete composite insulator to verify the safety of apparatus at normal and maximum service temperature.
- Testing methods and acceptance criteria for insulator tightness (§10.5 of IEC 61462) are subject to agreement between the manufacturer of the insulator,and the manufacturer of equipment taking into account end user requirements. As an example, for surge arresters it is recommended to verify the tightness after mechanical and thermal cycles.
- It may be appropriate to check specific functions/characteristics after mechanical testing e.g. PD performance for surge arresters.
- Pressure testing for unpressurized applications: IEC 61462 specifies that internal pressure testing is not to be performed in case of unpressurized applications. This aspect deserves specific considerations for applications implying the presence of liquid medium insulation (generally mineral oil). In this case the housing, even if not pressurized as in the case of gas media, must be tight to the insulating medium and withstand the internal pressure depending on the design and temperature range. Specific testing should therefore be considered.

7.3.2 Thermal aspects

As far as thermal aspects are concerned the composite insulator should be designed taking into account the highest and lowest temperature for the apparatus application, the apparatus design and manufacturing technology and on the environmental condition at site. According to IEC 61462 it is the responsibility of the equipment manufacturer to define the applicable service temperature values. If reference is made to IEC 62217, composite insulators are suitable for use under normal ambient air temperature between -40°C and +40°C. However, most apparatus manufacturers/end users ask for ambient temperature range -50°C/+50°C with some end-users in countries with extreme environmental conditions specifying higher (+55°C) and lower (-55-60°C) temperatures.

Maximum service temperatures are between +70°C for measuring transformers and +105 °C for Circuit-breakers/Bushing applications. Depending on the application and the technology, the housing may experience temperatures above 80°C or even above 110°C for specific applications and service conditions. For instance, apparatus with O.I.P technology (Oil insulated paper bushings) are subjected to high temperature cycles during manufacturing (the housing is subjected to maximum temperature T >110-120°C for several hours/weeks) which might affect the composite insulator if not specifically designed.

For circuit-breakers the highest temperature should take into consideration the maximum ambient temperature, the solar radiation, the heating by the rated current and the perfomance under breaking conditions. The lowest temperature should take into account the lowest ambient temperature.

Extreme service temperatures may affect the mechanical behaviour of composite insulators. It is advisable that equipment manufacturers specify the service temperatures and eventually agree on mechanical tests at higher or lower temperatures than those mentioned in the Standard, .

7.3.3 Other aspects

The § B.3, IEC 61462 suggests to insulators manufacturers to verify the quality of resin impregnation by the dye penetration test and/or water diffusion test as a routine/sample test, to verify the glass transition temperature T_g of the FRP tube according IEC 61006 and to verify the T_g of the glue used to fasten the end fittings onto the FRP tube. Some end users or equipment manufacturers may require the performance of one of the above mentioned design tests as a type/sample or even routine test for specific applications.
The short circuit performance depends not only on the housing characteristics but also on the overall equipment design and construction meaning that tests should be performed on the full equipment (see Appendix A-7.2 for surge arrester). Similarly seismic performance should be verified taking into account the specific application of the housing (see Appendix A-7.3)

7.4 Design and testing during manufacturing taking account of specific applications

Annex B of IEC 61462 "*General recommendations for design and construction*" gives information and recommendations for the proper design of polymeric insulators for electric equipment. It is left to the equipment manufacturer to provide the insulator manufacturer with the information to be taken into consideration in the polymer insulator design to assure the required long term mechanical performance. Insulators should then be designed in strict co-ordination between equipment manufacturers and insulator manufacturers taking into account all interactions to assure that the mechanical, electrical and environmental performance will be according to the specified requirements for the required life span.

Insulators should be designed to withstand the maximum design stresses by assuring that the maximum expected loads are below the damage limit of the FRP tubes and the elastic limit of the fittings. Once the requirements are given by the equipment manufacturer, the design of the housing can be made by the housing manufacturer based on traditional methods and/or by the use of more sophisticated methods such as by systematic application of finite element analysis. The housing and the individual components (FRP tube, aluminum fittings and silicone housing) may be precisely designed with accurate computer aided modeling, taking into account not only the basic requirements but also all mechanical/electrical and thermal interactions. Insulator modeling may simulate the insulator behavior under static and dynamic stresses, under thermo-mechanical stresses and under seismic or short circuit conditions, simulating the active parts together with the insulators [7.4]. This applies provided that the insulator manufacturer has the necessary experience and knowledge about aspects such as material choice and qualification, insulator design and the manufacturing process.

Factors affecting the mechanical behaviour are the material used for the FRP tube, the fittings, the assembly method and the shape of the tube (length, wall thickness and shape, winding angle, assembly shape and tolerances). These aspects are not covered by existing standards and should be considered during the design process:

- **The tubes** are to be qualified according to insulator manufacturers' and equipment manufacturers' internal specifications beyond IEC 61462 requirements. In particular some characteristics are also qualified according to equipment manufacturer proprietary technical specifications (for instance SF_6 decomposition products resistance). Insulator manufacturers' internal specifications should define qualification criteria about the following parameters of FRP tubes:
  - Glass fibres characteristics and rowing
  - Glass ratio
  - Glass transition temperature of FRP tube and of glue
  - Ageing and fatigue behaviours (FRP tube and glue)
  - Porosity of FRP
  - Water diffusion test (boiling water 100h)
  - Dissipation factor
  - Relative permittivity
  - Other dielectric properties (rigidity)
  - HF acid attack
  - Dielectric strength in direction of layers, etc.
- **The fittings** should be made with highly resistant aluminium alloy offering the best sealing ratio and corrosion resistance.
- **The assembly** method should assure the best mechanical behaviour, possibly qualified by long term thermo-mechanical combined cycles including bending and pressure stresses at specified temperatures. The glue transition temperature and the dimensions and tolerances of tube-fitting coupling should be designed to assure the specified mechanical performances over an appropriately wide range of temperature.
- **The silicone housing** should be qualified according insulator manufacturers' internal specifications and IEC 61462.

7.5 Conclusions

The analysis performed led to the following main conclusions:

- The mechanical and thermal interactions affecting the insulator behaviour during its life in HV electrical apparatus are not taken fully into consideration in IEC 61462 (as clearly stated in the introduction of the Standard itself) and are left to agreements between housing manufacturer and equipment manufacturer. These tests are usually defined in the respective IEC Standard for apparatus application and/or end-users specifications. The testing procedures indicated by IEC 61462 are thus to be taken as minimum requirements which should be integrated into specific requirements by end-users or by equipment manufacturers' standards/specifications.
- While IEC 62155 prescribes different safety factors for derivation of the test load depending on the continuity of the load, the derivation of MML and SML from the same information is not defined in IEC 61462 and this aspect may deserve further analysis. As an example a specified long term load and specified short-term load has been proposed for composite housing arresters.
- An insulator may be considered as appropriate for intended use only after the electrical equipment of which it is a part has satisfactorily passed the type tests called for by the particular standards with which the equipment must comply
- For equipment with a strong interaction between internal active parts and the housing (such as housings directly moulded onto the apparatus), it is evident that all mechanical tests have to be performed on complete equipments, not only on empty housings.
- Most apparatus works in a wide temperature range, which may be much more extreme than that foreseen in IEC 62217. Mechanical tests at representative temperatures may need to be agreed upon.
- IEC 61462 prescribes static bending tests which may not be representative for all realistic loads in service. Equipment is subjected to a number of different mechanical loads, of varying direction & amplitude, in service and a cyclic test considering the features of most equipment designs may be more representative for real service stresses. Cyclic application of the maximum continuous load specified by the manufacturer may result in significant deflection, which in turn may affect the moisture ingress probability and/or jeopardise the overall mechanical performance. Furthermore, the maximum short-term load that can be applied without breaking may be significantly reduced after the housing/equipment has been subjected to a continuous load in a cyclic manner. There is a risk that a specified short-term load verified on new housing/equipment may give a too optimistic value.
- Pressure test for unpressurized applications: IEC 61462 specifies that internal pressure testing is not to be performed in case of unpressurized applications. This aspect deserves specific considerations for applications implying the presence of liquid medium insulation (generally mineral oil). In this case the housing, even if not pressurized as in the case of gas media, must be tight to the insulating medium and withstand the internal pressure depending on the design and temperature range. Specific testing must be therefore considered.
- The short circuit performance depends not only on the housing characteristics but also on the overall equipment design/construction, thus when necessary, tests are to be performed on the full sets.
- Seismic performance is to be verified taking into account the specific application of the housing

7.6 References

[7.1] IEC 61462:2007 "Composite hollow insulators – pressurized and unpressurized insulators for use in electrical equipment with rated voltage greater than 1 000 V – definitions, test methods, acceptance criteria and design recommendations"

[7.2] IEC 62155 "Hollow pressurized and unpressurized ceramic and glass insulators for use in electrical equipment with rated voltages greater than 1000 V"

[7.3] IEC 62217 "Polymeric insulators for indoor and outdoor use with a nominal voltage >1 000 V- General definitions, test methods and acceptance criteria"

[7.4] G. Rocchetti, E. Moal "Computer-Simulated Design of High Performance Hollow Core Insulators for Specialized Applications" – INMR 2005 – Hong-Kong MacLean Power France –
R. Martin, E.Moal "Seismic performances of SEDIVER –MPF Composite Station and Apparatus Insulators" –INMR Barcelona 1999 -

Appendix A-7.1: Seismic tests

Examples of seismic tests are shown in Figure A-7.1.1, Figure A-7.1.2 and Figure A7-1.3. The seismic performance is a function of the full component characteristics. It may also depend on the application and on the characteristics of the full system (e.g. the case of a bushing for a transformer). Seismic performance can also be evaluated by calculations. Numerical seismic modelling results have been compared with shake table tests performed for different cases [A-7.1.1]. The broad experience in seismic testing has permitted the refinement and optimization of seismic modelling software. It is now possible to provide end users accurate and reliable data (mechanical and dynamic properties) for their own specific applications.

Figure A7-1.1: 242 kV disconnect switch mounted on conical composite insulators during the shake table test. The assembly also included the three phase pedestal

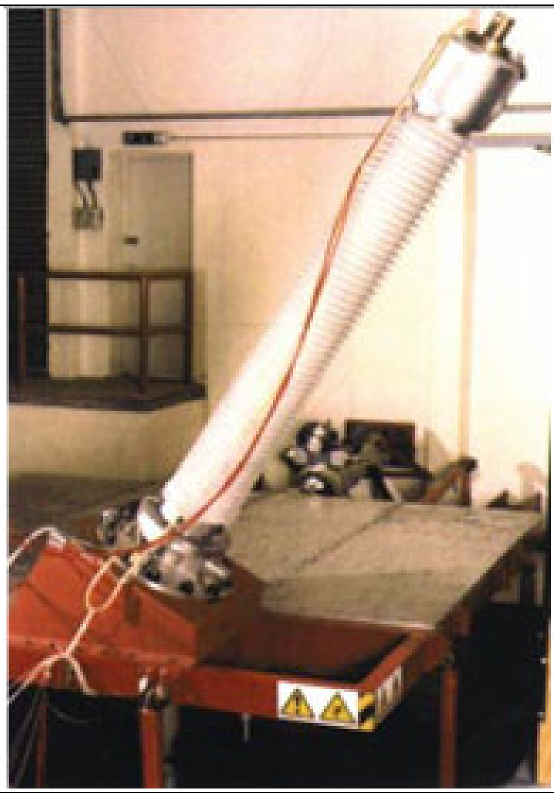


Figure A7-1.2: 196 kV composite oil bushing on the shake table.

Figure A-7.1.3: Seismic test on a polymer housed surge arrester (composite hollow core insulator) for a 550 kV system.

Figure A-7.1.4 shows a solution where an HV surge arrester with housing directly attached to the metal-oxide stack (without internal gas volume included), which usually has only limited mechanical strength, is provided with suspension insulators connected to a mechanical natural frequency oscillation node point in order to improve seismic performance.

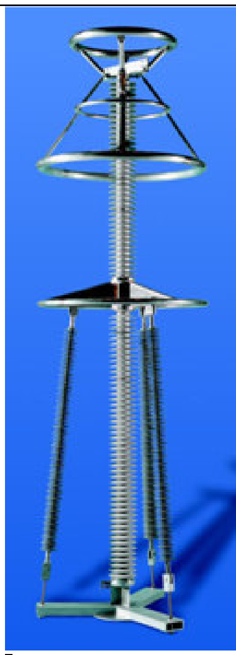


Figure A-7.1.4: Polymer housed arrester (housing without internal gas volume) for a 550 kV system especially equipped for severe seismic stress

References

[A-7.1.1] R. Martin, E.Moal "Seismic Performance of Composite Station & Apparatus Insulators" INMR Barcelona 1999

[A-7.1.2] Volker Hinrichsen "Metal-Oxide Surge Arresters – Fundamentals" Siemens AG, 1st Edition 2001

[A-7.1.3] M. Mobedjina, B. Johnnerfelt, L. Stenström "Design and testing of polymer-housed surge arresters" GCC Cigré 9th Symposium, Abu Dhabi, October 28-29, 1008

8 CHEMICAL INTERACTIONS WITHIN NON-CERAMIC INSULATOR HOUSINGS

8.1 Introduction

Glass fibre reinforced plastics (GFRP) and/or particulate-filled epoxy resin systems are commonly applied as structural elements of non-ceramic outdoor insulators such as hollow core and post insulators that are widely used for circuit-breakers, instrument transformers, bushings and surge arrestors. The hollow insulators may be filled with gases and fluids, as shown in Chapter 2. It is thus important to assure and verify the compatibility of the filler with the inner housing material.

8.2 Interactions with sulphur hexafluoride (SF_6)

Traditionally, sulphur hexafluoride (SF_6) is used as a gaseous insulation medium because it has very high insulating capabilities, outstanding arc extinguishing properties, and superior thermal properties. On the other hand it is known that SF_6 arc decomposition products are chemically aggressive and can interact with organic and inorganic materials leading to changes of the electrical and mechanical characteristic of the materials.

For example, under high temperature stresses which are likely to occur for electric arcs, sparks or partial discharge activities, the SF_6 molecules may decompose. This energetic status, however, is metastable and almost all atomic particles recombine again completely to SF_6 molecules in the subsequent cooling process. Nonetheless, low quantities of gaseous decomposition products such as sulphur tetrafluoride (SF_4) and hydrogen fluoride (HF) can be formed by the process illustrated in **Figure 8-1** [8.3], [8.4], [8.5].

$$SF_6 + M \longrightarrow SF_4 + MF_x \qquad (1)$$

$$SF_4 + H_2O \longrightarrow SOF_2 + 2\,HF \qquad (2)$$

$$SiO_2 + 4\,HF \longrightarrow SiF_4 + 2\,H_2O \qquad (3)$$

$$SiF_4 + 2\,HF \longrightarrow H_2SIF_6 \qquad (4)$$

Figure 8-1: SF_6/SF_4 decomposition reaction in presence of molecular water traces (reaction 1 and 2). Corrosive SiO_2 attack by hydrogen fluoride (HF), followed by the formation of conductive species SiF_4 and H_2SiF_6 (reaction 3 and 4).

The highly corrosive and gaseous hydrogen fluoride (HF) species diffuse into the polymer matrix and attack chemically all silicone (Si) containing compounds (reactions 3 and 4). In particular, SiO_2 containing materials like glass fibres, quartz and silica fillers are inherently susceptible to these reactions, where SiF_4 and subsequently fluorosilicic acid (H_2SiF_6) are formed as a conductive surface layer limited to a thickness δ (Figure 8-2). The final result of this electro-corrosion process is a partial massive increase of the electric surface conductivity and a corresponding decrease of the electrical stability which may cause flashovers and thus an electrical insulation failure [8.1], [8.2].

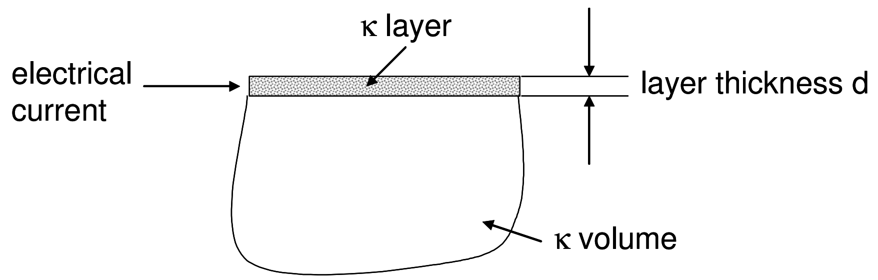


Figure 8-2: Schematic view of a component surface corroded by SF_6 decomposition products

In addition, the chemical attack of Si-containing materials results in irreversible interface damage between the polymeric matrix and the filler, which consequently leads to a decrease of the mechanical integrity of the insulation components.

Summarizing the process:

- Critical SF_6 decomposition products (e.g. SF_4 and HF) are generated by partial discharge activity, arcing and/or sparking.
- SF_4 and HF species migrate into the surface layers of the insulation material by diffusion processes and initiate an electrochemical corrosion process.
- The reaction rate of the electrochemical corrosion reaction depends upon the concentration of SF_6 decomposition by-products and the moisture concentration. In particular, SiO_2 containing insulation materials are prone to the electro-chemical corrosion process.
- The corrosion reactions generate conductive species (SiF_4 and H_2SiF_6) that decrease the surface resistivity and consequently decrease significantly the flashover voltage of the insulation.
- Critical surface conductivity values cause insulator component failure within short-time testing. For any defined component geometry and applied electric field strength there is a maximum tolerable electric surface conductivity up to which the current density can be continuously maintained and up to which thermal runaway and subsequent flashover is not expected [8.3], [8.5].
- The corrosion reaction attacks the polymer/filler matrix resulting in the reduction of the mechanical interface strength.

From the above it can be concluded that, for SiO_2 containing insulation materials (e.g. the composite core of a hollow core insulator) that are applied in environments where SF_6 decomposition by-products may be present, an appropriate protective gas barrier layer or molecular sieves (e.g. activated alumina) should be used to improve the corrosion resistance of the inner insulator surface. [8.5]

IEC standards to verify the performance of housings for applications involving SF_6 are not available at the time of writing. However, many apparatus manufacturer have developed various qualification procedures, specifying test conditions in terms of temperature, aggressive gas concentration and exposure duration, and finally acceptance criteria. The development of new standards on this aspect could be useful.

The following non-standardized test procedures are typically applied.

A test vessel with a defined volume and material can be used for the resistivity measurement. A typical SF_4/SF_6 gas mixture, where the concentration of SF_4 is defined in percentage by volume, can be used to represent arc-decomposed SF_6 gas. Before introducing the corrosive SF_4/SF_6 gas mixture, the specimen is put in the vessel filled with pure SF_6 gas for at least for 24 hours and the reference resistivity is determined. Surface resistivity measurements should also be performed in accordance with various procedures as described in IEC 60093 as a function of exposure time to the corrosive gas media.

Another simple test procedure is the filling of a complete composite insulator with decomposed SF_6 gas in typical concentrations deriving from circuit-breaker high-power tests. After defined exposure durations, e.g. some weeks, the test object is opened and a visual inspection gives an indication of the SF_6 decomposition products resistivity. This procedure can be repeated over some cycles to accelerate the moisture ingress, which will be much slower under service conditions without ambient air contact. In addition, high-voltage tests can be performed to verify any degradation of the strength after ageing. In comparison to service conditions, this test procedure is very severe and gives only an indication of a possible risk.

A third test procedure includes the application HF fluid of concentration in the range 1% to 4% on small material samples for 100 hours. After exposure to the fluid, a high-voltage test is performed with adapted electrical field stress.

8.3 Oil interaction

Before the use of any oil type within a specific housing material, equipment manufacturers may ask for verification of full compatibility in terms of material and manufacturing process. This is especially of interest when new types of oils or fillers are considered. To cater for this some manufacturers have developed their own qualification procedure, specifying test conditions in terms of temperature, duration, and finally acceptance criteria. The development of new standards on this aspect could be useful.

8.4 References

[8.1] T. Nitta et al., IEEE-PAS 97 (1978) 959

[8.2] S. Tominaga et al., "Influence of Arc-Decomposed SF6 gas on Cast Epoxy Insulators for Gas Insulated Switchgears", IEEE -PAS, Vol. PAS-98, No. 6, 1979

[8.3] Bruehl et al., "Monitoring of Electrical Properties of Particulate Filled Epoxy Resins Under Corrosive Stress" EEIC/ICWA Conference, Chicago, pp. 13-16, 1993

[8.4] M. Miyashita et at., "Influence of Surface Resistivity on Flashover Properties of Epoxy Insulator in Arc Decomposed SF6 Gas", ICPADM 2006, 2006

[8.5] E. Nagao et al., "Electrical Surface Resistivity of Organic Coating Resin in Arc-Decomposed SF6 Gas", CEIDP 2006, pp. 696-699, 2006

9 HANDLING AND MAINTENANCE

9.1 Introduction

This chapter deals with the different procedures related to the handling of hollow core composite insulators. As mentioned in CIGRE's thematic brochure N°184 "*Composite Insulator Handling Guide*", which is specific to overhead line insulators, most damage can be attributed to errors during transport, un-packing, re-packing, manipulation and storage of the insulators. In this chapter, CIGRE's thematic brochure N°184 has been adapted to composite hollow core insulators. Procedures and rules are given for:

- Un-packing and re-packing
- Methods of storage
- Handling and cleaning.

9.2 Un-packing and re-packing the insulators

Prior to un-packing, an examination of the crate should be done to check for impact damage due to a collision during transport. Before opening the crate, check that it is in its upright position; a crate delivered in an upside-down position could imply damage due to insulators not being maintained properly during transport. Once the crate has been checked it can then be opened. Special care should be exercised when taking out the insulators since nails are often left protruding from the internal walls of or the top of the crate. These must be removed or bent flat before the insulators are taken out as they can cause severe damages to the housing.

Once taken out, if the insulators are wrapped with a plastic slipcover, special care should be taken when removing this protection. The use of cutting tools like a Stanley knife is not recommended as it could severely damage the sheds. **Figure 9-1** shows, beside the conventional caution sign, an example of damage inflicted on an equipment insulator by the use of a cutter.

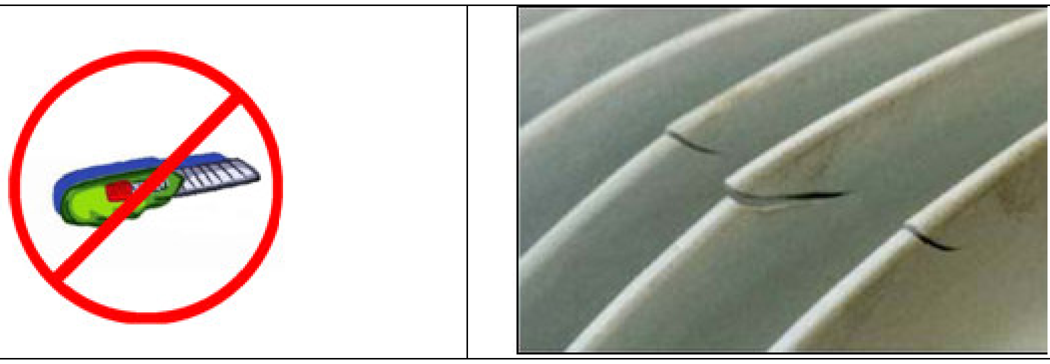


Figure 9-1: Example of a damage caused by the blade of a cutter

Special procedures may be required for each application. As an example, after unpacking a bushing, the bushing and its accessories should be carefully inspected for transport damage, with particular attention to end connections, joints between flanges and their screw connections, gas valves, density monitor and bursting disc. The internal pressure of the bushing may be measured by precision manometer covering at least 0 – 50kPa (0 – 0.5 bar) gauge pressure to verify that it is still at transport pressure. The ambient temperature should be taken into account when interpreting the resulting measurement.

If after inspection, insulators may have to be re-packed for storage, this should be done using their original packing with their plastic slipcover. When replacing the crate lid ensure that no nails, staples or other sharp objects can come onto contact with the insulators. If the crates were strapped, they should be re-strapped.

9.3 Storage

Insulators should be kept in their original packaging for as long as possible prior to installation and should be stored in a dry, covered area with the crates raised off the ground. If crates are completely sealed they should remain this way for as long as possible to prevent the access of rodents. **Figure 9-2** is an example of warning sign indicating the necessity to store the equipment in a dry location.

Figure 9-2: Warning sign indicating the necessity to avoid wetting during storage

When the insulators are un-packed they should be kept away from possible contaminants and abrasive materials. Storing insulators without proper protection in the vicinity of other equipment, tools and vehicles is not recommended. When stored outside of their crates insulators should be supported properly. If they are stored horizontally they should never be laid directly on the ground and supports holding them by the flanges must always be used as shown below (***Figure 9-3***) so as to avoid contact between the supports and the housing.

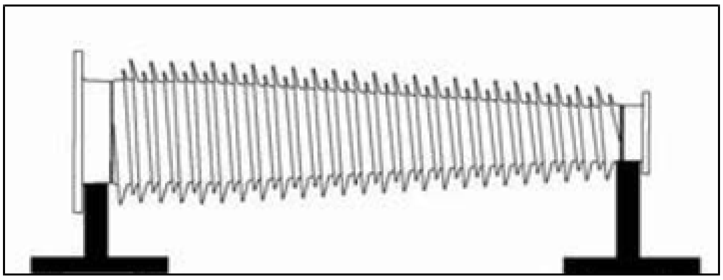


Figure 9-3: Horizontal storage of insulators supported at the flanges.

Stacking insulators one above the other is not recommended unless supports are used between each insulator to avoid the sheds touching one another. If they are stored vertically insulators should be placed on a clean and soft surface to avoid damage to the sealing surface of the bottom flanges and should not be so close that their sheds are in contact with each other.

When stored the insulators should be adequately protected, placed at sufficient distance from the main area activity and their position should be clearly marked. The potential for damage is reduced if the delivery of the insulators to their final position is properly planned so as to occur immediately before they are required. In this way they are not left on the ground for lengthy periods.

9.4 Handling

9.4.1 Hoisting the insulator:

When hoisting an insulator do not put the sling around the sheds. Hoisting should always be done by fixing the slings on the flanges in order to have the insulator completely horizontal or completely vertical (see **Figure 9-4**). Use the correct equipment to fix the slings to the flanges in order to avoid damaging the flanges.

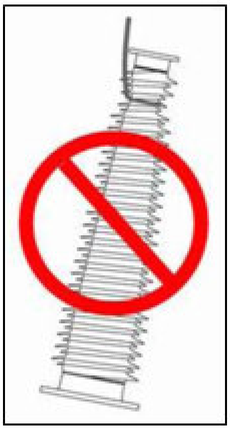
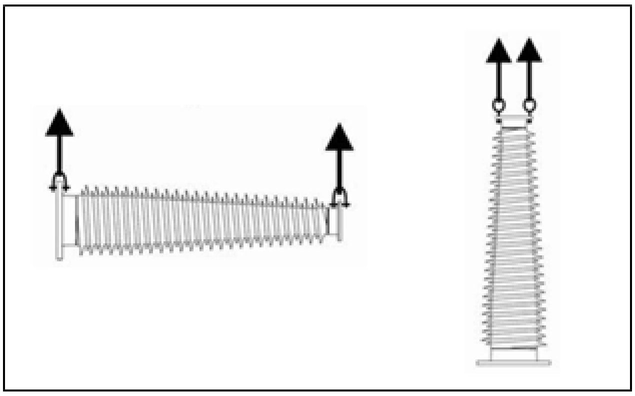



Figure 9-4: Examples of proper ways to hoist insulators

9.4.2 Moving the insulator:

When moved, the insulator should not be dragged on the ground. If moved in its vertical position, beware not to damage or scrape the sealing surface of the flange (see **Figure 9-5**).

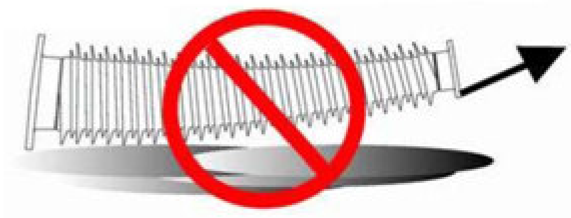


Figure 9-5: Sign indicating the dangers linked with the improper lifting of the insulators

9.5 Cleaning before installation

9.5.1 Inside the FRP tube

To clean the inside of the FRP tube use a cotton cloth, dry or moisturized with water or isopropyl alcohol. Once cleaned rinse with water or a solvent and wipe dry with a clean and dry cotton cloth.

9.5.2 The silicone housing

Insulators can be cleaned manually with solvents such as a solution of isopropyl alcohol (greater than 90%) and soft cloth. No oils or detergents should be used. Observe safety precautions when using solvents. Once cleaned, the insulator can be rinsed with a solution of isopropyl alcohol or with water. Once rinsed, wipe dry the insulator.

9.6 Cleaning in service

Experience has demonstrated that cleaning composite silicone insulators is not generally required or recommended. Composite silicone insulators are routinely used to replace ceramic insulators and significant savings on maintenance expenses are realized. Contamination that accumulates on composite silicone insulators is encapsulated with low molecular weight silicone polymer and remains hydrophobic, minimizing leakage currents and preventing contamination flashovers.

9.6.1 Acceptable methods for high voltage apparatus insulators

For exceptionally severe site conditions, in case the cleaning of insulators is required, the following methods have been evaluated and employed successfully by utilities in test programs. The following method may be used for the cleaning of any silicone housed apparatus.

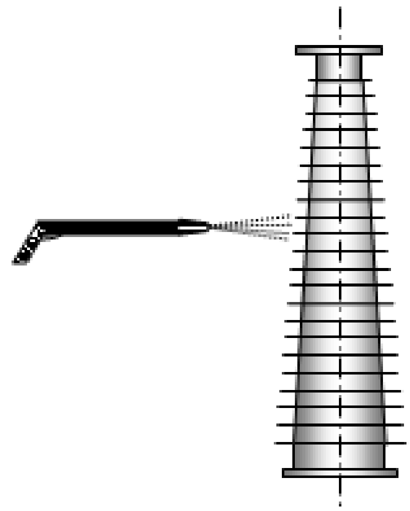


Figure 9-6: example of washing configuration

High pressure water washing (live or de-energized) can be used (Figure 9-6) with a maximum nozzle Pressure of 70 bars. Differences between pump types will result in inconsistent nozzle pressures and therefore, it is important to know the nozzle pressure prior to power washing. lt is recommended that pressures be limited to the minimum pressure that provides acceptable cleaning. A minimum distance of 0.5 m should be maintained between the nozzle and the insulator whilst the maximum effective distance has been shown to be 0.7m. Spraying should be done in a continuous up & down motion and it is important not to focus the spray on a localized area during cleaning. Using a "sweeping" motion will provide adequate cleaning without overstressing the polymer sheds.

9.7 Repairing the housing

In the event of damage to the silicone housing, silicone insulator technology allows for housing repair. Insulator manufacturers have procedures for evaluation of the damages and repair methods including a material and tool kit. Before disposal of the damaged insulators, refer to the insulator manufacturer for possibility to repair.

9.8 Conclusion

Observing all of these recommendations will greatly reduce the risk of damaging composite insulators.

9.9 Reference

[9.1] CIGRE thematic brochure N°184 “Composite insulator handling guide” – Working group 22.03 – April 2001.

10 ENVIRONMENTAL AND ECONOMICAL IMPACTS EVALUATIONS

The Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) techniques have been used to compare respectively the environmental and economical implications of different technological solutions for equipment insulators, making reference to bushings as a representative case study.

10.1 Environmental impact assessment

A comparative environmental impact assessment was carried out according to the ISO 14040 Standards series [10.1] to [10.4], considering the production and end-of-life management of bushings insulated with porcelain or silicon rubber with rated voltages ranging from 245 kV to 1100 kV. Typical LCA results for electrical components show that the service life is the most significant phase of the lifecycle because of the presence of Joule losses. However, for the purposes of a comparative study between different insulation configurations with same internal active parts, it is better to focus on the production and end-of-life phases, thereby assuming an equivalent service life for each technology.

The functional unit considered is defined as follows: "The connection of an electric device to power supply, shielding the conductor from the external environment and assuring the electric insulation towards the ground potential."

When analysing the production phase, the type and quantity of materials used is of utmost importance. **Figure 10-1** shows, as an example, an estimate of total weights for different bushing types as a function of the voltage rating, ranging from 245 kV to 1100 kV.

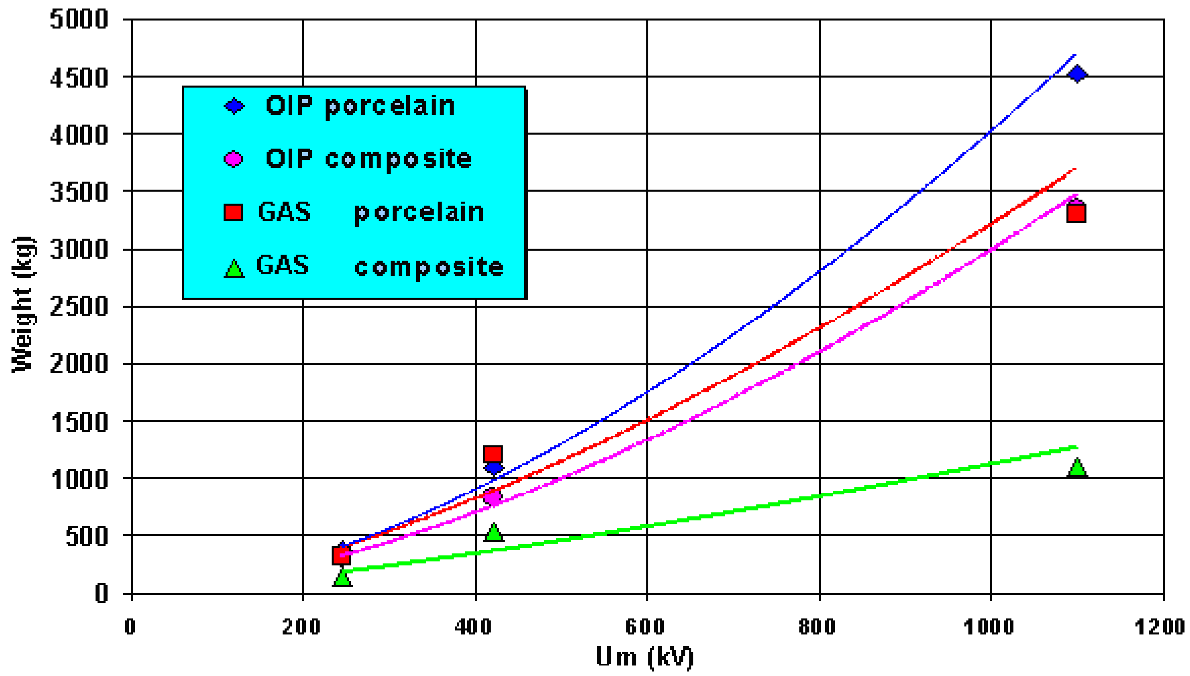
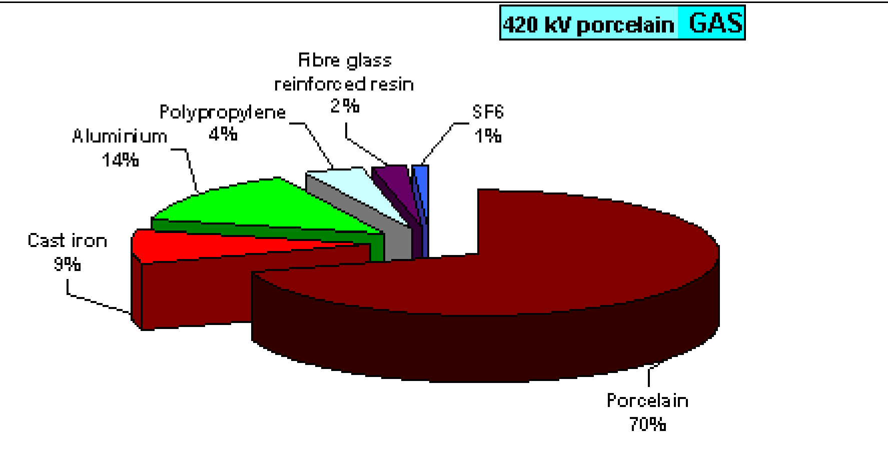
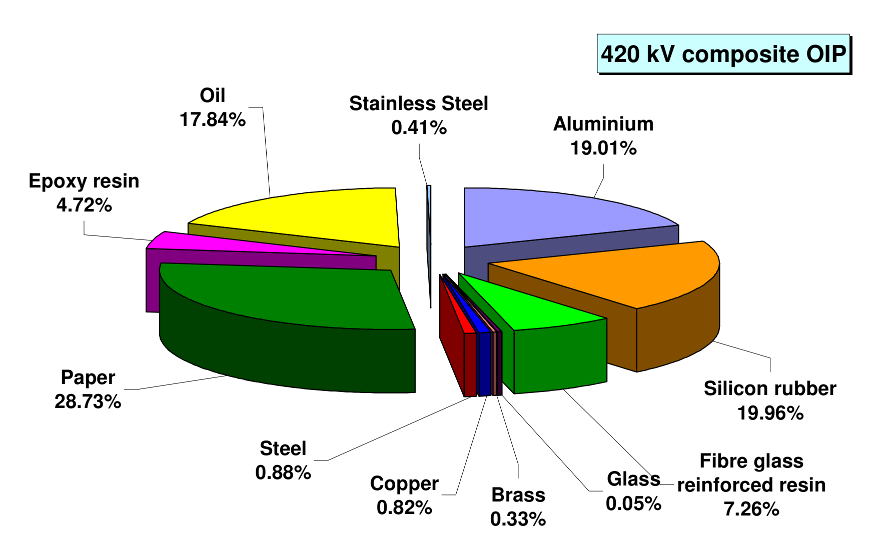


Figure 10-1: weight of porcelain and composite insulated bushings as a function of the voltage rating:
OIP: Oil Impregnated Paper bushing type
GAS: Gas insulated bushing

Figure 10-2 reports, as an example, the proportion of different materials used to produce EHV bushings of two different types.



(a): porcelain type – gas insulated bushing



(b) polymeric type – oil insulated bushing

Figure 10-2: percentage composition of different materials for the construction of 420kV rated porcelain gas insulated bushings (a) and composite oil insulated bushings (b)

Further details of the lifecycle phases and assumptions considered are as follows:

- *Production* comprising the production of the constituent materials and the energy consumption to manufacture the hollow insulator.
- *End-of-life management* including:
    - transport to a waste collector, landfill, furnaces and incineration plant
    - recycling of metals with 95% mass efficiency and energy consumption, with the landfilling of scraps.
    - oil recycling for OIP bushings.
    - incineration with energy recovery of the silicon rubber case, paper, epoxy resin and polypropylene, when present.
    - secondary recycling of the porcelain as filler in concrete, avoiding the excavation of the sand, or of the fibreglass tube to replace inert filler in road building.

The evaluation of the environmental impact was carried out considering the following categories:

- WH: Waste Hazardous production
- WT: Waste Total production
- TPE: Total Primary Energy consumption
- EL: Electricity consumption
- ACID: Air Acidification compiled by CML[1]
- DEP: Depletion of non renewable resources compiled by CML
- EUT: Eutrophication compiled by CML

[1] Centre for Environmental Science Leiden University (The Netherlands)

- GHG: Greenhouse effect (direct effect over 20 years) produced by IPCC[2]
- HTX: USES 2.0 Human Toxicity model developed by CML and RVM[3]
- ODP: Ozone layer Depletion (average) compiled by WMO[4]
- POF: Photochemical Oxidant Formation (average) compiled by WMO
- EPS Total Environmental Priority Strategies, developed by Swedish Environmental Research Institute (IVL), was used as an aggregated indicator[5].

Figure 10-3 considers a 245kV composite OIP bushing as an example and shows the environmental impacts of the production and end-of-life phases. In order to cope with the much extended range of units of each single quantity, each value is expressed in per unit of the corresponding total impact. It can be observed that, for most of the categories considered, impacts having a positive sign occur during the production phase, while negative values (i.e. avoided impacts) can be seen in the end-of-life phase. Effective end-of-life management allows the partial compensation of the impacts of the production phase, particularly of depletion of non renewable resources, owing to closed-loop metal recycling However, metal scraps produce hazardous waste, increasing the waste of the whole life cycle for each bushings.

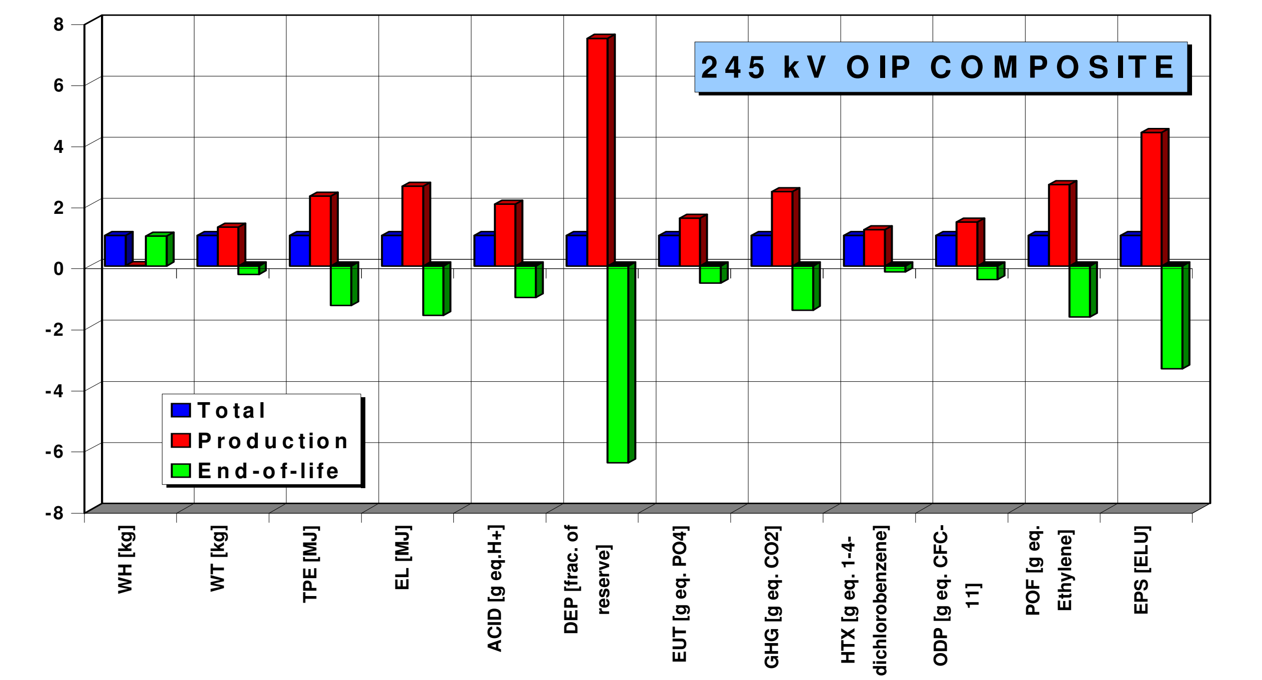


Figure 10-3: Environmental impacts of the 245 kV composite OIP bushing during the production and end-of-life phases expressed in per unit of the impact of the considered lifecycle

Figure 10-4 reports the trend of the EPS indicator as a function of the bushing type and rating.

[2] Intergovernmental Panel on Climate Change (United Nation Organisation)
[3] National Institute of Public Health and Environmental Protection (The Netherlands)
[4] World Meteorological Organisation
[5] EPS method (Environmental Priority Strategies) is a valuation system: emissions and extractions are valued to a common measure so that they can be added. EPS assign an emission or resource to an impact category when actual effects have occurred or are likely to occur in the environment and identified from five safe guard subjects: human health, ecosystem production capacity, abiotic stock resources, bio-diversity and cultural and recreational values. A willingness to pay for damages has been assigned to each subject and represents an estimated average societal value. An environmental load index for a given resource or emissions then results from the estimated impacts and the societal values for the safeguard subjects. Emissions are thus multiplied by this index to yield a dimensionless Environmental Load Unit (ELU).

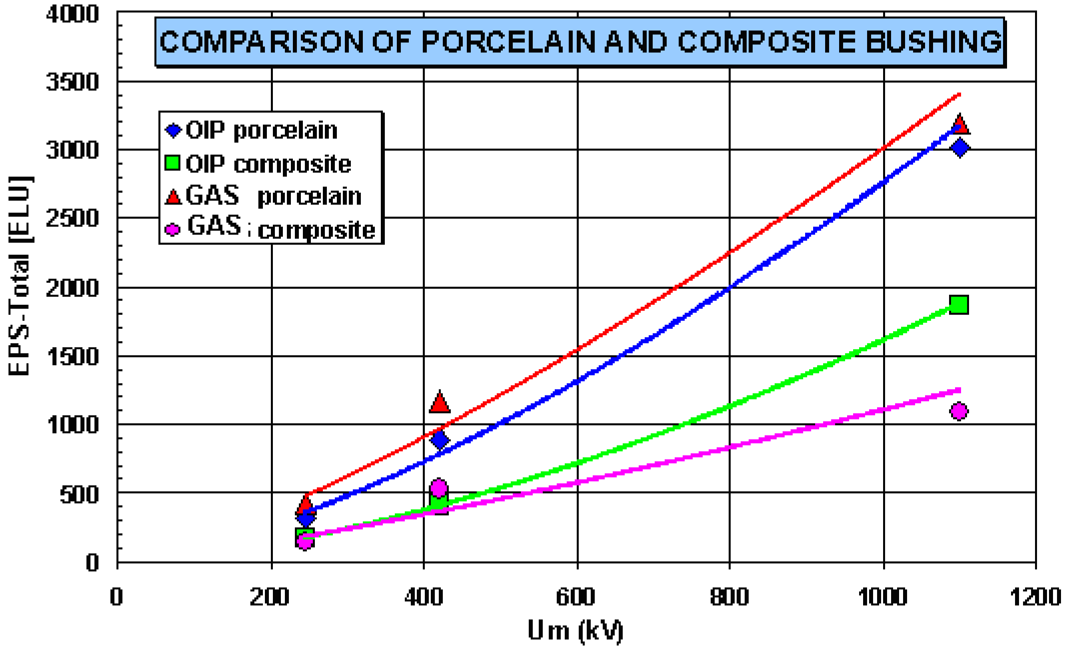


Figure 10-4: EPS value of different types of bushings, as a function of their voltage rating

As Figure 10-4 can be read with a "less is better" logic, composite technologies show, for all voltage ratings, environmental impacts that are well below those of porcelain. This is due to their lower material content and to the management of end-of-life where rubber and plastics can be recycled by incineration with a very important recovery of energy, thus avoiding impacts. For polymeric types, the slope of the curve with increasing voltage ratings is quite low because of the relatively light weight of insulating parts and the predominant presence of fully recyclable metals. On the other hand, porcelain bushings, whose weight increases rapidly with voltage, have a much steeper trend and their environmental profiles suffer as a result. It should be noted that maintenance operations during service, e.g. due to pollution were neglected in the assessment.

10.2 Economical evaluation

A comparative Life Cycle Cost analysis (LCC) was carried out according to the general principles specified in the IEC Guidelines IEC 60300-3-3 (2004-07): Dependability management - Part 3-3: Application guide - Life cycle costing. The method is aimed at estimating and optimising the costs of equipments and systems on a lifecycle approach, i.e. taking into consideration not only the CAPEX (capital expenses) but also the OPEX (operation expenses) over the entire lifecycle.

The general approach considers the following phases: conceptualisation, design, development, manufacturing, transport, installation, operation, maintenance and end-of-life management. Depending upon the perspectives of interest, the evaluation can be carried out considering part of the costs; in particular, in the view of an equipment user, the following cost categories can be taken into consideration:

$$LCC = CINV + CAU + CPM + COP + CUN + CEL$$

where:

- LCC : life cycle cost considered
- $CINV$: investment cost
- CAU : additional costs for the user (costs of the user personnel to deal with the installation, commissioning and training)
- CPM : costs of planned maintenance
- COP : costs of operation (joule and additional losses)
- CUN : costs of unavailability (planned and unplanned)
- CEL : costs for the end-of-life management

In the streamlined, comparative case used here, the LCC calculation is reduced to the following:

$$LCC = CINV + CPM$$

An example of cost comparison over a 30 years life of a 420 kV porcelain bushing and composite bushing solution having the same profile and length is made in **Figure 10-5**. The assumption is made that, in the environment considered, porcelain is to be maintained, while composite can be exploited without maintenance. The cost of maintenance depends on the maintenance frequency and solution and for the porcelain case three approaches are presented: RTV coating with renewal every 10 years, silicon greasing with re-coating every 18 months and washing every three months. Whilst many variables and options can influence the calculation, a qualitative conclusion can be derived from this exercise in that the silicon housing is the least costly solution followed by porcelain with RTV, washing and greasing.

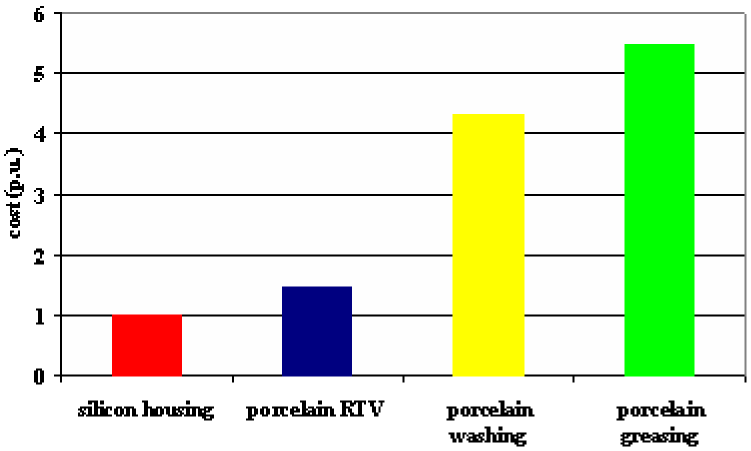


Figure 10-5: Example of life cost for composite and porcelain with different maintenance procedures.

10.3 References

[10.1] UNI EN ISO 14040 – Environmental management - Life cycle assessment - Principle and Framework, 1997

[10.2] UNI EN ISO 14041 – Goal and Scope Definition and Inventory Analysis, 1998

[10.3] UNI EN ISO 14042 – Life Cycle Impact Assessment, 2000

[10.4] UNI EN ISO 14043 – Interpretation, 2000

11 UHV AC AND DC

11.1 General

Studies of the external insulation for UHV equipment started already in the last century [11.1], [11.2], [11.3] and the electrical design of the external insulation for UHV equipment is dominated by the switching overvoltage and pollution requirements [11.1],[11.2],[11.4],[11.8]. Technical and economical aspects have to be considered for the development of UHV equipment and design optimization implies a minimization of the dimensions for reasons of cost and manufacturability, whilst complying with the specified electrical & mechanical requirements [11.1], [11.2] [11.5]. The required insulator length for UHV equipment can be of the order of 10 m or more and the adoption of composite insulators may contribute to optimisation of the insulator lengths due to their good performance under pollution [11.6]. In several HVDC projects in China composite insulators with 75% creepage distance compared to porcelain are in operation since several years and show excellent performance [11.7], [11.8].

To obtain more precise indications of the advantages of composites, reference is made as an example to a specific application: bushings. It is pointed out that the purpose of the example is to give qualitative indications of important aspects and is outside of the scope of the present report to give general design rules.

11.2 Bushings

Calculations of the dimensional requirements dictated by switching impulse (SI) and pollution were made under the simplified assumptions in [11.1] and [11.2] and are reported in Figure 11-1, **Figure 11-2** and **Figure 11-3**. The solid lines indicate the lengths required to comply with minimum and maximum level of switching impulses prescribed by the Standard for AC bushings with Um up to 800 kV [11.9] and those predicted for UHV. The dotted lines indicate the lengths required to comply with pollution requirements for very light (PVL), light (PL), medium (PM), heavy (PH) and very heavy (PVH) contamination [11.10]. The pollution requirements are evaluated considering typical bushing diameters and a creepage factor of 4 [11.1], [11.2].

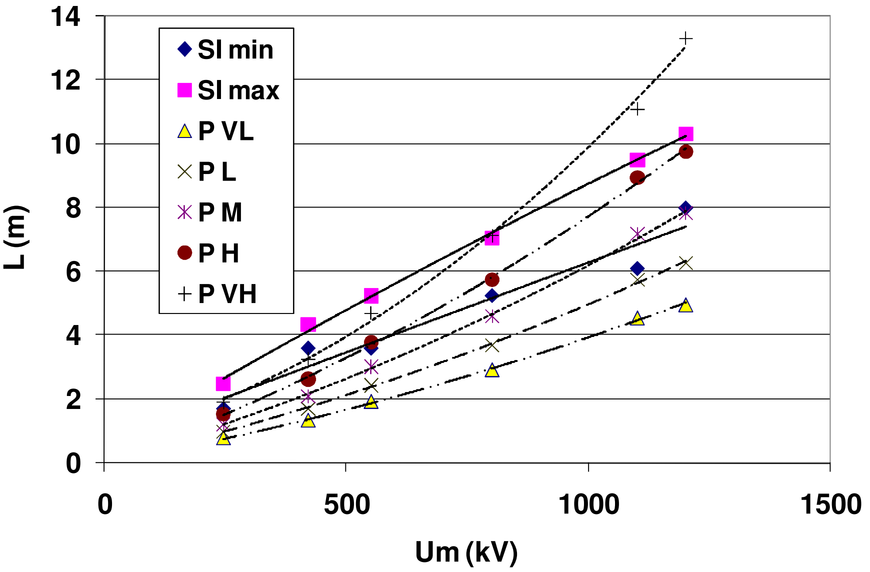


Figure 11-1: AC bushings: Arcing distance as a function of system voltage. Porcelain insulators with Creepage Factor=4.

As shown in Figure 11-1, SI generally dominates the design for AC, even when considering the heavy pollution requirements for insulators of large diameter. The predominance of SI would be even greater if composite housings were adopted, with a better pollution performance than porcelain e.g. with a required creepage distance of about 80% of that needed for ceramic insulators and reduced influence of the diameter.

The same evaluations are made in **Figure 11-2** for DC [11.1], [11.2] considering SI overvoltages of 2.1 p.u. since SI levels are not standardized for DC [11.11]. For pollution performance, since the required specific creepage distances are not standardized, reference was made to [11.12] for the evaluations suggesting that, for DC, pollution is always the dominating design stress. Taking into account existing constraints in length (of about 10 m based on manufacturing and transportation limits), only light to medium contamination bushing may be today produced for UHV DC with porcelain housings.

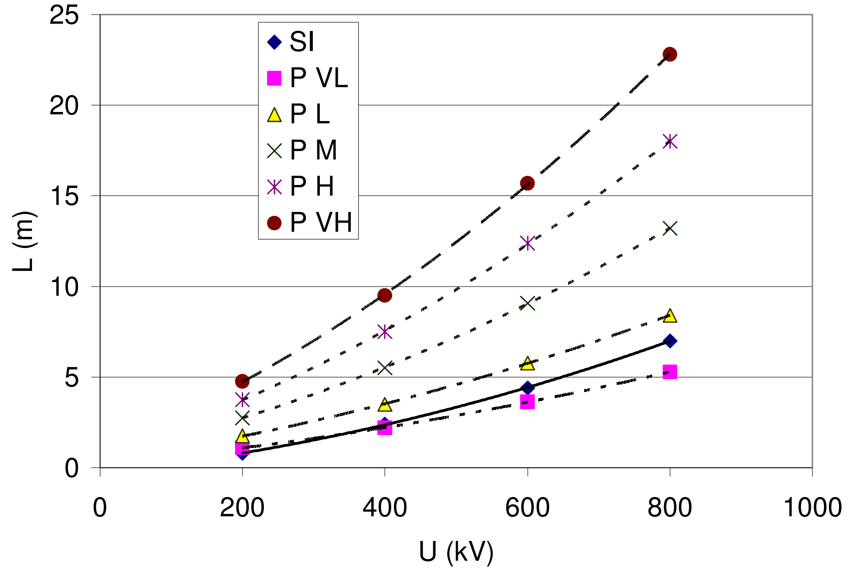


Figure 11-2: DC bushings: Arcing distance as a function of system voltage Porcelain insulators with Creepage Factor=4.

By adopting composite housings, requiring less specific creepage distance and with a limited influence of the housing diameter it is possible to realize UHV bushings for medium to heavy pollution conditions, as shown in **Figure 11-3**. The above considerations point out that the development of the composite solution is essential for efficient UHV development and confirm the need to further investigate, agree and standardize the performance of composite solutions.

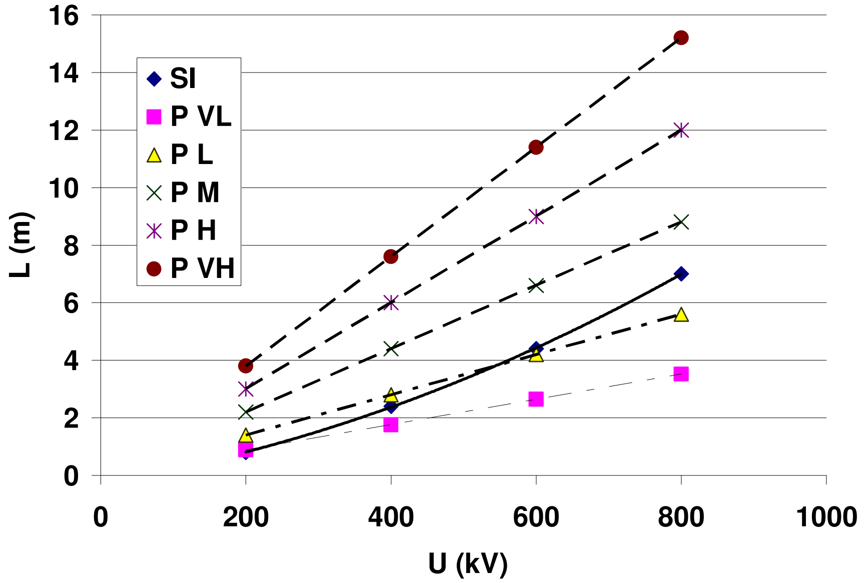


Figure 11-3: DC bushings: Arcing distance as a function of system voltage. Composite insulators with a creepage factor =4.

11.3 Examples of applications of composites in the UHV range

11.3.1 UHV DC equipment

UHV DC transmission systems over distances of up to 2000 km are currently being planned or constructed for various projects in India and China. Manufacturers of HVDC equipment have developed components for 800 kV DC, e.g. converter transformers composite bushings, wall bushings, surge arresters, DC bypass circuit-breakers and disconnectors (**Figure 11-4**). The long term performance of the developed components has been verified in test stations as can be seen in **Figure 11-4**5).

Severe constraints such as installation at altitudes of more than 1000 m above sea level, high pollution degrees, high wind loads, transport limitations and seismic loads were considered in design and, c Considering all these aspects, almost all equipment was designed with composite solutions.

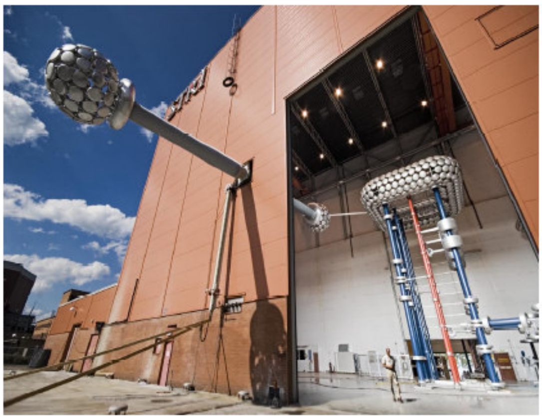
a) bypass circuit-breaker

b) disconnector

c) transformer bushing

Figure 11-4: composite insulators for 800 kV DC equipment [11.8][11.13]

a): General view of different apparatus



b) Wall bushing

c) Wall and transformer bushing

Figure 11-5: 800 kV DC apparatus under long duration tests [11.14]

11.3.2 UHVC AC equipment

New UHV AC projects are developing in China and India and composite solutions are going to be widely applied as shown by the example in **Figure 11-6** and **Figure 11-7**.

Figure 11-6: Fig, 6 1100 kV circuit-breaker with composite bushings [11.15]

Figure 11-7: GIS module equipped with composite bushings [11.16].

Figure 11-8 shows an example of application of 800 kV SF_6 insulated current transformer in Brazil (source Furnas)

Figure 11-8: 800 kV current transformer installed in Brazil

11.4 References

[11.1] P. Cardano, A.Pigini, G.Testin "Design and testing of UHV bushing". Paper to be presented at ISH South Africa 2009

[11.2] P. Cardano, G. Testin, L. Perego, L. Crocco, A. Pigini "UHV bushings: developments and experience" World Congress& Exhibition on insulators, arresters and bushings - Crete 2009

[11.3] W. Lampe, D. Wu, “Dimensioning outdoor insulation for ±800 kV transmission”, CIGRÉ SC 33 Colloquium, 2.9, New Delhi, 1993
[11.4] D. Wu, U. Åström, V. Lescale, “800 kV DC: External insulation, insulation co-ordination, test levels” IEC/ CIGRÉ UHV Symposium, Beijing, 2007
[11.5] G. Asplund, U. Åström, D. Wu, “Keynote Lecture: Advantage of HVDC transmission at 800 kV” 14th ISH, Beijing, 2005
[11.6] D. Wu, U. Åström, Z. Su, W. Ma, ” Critical issues on the dimensioning of external insulation for UHVDC converter stations” 2006 International Conference of UHV Transmission Technology, Beijing, 2006
[11.7] U. Åström, B. Almgren, D. Wu, “Outdoor insulation design for the Three Gorges-Changzhou ±500 kV HVDC Project”, Proceedings of International Conference on Power Systems, Wuhan, 2001
[11.8] M.Haeusler, H. Huang, K. Papp „Design and testing of 800 kV HVDC equipment“CIGRE session paper B4-115, Paris, 2008
[11.9] IEC 60137 Ed. 6.0 2008 “Insulated bushings for alternating voltages above 1 000 V”
[11.10] IEC 60815 - 2008: Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 2: Ceramic and glass insulators for AC systems
[11.11] IEC 62199 2005 “Bushings for DC application “
[11.12] A. Pigini, AC Britten, C. Engelbrecht “Development of guidelines for the selection of insulators with respect to pollution for EHV- UHV DC: state of the art and research needs” CIGRE 2008
[11.13] M. Haeusler, “Equipment design for the Yunnan Guangdong UHV DC Project”, Second IEC CIGRE Int. Symposium on Standards for UHV, New Delhi 2009
[111.4] A. Kumar, D. Wu, R. Hartings, “Experience from first 800 kV HVDC test installation” International conference on Power systems (ICPS-2007), Bangalore, India, 12-14 Dec. 2007
[11.15] R. Goehler, D. Helbig et.al. „1200 kV AC substations: Full-scale products and integrated solutions”, Second IEC CIGRE Int. Symposium on Standards for UHV, New Delhi 2009
[11.16] W. Holaus, U. Riechert, D. Sologuren, U. Krüsi “Development and testing of 1100 kV GIS” Second IEC CIGRE Int. Symposium on Standards for UHV, New Delhi 2009

ANNEX A: THE SPECIFIC CASE OF SURGE ARRESTERS

ANNEX A-1: DESIGN PRINCIPLES OF POLYMER HOUSED HV ARRESTERS

A-1.1 Introduction

"HV" actually ranges from Um = 72.5 kV up to Um = 800 kV (higher levels are currently emerging). This wide range may be further sub-divided into two parts where different philosophies govern the decision process for an arrester purchase. In the voltage levels up to Um = 300 kV, i.e. the lower transmission and the sub-transmission levels, in most cases just technical standard requirements apply. There is only little need for special features like extra-high mechanical strength or safety considerations. These are the voltage levels of standard applications, where more and more the same criteria as in distribution systems are applied and not too much time or money is spent to optimize the arrester layout for a particular location. It is the domain of "low cost" (in its positive meaning) arresters. For the EHV and emerging UHV levels, U_m = 360 kV and more, requirements especially on mechanical characteristics plays an increasingly important role, which cannot easily be fulfilled by the "low cost" designs. Further, users are less willing to take any risk of possible arrester failures. The electrical and mechanical requirements on these arresters are often evaluated by system studies, and in many cases the user has detailed knowledge and information about the system configuration and clear ideas about the optimal arrester for his particular application. This is the domain of "special feature" arresters. Both types of arresters are available today in polymer housed design [A-1] to [A-10].

A-1.2 The mechanical supporting structure

Figure A.1 gives a classification of the mechanical design principles of arresters, suggested in [A-10], which is not only limited to polymer housed arresters. All new makes of arresters that have appeared on the market in the meantime can be assigned to one of the suggested classes. According to this suggestion a differentiation is made between designs using a hollow core insulator with an intentionally enclosed gas volume and such designs, where the housing is put onto the metal-oxide (MO) column without any intentional internal gas volume. With respect to the polymer housed arresters, the mechanical designs can be characterized as follows:

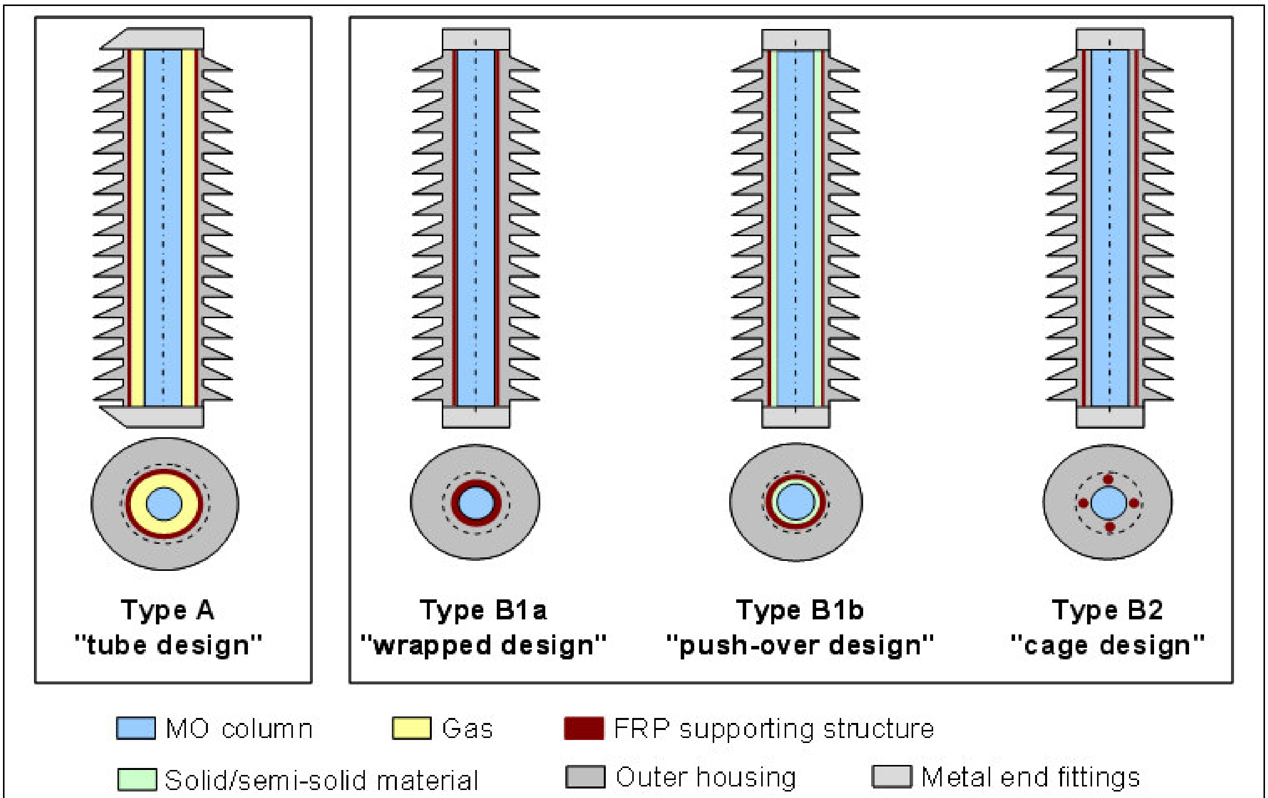
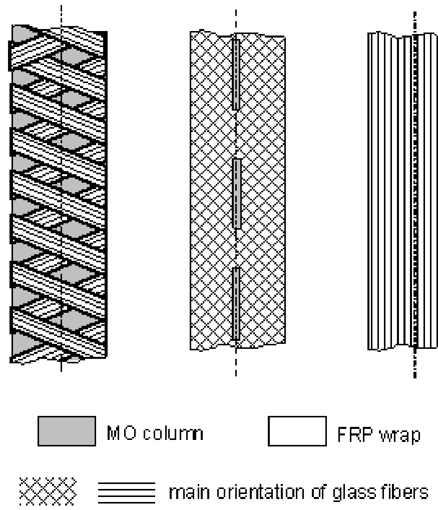


Figure A.1: Design variants of polymer housed surge arresters (according to [A-2-10])

- Type A ("tube design"): an arrester using a housing with an intended included gas volume. It must consequently have a sealing and a pressure relief system. The housing may be a "conventional" porcelain housing or a non-ceramic composite housing, formed e.g. from a tube of fibreglass reinforced plastic (FRP), which is covered by outer weather sheds. The outer weather sheds may be directly moulded to the tube or pushed over as individual parts in different possible ways.
- Type B: an arrester using a housing which is directly applied to the stack of MO resistors, without an intended gas volume included. This class may be subdivided into:
    - Type B1a ("wrapped design"): where the mechanically supporting part of the housing is formed by a wrapped FRP structure; this may be implemented by epoxy resin soaked glass rovings or pre-impregnated mats or bands that are wound around the MO stack and then cured in an oven. The resulting FRP structure may be open, totally closed or closed and weakened by slots which enable pressure relief under short-circuit conditions. Examples are shown in Figure A-2



Figur A-1: Examples of internal mechanical structures for Type B1a ("wrapped design") arresters [A-10]

    - Type B1b ("push-over design"): where the housing consists of a prefabricated FRP tube having a diameter slightly larger than that of the MO stack and which is pushed over the stack of MO resistors; the resulting small gap between MO resistors and FRP tube is then filled by some elastic material.
- Type B2 ("cage design"), where the stack of MO resistors is clamped by FRP loops or rods or bands (see Figure A-3) at extremely high mechanical tension forces; the MO resistors themselves thus act as part of the mechanically supporting structure, and the FRP elements form an open cage; the outer weather sheds have to be directly moulded to these modules, usually making use of silicone rubber. Main technical advantages of the cage designs are that they offer comparatively high mechanical strength combined with an inherently good short-circuit performance as no internal dangerous pressure can build up.

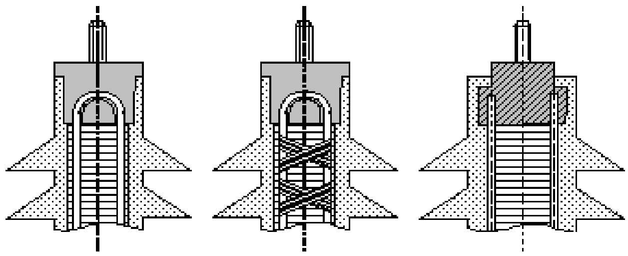
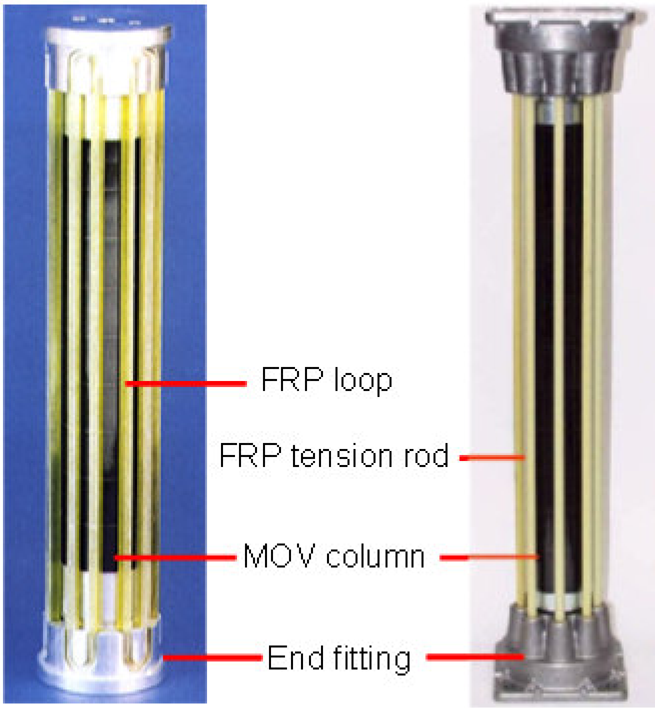


Figure A-2: Examples of internal mechanical structures for Type B2 ("cage design") arresters [A-10]



Left: loop design Right: rod design

Figure A-3: Internal mechanical structure of Type B2 arresters [A-10]

With regard to commercial aspects it is impossible to give any statement here on production cost, which greatly depends on the total manufactured quantities, the degree of automation and process optimization, the quality of the applied materials and the degree of type diversification etc. However, it can be noticed that the Type B arrester in general constitutes the most economical way to produce an arrester. At the same time it offers a technical performance, which in most cases ranks between comparable porcelain and polymer housed Type A arresters. The Type B arrester is therefore the typical "low cost" arrester as mentioned above, but not limited to distribution voltage levels. This is one of the reasons for the success of this design on the market.

A-1.3 Outer housing and sheds

As for the mechanical design, there are numerous possibilities to realize the outer housing and sheds. With regard to material, however, with only few exceptions there has been a clear tendency towards SiR (silicone rubber). All the other materials, such as EPDM (ethylene propylene diene copolymer), EPDM/SiR blends, EVA (ethylene vinyl acetate), which are widely used in distribution and may perform well there, are usually not being accepted in HV or EHV. Only SiR offers hydrophobicity which lasts for decades, and from its chemical structure it is inherently least sensitive to solar radiation, because its basic component – poly-dimethyl-siloxane – has bonding energies above the intrinsic energy of UV light, the main aging factor for polymeric materials.

For Type A arresters there has never been an alternative to SiR, for production as well as for performance reasons, since these arresters mostly belong to the family of "special feature" arresters, where traditionally "high-end" materials have been used. From a production point of view, the only way to cover a hollow core tube is by using SiR. One of the very first designs used an insulator with sheds from HTV (high temperature vulcanizing) SIR individually slipped over the FRP tube [A-2-4], but today's composite hollow core insulators are in the majority covered by a direct moulding process, using RTV (room temperature) SiR or LSR (liquid silicone rubber).

The same applies for the Type B2 arresters, which only can be covered by a direct moulding process. All common types of SiR can be found with the actual arresters of this design on the market.

Most alternatives exist for the Type B1 design, where the housing basically can be produced either by direct moulding or by pre-fabricated housings slipped over the modules. The latter concept offers highest flexibility in production [A-1], but special care is required for its implementation. Since most of the Type B1 designs do not have a smooth surface, a sealing material (e.g. a silicone compound) must be put between the internal parts and the outer housing. This has to be done in a way to ensure absolute freedom from internal voids, which would affect the long term performance (potential locations of partial discharges and moisture). Further, an appropriate sealing system at the end fittings must be provided.

A-1.4 References

[A-1] Arresters: Market Forces, Current Technologies & Future Directions - Part 1 of 2 – Distribution Arresters INMR November/December 2002, Volume 10, Number 6

[A-2] Arresters: Market Forces, Current Technologies & Future Directions - Part 1 of 2 – HV Arresters INMR January/February 2003, Volume 11, Number 1, pp. 22-44

[A-3] Torbjörn Skytt, Hans E. G. Gleimar Changing of the guard – Polymer replaces porcelain for surge arresters ABB Review 1/2002, pp. 43-47

[A-4] V. Hinrichsen, H. Fien, H.-B. Solbach, J. Priebe - Metal Oxide Surge Arresters with Composite Hollow Insulators for High-Voltage Systems CIGRÉ 1994 Session, 28 August - 3 September 1994, Paris, paper 33-203

[A-5] K. Steinfeld, B. Kruska, W. Welsch Manufacturing and Application of Cage Design High Voltage Metal Oxide Surge Arresters - XIIIth International Symposium on high Voltage Engineering (ISH), Delft/Netherlands, August 25 to 29, 2003 - Proceedings: Millpress, Rotterdam, ISBN 90-77017-79-8

[A-6] Walter Schmidt - New POLIM medium-voltage surge arresters with silicone insulation ABB Review 2-96

[A-7] IEC 60099-4, Ed. 1.2, 2001-12 Surge arresters – Part 4: Metal-oxide surge arresters without gaps for AC systems

[A-8] Volker Hinrichsen: Using High-Voltage Polymer Housed Surge Arresters as Post Insulators CIGRÉ conference 2000, Paris, Contribution to Group 33, Pref. Subj. 1, Question 2.2

[A-9] Volker Hinrichsen: Metal-Oxide Surge Arresters – Fundamentals; Siemens AG, 1st Edition 2001

[A-10] V. Hinrichsen,"Latest Designs and Service Experience with Station-Class Polymer Housed Surge Arresters INMR World Congress & Exhibition, Marbella, Spain, 2003

ANNEX A-2: MECHANICAL INTERACTIONS: THE SURGE ARRESTER CASE

The IEC surge arrester committee (IEC TC37 MT4) has considered the adoption of new definitions and test methods for mechanical loads for the next revision of the arrester standard, IEC 60099-4, Edition 2.2, rather than to use those already established in IEC 61462 for hollow-core insulators. Main reasons for this are as follows (partly cited from the introductory note of document IEC 37/345/CDV [A-11]):

There are many different designs of polymer-housed arresters on the market, as analysed in Chapter 2. Most modern polymer housed arrester designs are such, with a housing directly attached to the stack of metal-oxide resistors, and only in rare cases, where high requirements on mechanical strength and short-circuit performance exist, composite hollow core insulators are used. For many arrester designs, the internal components, including the metal-oxide resistors, form an integrated part of the arrester and thus play an important role in determining the mechanical performance of the complete arrester. IEC 61462, on the other hand, does not consider the components inside the composite hollow insulator. The definitions and procedures of IEC 61462 are therefore in most cases not applicable. The arrester standard IEC 60099-4 [A-12] is an apparatus standard and thus must consider the complete design, not only the insulating housing. The approach was to create a standard valid for all designs and not to consider any exception for particular designs (e.g. with hollow core insulators) [A-13], [A-14], [A-15].

For surge arresters, mechanical loads are defined as follows (see also Fig. A-5):
The "specified long term load" (SLL) is, per definition, a "force perpendicular to the longitudinal axis of an arrester, allowed to be continuously applied during service without causing any mechanical damage to the arrester".
As well, the "specified short-term load" (SSL) is the "greatest force perpendicular to the longitudinal axis of an arrester, allowed to be applied during service for short periods and for relatively rare events (for example, short-circuit current loads and extreme wind gusts) without causing any mechanical damage to the arrester"

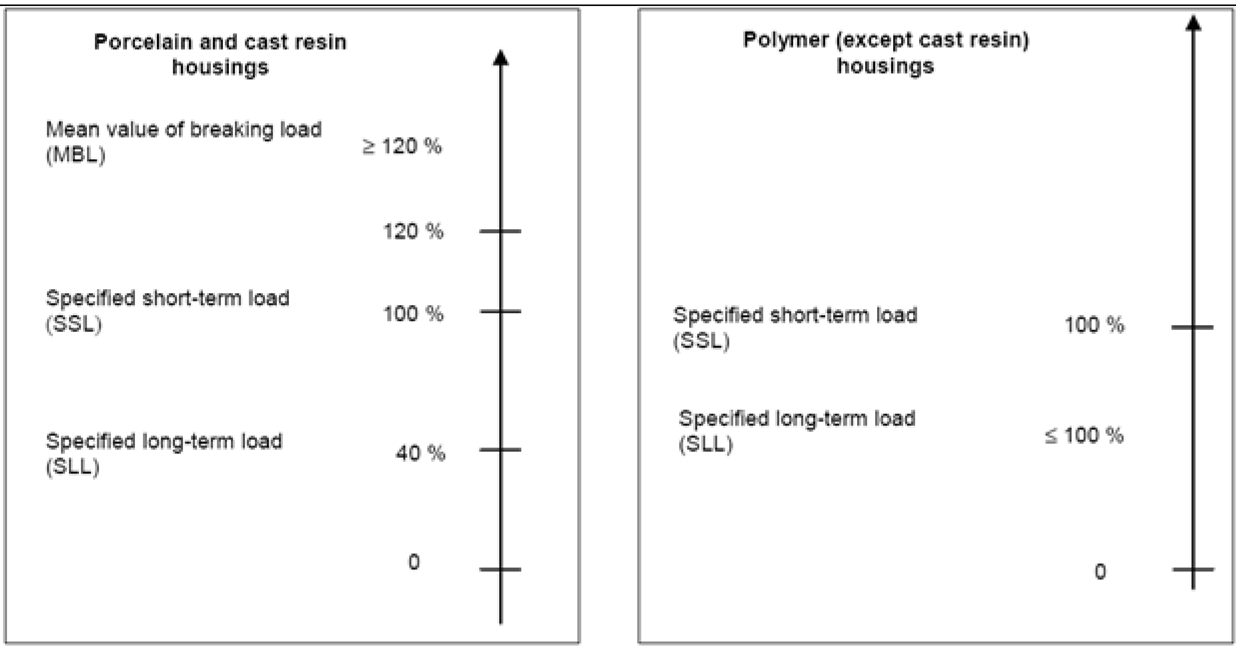


Figure A-5: Mechanical loads as defined for surge arresters in [A-12]

In particular, a specified long term load SLL and specified short-term load SSL as already adopted for porcelain housing arresters have been introduced.

It is difficult to find common acceptance criteria based purely on mechanical loading tests, except when obvious breaking occurs. It was recognized that moisture ingress has been one of the prevalent causes of polymer-housed arrester failures in the past, and it was therefore considered appropriate to use a moisture ingress test as a mean of evaluating the arrester after application of mechanical loading. Furthermore, to limit the number of new tests, moisture ingress tests and mechanical tests have been combined, instead of having them as independent and separate tests.

A cyclic test for taller arresters (arresters for system voltages > 52 kV) considering the features of most arrester designs has been seen as more representative for real service stresses than a static bending test. Surge arresters are subjected to a number of different mechanical loads in service. The direction and amplitude of the loads vary. A static bending test, therefore, is not representative for all realistic loads in service. As arresters usually do not carry any load (different from, e.g., post insulators) they are often of rather weak mechanical design. But if a manufacturer declares a maximum continuous load rating for an arrester, then it is expected that the arrester can withstand this load even if it varies dynamically due to environmental or other effects.

Much more important is the fact that many arrester designs with polymeric housings are more or less flexible. Subjecting the arrester, in a cyclic way, to maximum continuous load specified by the manufacturer may result in significant deflection which in turn may affect the moisture ingress probability and/or jeopardise the mechanical integrity of the metal-oxide blocks, which are part of the mechanically supporting structure.

Furthermore, the maximum short-term load that can be applied without breaking may be significantly reduced after the arrester has been subjected to a continuous load in a cyclic manner. A specified short-term load verified on new arresters not previously subjected to any test, therefore, may give a too optimistic value.

There is no simple way in general to check that a continuous load has damaged the arrester or not. Therefore, it was decided to introduce a cyclic load test. If the arrester passes 1000 cycles at the specified long term load (SLL) and subsequent water immersion and evaluation tests, it is considered likely that the arrester can continuously be subjected to the SLL. Furthermore, the SSL must be a load which the arrester could be subjected to even after many years in service. Thus it is considered necessary to specify that verification of SSL shall be carried out after the cyclic test in order to take into account some mechanical "ageing" of the arrester.

Leakage checks and partial discharge checks are foreseen after mechanical tests to assure that mechanical stress comply not only with the housing but also with the full arrester characteristics. It is therefore evident that all mechanical tests have to be performed on complete arrester units, not only on empty housings.

References

[A-11] IEC 37/345/CDV "IEC 60099-4 A2 Ed. 2.0: Surge arresters - Part 4: Metal-oxide surge arresters without gaps for AC systems – Revision of mechanical requirements and definitions" Date of circulation 2007-12-14

[A-12] IEC 60099-4, Ed. 2.1:2006: "Surge arresters – Part 4: Metal-oxide surge arresters without gaps for AC systems"

[A-13] V. Hinrichsen, H. Fien, H.-B. Solbach, J. Priebe „Metal Oxide Surge Arresters with Composite Hollow Insulators for High-Voltage Systems" Cigré 1994 Session, 28 August - 3 September 1994, Paris, Report 33-203

[A-14] Volker Hinrichsen „Metal-Oxide Surge Arresters – Fundamentals" Siemens AG, 1st Edition 2001

[A-15] V. Hinrichsen "Latest Designs and Service Experience with Station-Class Polymer Housed Surge Arresters" INMR World Conference on Insulators, Arresters and Bushings, Marbella (Málaga), Spain, November 16-19, 2003, Proceedings pp. 85-96

ANNEX A-3: SPECIFIC TESTS TO ASSESS THE SHORT CIRCUIT PERFORMANCE: THE SURGE ARRESTER CASE

Severe explosions of porcelain housed circuit-breakers, instrument transformers and surge arresters, have strongly promoted the development of polymer housing technology in the 1980s. in contrast with other equipment in the system, an arrester always bears a certain risk of being overloaded by excessive energy stress. Even if there is no systematic design weakness, the failure rate of surge arresters can virtually not be zero (though service experience has shown that for HV arresters it is actually very close to it). It has been a problem for porcelain housed arresters that the current through the internal arc that develops in the housing after an overload may be in a wide range from only few tens or hundreds of amperes up to 100 kA (r.m.s. value), with peak values of up to 2,6 times these values. It is difficult to design a porcelain housing with pressure relief devices that can handle all these scenarios in the same good manner.

The short-circuit performance of polymeric housings is usually better than that of porcelain housings. Following criteria have to be considered in case of an internal failure [A-16], [A-17]:

- the housing should not violently shatter;
- no internal parts should be violently ejected;
- the failed object should be able to self-extinguish in case of catching fire.

For the short-circuit performance, one must distinguish between housings with an included gas volume and housings, which are directly attached to the internal parts without any intended gas volume included. In the first case, a sealing system is required which on one hand ensures tightness against moisture ingress over the full design lifetime, and which on the other hand will quickly open in case of an internal failure in order to provide pressure relief. In the second case, the housing usually opens at any point, or at several points, and no internal pressure is built up or has to be released. Both basic mechanisms are depicted in Figures A-6 and A-7.

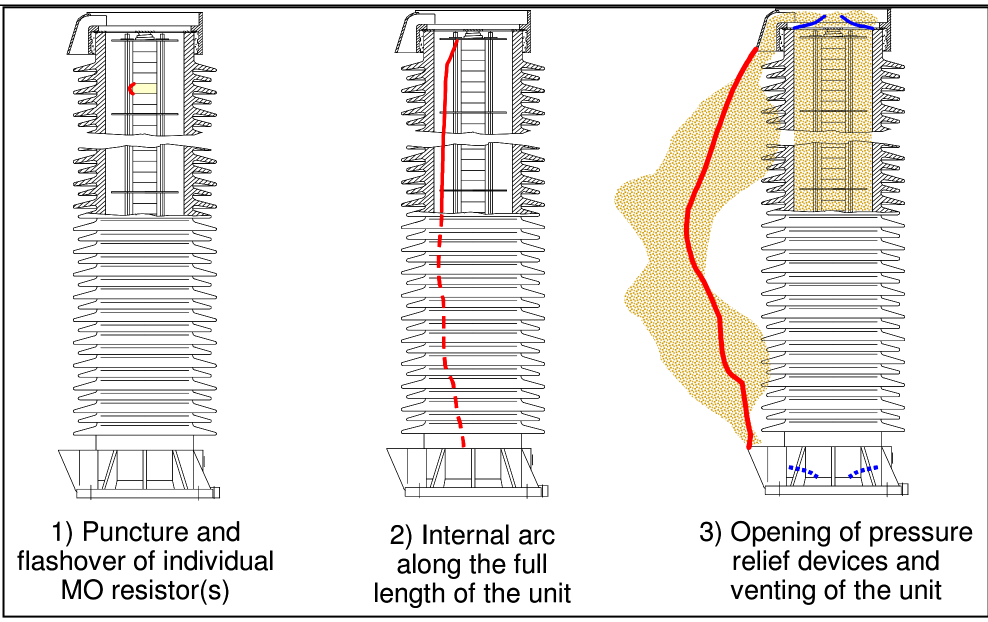


Figure A-6: Pressure relief of an arrester (porcelain of composite hollow core) housing with internal gas volume included [A-16]

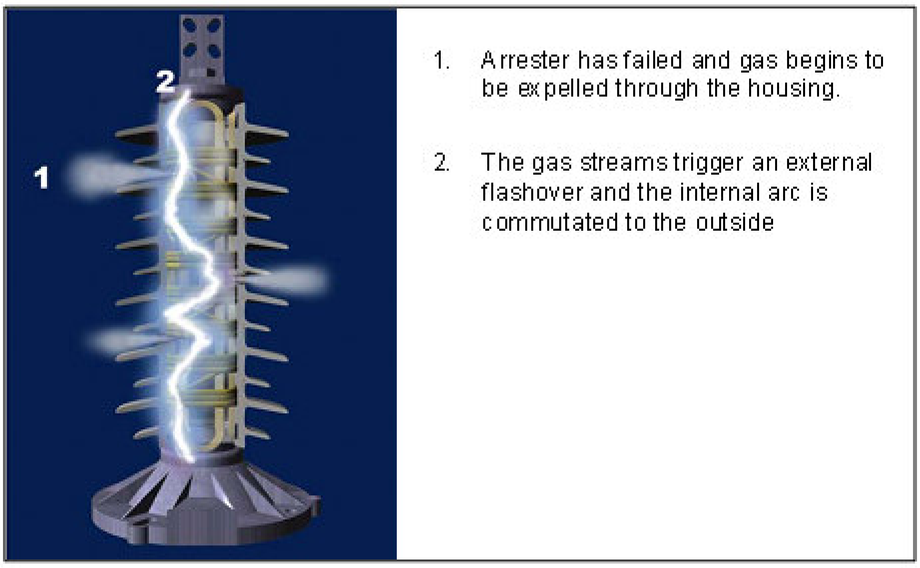


Figure A-7: Short-circuit behaviour of an arrester with polymeric housing without internal gas volume

Figures A-8 and Figure A-9 show typical examples of arresters after the high-current short-circuit test. It must be noted that even the sample of Figure A-8, right, has successfully passed the test according to the standard requirements: Porcelain may suffer a thermal, "secondary" breakdown, even if the internal pressure has successfully been relieved. This an other benefit of polymer housings, where this behaviour will not occur.

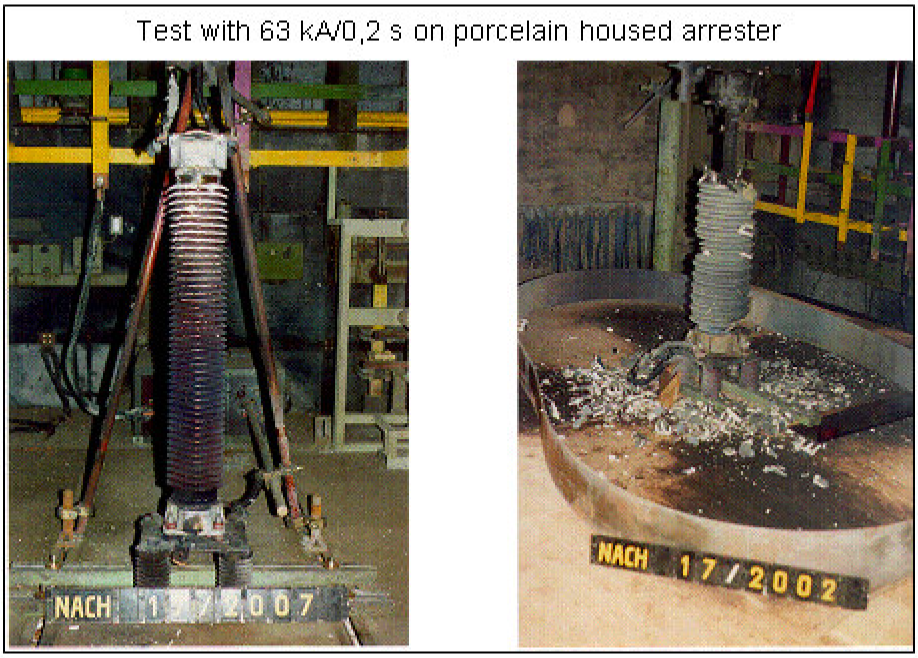


Figure A-8: Two porcelain housed arresters after high-current short-circuit tests [A-7.2.4]

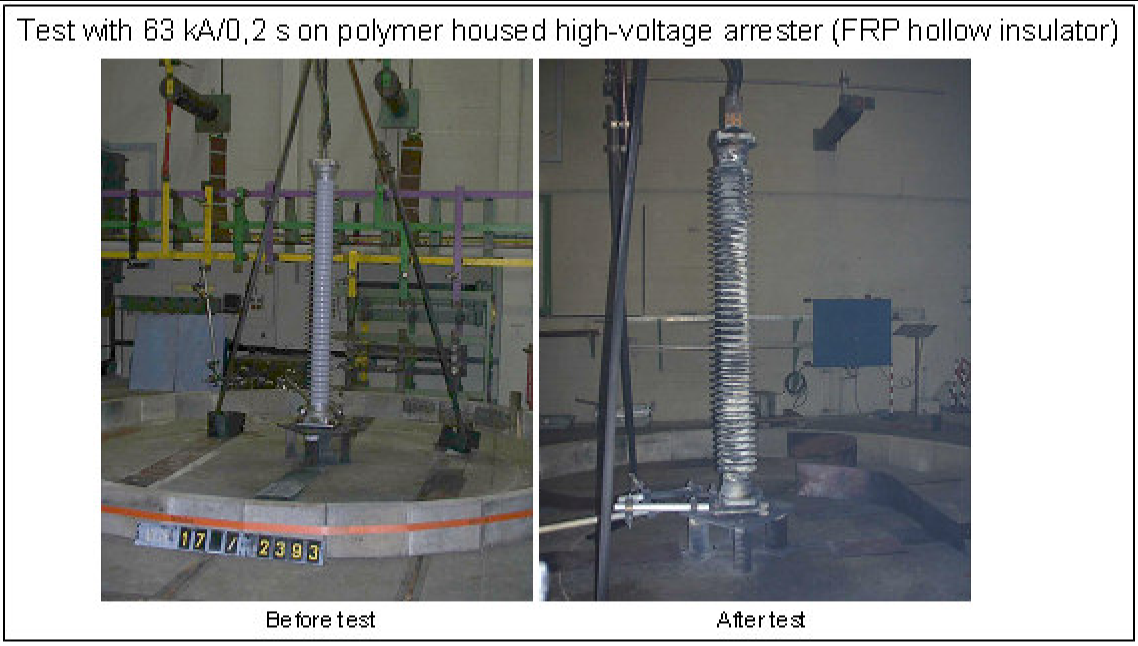
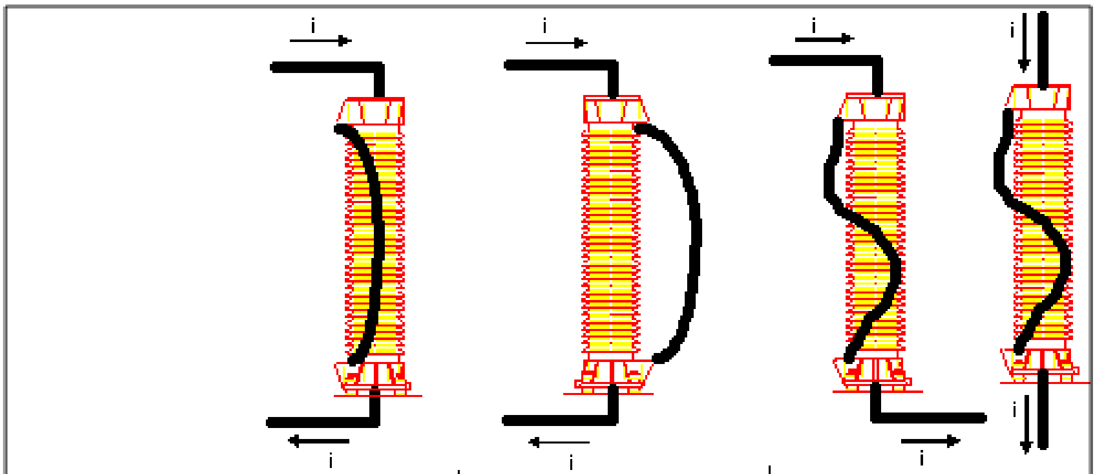


Figure A-9: Arrester with composite hollow-core insulator housing before and after a high-current short-circuit test

Figure A-10: Arrester with polymeric housing without internal gas volume after a high-current short-circuit test

Short-circuit tests can be problematic for housing lengths of more than about 1,5 m (as an example, only few test laboratories worldwide are able to run a short circuit test at up to currents of 80 kA rms value at a test voltage of more than 30 kV, which would be necessary to keep the long arc burning for some arrester designs). Therefore, many exceptions have been foreseen in the test procedure of the arrester standard IEC 60099-4, making the full test procedure difficult to understand for the user.

As the ability to self-extinguish any open fire in a given, short time is also an important requirement - not only for surge arresters – worst case test conditions with regard to this aspect have to be specified. The way the conductors are arranged is of importance here (as well as in real service), as this will have impact on the movement of the burning arc. Different possibilities are shown in Figure A-11



Porcelain	worst case	most favorable case	neutral case
Polymer (with gas volume included)	favorable case	most favorable case	worst case
Polymer (without gas volume included)	most favorable cases		worst case

Figure A-11: Impact of conductor arrangement in the short-circuit test on the movement of the arc and the short-circuit performance of an arrester

References

[A-16] V. Hinrichsen "Latest Designs and Service Experience with Station-Class Polymer Housed Surge Arresters" INMR World Conference on Insulators, Arresters and Bushings, Marbella (Málaga), Spain, November 16-19, 2003, Proceedings pp. 85-96

[A-17] R.P.P. Smeets, H. Barts, W.A.Van der Linden, L.Stenström "Modern ZNO Surge Arresters under Short-Circuit Current Stresses: Test Experiences and Critical Review of the IEC Standard" Cigré 2004 Session, 30 August - 3 September 2004, Paris, Report A3-105