Analysis of the possibilities of using dielectric foam in the construction of composite high voltage post-insulators

T Mączka, G Paściak, A Jarski, M Piątek,
Electrotechnical Institute Division of Electrotechnology and Materials Science
M. Sklodowskiej-Curie 55/61
50-369 Wroclaw, POLAND
E-mail: t.maczka@iel.wroc.pl

Abstract. This paper presents the construction and basic performance parameters of the innovative tubular construction of high voltage composite insulator filled with the lightweight foamed electroinsulating material. The possibility of using of the commercially available expanding foams for preparing the lightweight foamed dielectric materials was analysed. The expanding foams of silicone RTV and compositions based on epoxy resin and LSR silicone were taken into account. The lightweight foamed dielectric materials were prepared according to the own foaming technology. In this work the experimental results on the use of the selected foams for the preparing of the lightweight filling materials to the tubular structure of composite insulator of 110 kV are presented.

1. Introduction
For years the market of high voltage post-insulators line and traction (outdoor and indoor) is entirely occupied by ceramic insulators. They are characteristic by the high specific weight (approx. 2500 kg/m$^3$) of the porcelain cores (rods) and sheaths of the insulator, and by the need of use of massive mounting and protective hardware. In addition, ceramic insulators are very sensitive to operating conditions, in particular they are low resistant to mechanical impact and thermal shocks that occur, eg. during surface discharge, as a consequence of short circuits and/or surges in the power system [1,2].

There are also composite high voltage post-insulators composed of a fully filled cylindrical core made of mineral (sometimes organic) fibers glued together with the use of an organic binder (typically epoxy resin). In this case on the core, whose function is to transfer various kinds of mechanical loads (bending, stretching, torsion, compression), the sheath of an elastomeric silicone material is applied. According to the authors [1-4], composite insulators with the outer shield made of silicone elastomer is a better option compared to porcelain insulators because they are more resistant to dirt (high hydrophobicity and the ability to self-cleaning reduces the need for periodic cleaning of insulators). The risk of mechanical damage of composite insulator during transport, assembly and maintenance as well as in the case of emergency (thermal effect of electric arc) is also reduced. Composite insulators with fully filled core have slightly lower weight compared to their counterparts ceramic.

The disadvantages of high voltage composite insulators include the lack of rigidity and a relatively large deflection during application of bending and/or compressive stress (insulators bend and reshape). They also undergo significant angle distortion (twisting) under a load of torque. Better stiffness, relatively low deflection and high torsional endurance have a composite high voltage post-insulators of tubular structure (composite hollow insulators).

---

1 t.maczka@iel.wroc.pl.
Insulators of tubular construction with a hollow core are suitable, for example for indoor use, where there are no sudden changes in temperature and are maintained above the dew point (in order to prevent condensation of water from the air in the closed space of the insulator thus to prevent the emergence of discharge on the inner surface of the tube). Composite tubular insulators are also commonly used as insulators with internal gas insulation and used as pressure lead-in bushings, (traction or transformer) insulators and as pressure protective insulation for high-voltage circuit breakers (GIS / GCB).

There are not known to the authors currently commercially available composite insulators of tubular construction filled with a dielectric of low density (not more than 1100 kg / m3). It was therefore decided to develop a new generation of composite high voltage post-insulators of tubular construction with an inner dielectric light filling whose structure is schematically shown in Figure 1.

![Figure 1. Composite high voltage post-insulators of tubular construction with an inner dielectric light fulfilment](image)

1 – bearing structure (tube) of insulator, 2 – light filling with dielectric foam, 3 - elastomeric sheath, 4 – fittings, 5 – link of glue, 6 – operating hole.

The essence of this design consists in the fact that the interior of the glass-epoxy insulator support tube is tightly filled with expanding foam of dielectric material having a density of 250-500 kg/m3. Due to the bearing structure in a form of suitable composite tube these insulators are characterized by high rigidity and good mechanical strength to tensile, bending, compression and torsion. On the other hand elastomeric sheath provides the appropriate creepage, thus and dielectric strength under severe outdoor operating conditions (external) in all environmental zones.

It is believed that a properly made lightweight dielectric filling, eg. foam with high adhesion to both the epoxy tube and metal fittings, fully fulfill the interior of the bearing structure of insulator (tube), thus eliminating the possibility of collection of the moisture inside it and prevent the formation of discharge (creep lines) on the inner surface of the tube.

It is assumed that a composite post insulator with a rated voltage of 110 kV will have the following parameters:

- creepage distance of at least 3813 mm
- striking distance of at least 1075mm,
- rated bending load (SCL) at least 16 kN,
- deflection at a bending force of 4 kN at most 8 mm,

and that they will have to withstand lightning impulse voltage (dry) of more than 575 kV and withstand voltage in rain of more than 275 kV (AC, 50 Hz, effective value).
Preliminary analysis of market showed the economic viability of the planned investment. Developed insulator should ensure trouble-free operation under operating conditions for all environmental zones and possibly optimally meet the (often contradictory) requirements: electrical, mechanical and economical. It is believed that the newly developed product will be 30% lighter than ceramic insulator with the same electromechanical parameters and about twice cheaper. The planned product is to meet outlines and standard requirements for these type of products [5-12].

2. The selected dielectric foams and preliminary research

Choosing the foams for filling the supporting structure of the insulator (tube) you are to take into account material and technological properties such as a high degree of expansion giving the possibility to obtain closed-pore structures with a density of less than 500 kg m $^{-3}$ and good adhesion to both the fitting and the composite tube core. Not without significance was also uncomplicated way of preparing the composition, the relative low viscosity of components, before and after mixing, the possibility of expansion at room temperature and a short (but not violent) foaming time. What else, material have to be non-combustible or slightly combustible at normal ambient conditions (oxygen index at least 23%) with electrical resistivity of at least 1011 $\Omega$m resistant to temperature changes and thermal shocks $-35 / + 50 \, (\Delta T \geq 85K)$ and of E temperature class of insulation (not lower than 120$^\circ$C), resistant to moisture diffusion (in case of lack of tightness of the elastomer-fitting-composite triple point or damage of supporting structure of an insulator (a tube). Not without significance is also the availability of material on the market and its price.

### Table 1. Some physical properties of dielectric foams selected for testing

| Symbol of Material | Type of Material | Characteristics |
|--------------------|------------------|-----------------|
| P1-EPA             | Expanding epoxy foam | Bulk density 220 kg/m$^3$
|                    |                  | Oxygen index 21% |
|                    |                  | The resistivity $> 10^{13} \, \Omega$m, |
|                    |                  | Dielectric loss factor $<0.005$ |
|                    |                  | Electric strength $> 45 \, kV/cm$, |
|                    |                  | The temperature of continuous operation 120$^\circ$C, |
|                    |                  | Colour: white, |
|                    |                  | Rigid foam, slightly elastic |
| P2-RTV             | Expanding foam based on RTV silicone | Bulk density 300 kg/m$^3$
|                    |                  | Oxygen index 30% |
|                    |                  | Resistivity $> 10^{12} \, \Omega$m, |
|                    |                  | Dielectric loss factor $<0.005$ |
|                    |                  | Electric strength $> 55 \, kV / cm$, |
|                    |                  | The temperature of continuous operation 140$^\circ$C, |
|                    |                  | Colour: gray, |
|                    |                  | Elastic foam, flexible |
| P3-RTV             | Expanding foam based on RTV silicone | Bulk density 320 kg /m$^3$
|                    |                  | Oxygen index 35% |
|                    |                  | Resistivity $> 10^{13} \, \Omega$m, |
|                    |                  | Dielectric loss factor $<0.005$ |
|                    |                  | Electric strength $> 60 \, kV / cm$, |
|                    |                  | The temperature of continuous operation 160$^\circ$C, |
|                    |                  | Colour: graphite, |
|                    |                  | Elastic foam, very flexible |
| P4-LSR             | Foam made of physically foamed LSR silicone | Bulk density 400 kg /m$^3$
|                    |                  | Oxygen index $\leq 35\%$ |
|                    |                  | Resistivity $> 10^{14} \, \Omega$m, |
|                    |                  | Dielectric loss factor $<0.005$ |
|                    |                  | Electric strength $> 65 \, kV / cm$, |
|                    |                  | The temperature of continuous operation 180$^\circ$C, |
|                    |                  | Colour: light gray, |
|                    |                  | Elastic foam, flexible |
After analyzing of the commercially available materials suitable for the production of dielectric foams, and after an initial determination of their basic material and technological properties the following ones were chosen for testing: a foaming epoxy resin; two types of RTV expansive foams, based on silicone; and the LSR foam obtained with the use of our own method of foaming of silicone. From the selected materials the samples of foams were made using free foaming method under normal ambient conditions. An example of the free foaming of the expanding foam of RTV (P2-RTV) silicone in the glass vessel is shown in Figure 2.

The foam samples were then tested for their suitability for use as light electrically insulating filling in high voltage post-insulators of tubular construction. The results are given in Table 1.

3. Technological trials to fulfill with foams the full-size models of isolators
In the first stage of the work the tests consisting in choosing optimum process parameters for foaming of material so as to obtain as homogeneous foam as possible with a density of about 200-400 kg / m³, having a closed pore structure and a spherical pores 1-3 mm in diameters.
Trials of foaming were performed within the bearing structure of composite post insulator tube) having an inner diameter of 120 mm and a length of 1200 mm. In order to observe the process of foaming and the expanding of the material and the quality of fulfillment the interior of the tube was closed from both sides with the Plexiglas plates (plates were fasten with metal pins). The surfaces in contact with the foams were coated with the resolving agent. In the Plexiglas plates some operational openings were made, for filling and venting of expanding composition. Thus prepared closed tubes imitated prototypes of bearing structures of an insulator and were filled with selected foams.
The process of filling of tubes was performed in the horizontal position using a suitable amount of a composition prepared by a low pressure method. After filling the composition expanded the length of its body thus to form a homogeneous foam filling. In the process of foaming the insulator tube was slowly rotated around the long axis of symmetry making one rotation in approx. 5 sec. When it was found that the foam filled the entire space of the tube, the tube was put into a forced-air drier for a few hours at a temperature of 70°C. An example of the tube after heat conditioning and cooling to room temperature is shown in Figure 3.
Then the supporting insulator tubes (filled with dielectric foams) were cut to a nominal length and their outer surfaces cut to the size of fittings, using a standard technique of cutting. Next the processed and degreased surfaces of the outer ends of the insulator tube and the inner surfaces of the fittings were covered with a thin layer of epoxy adhesive. Then the carrier element of the insulator was push-mounted on -fittings and model of the insulator put into a drier and held at 70°C for about two hours in order to complete fixation of laminated structure.
For each dielectric foam, one full size model of an insulator (without elastomer sheaths) has been done, a sample of which is shown in Figure 4.

After the work proceeded to the end of technological stage the selected tests and checks were performed, in order to evaluate the suitability of the foams as a dielectric light fulfillment for high voltage insulators.

4. Research verification

4.1. Evaluation of the structure of foams and their adhesion to the structure of the tubular insulator

For the morphological evaluation of the foams, cylindrical samples, with a height of approx. 40 mm, were cut (with diamond saw) from the filled tubes perpendicular to the main axis and subjected to a visual examination.

Figure 5 shows a selection of images of samples taken during the assessment. During visual examination the quality of fillings and macroscopic structure of pores was also assessed. Furthermore the mechanical strength of foams was examined, especially at composite material–foam junctions. Also foam adhesion to the composite tube was checked, by pressing with a sharp knife.

Figure 3. The supporting insulator tube filled with P3-RTV foam.

Figure 4. Model of supporting element of composite 110 kV insulator.

Figure 5. Images of foam samples taken during the examination of their macroscopic structure and adhesion.
When assessing the foam structure, the observations were carried out using metallographic microscope Nikon ECLIPSE MA200 using optical measurement program NIS-Elments BR3.10, equipped with camera of DS-FI1 type. Microscopic examination was performed by light reflected from the surface of the foam method, at a magnification of 50x. Figure 6 shows this observation for the P3-RTV foam, taken in the form of a 3D image. Observations from organoleptic inspection and microscopic inspections of dielectric foams are summarized in Table 2.

![Figure 6. The 3D microscopic image of P3-RTV foam (side view, the scale of 0.10 - 1.00 mm).](image)

**Table 2.** Morphological evaluation of foams to fill the supporting structure of insulators

| Type of foam          | Structure                                                                 | Adhesion                                      | Remarks                                                                 |
|-----------------------|---------------------------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------------------|
| P1-EPA Expanding epoxy foam | Hard and rigid foam, rough to the touch, withstands a strong pressing of thumb, quite mechanically resistant. Very good foaming, density 250 kg / m³, at average. Rather uniform pore structure, most of spherical pores with a diameter less than 1.5 mm. In the cross-break was detected a single spherical cavities in length of 3 mm were detected. | Moderate adhesion to epoxy-glass composite (tubes). Using a sharp edge of the knife it can be easily removed. | Washing the composite before foaming with extraction petrol, and then with acetone improves adhesion. |
| P2-RTV Expanding foam based on RTV silicone | Foam flexible, soft, with a poor tear strength, under moderate thumb pressure cracks with tending to tear. Generally weak mechanically. Pores structure rather uniform. Well foamed density 320 kg / m³, at average. Most pores are spherical, less than 1.0 mm in diameter. In the cross-break a few uniformly distributed spherical pores (caverns) 2.5 mm in diameter were spotted. | Very good adhesion to the epoxy-glass composite (tubes). Using a sharp edge of the blade it can be easily separated, however it leaves a film on the composite surface, which can be removed only by scraping. | It does not require special preparation of the surface of the composite. |
| P3-RTV Expanding foam based on RTV silicone | Resilient foam, with moderate tear strength. Under strong thumb pressure splits locally. Generally weak mechanically. | Good adhesion to epoxy-glass composite (tube). Using a sharp edge of the blade it can be quite easily separated. It leaves a film | It does not require special preparation of the surface of the composite. |
4.2. Dye penetration test

Dye penetration test fall within the scope of the design qualification and is an essential structural and material test when verifying the quality of core of composite post-insulators, line and traction ones [5,14].

Dye penetration test was carried out according to section 9.4.1 of PN-EN 62217: 2013. For the dye penetration test, the 10 discs, 10 mm high, were cut from the supporting elements of an insulator model so as to the test specimens from them. The samples were then placed in a jar with steel beads flooded with dye 2-3 mm above the level of the beads. The test relied on visual inspection of the dye penetration through the upper edge of the samples and measuring the penetration of the dye (observation period up to 15 minutes). Dye penetration was also evaluated at the foam-composite tube contact. During the evaluation of dye penetration some photographic documentation of foams was made. Figure 7 shows the P1-EPA foam images taken during this test.

During the test, through any the foam samples, the dye did not penetrate a thoroughly, and there was no penetration of the dye to the upper edge of the sample at the foam-epoxy tube interface. Thus, in accordance with the evaluation criteria specified in the PN-EN 62217: 2013 section 9.4.1.2 must be recognized that the dielectric foams passed the test of dye penetration with a positive result.

4.3. Test for water diffusion

Due to the fact that they are not known to the authors standards for testing hollow insulators with filling, and the more with the light fulfillment as a dielectric foam, it was decided to subject the models of isolators to water diffusion test according to the procedure outlined in the standard [6]. Testing for diffusion of water also falls within the scope of the design qualification and is an essential structural and material test when verifying the quality of supporting element of composite insulators designed for lines and tractions [5, 14]. It should be noted that this test is designed for composite insulators with solid core. As for the dye penetration test, the test specimens in a form of 30 mm high discs were made from the supporting element of insulator models. The samples were boiled for 100 h
in deionized water containing 0.1% NaCl (in accordance with the guidelines added in BS EN 62217: 2013 standard, section 9.4.2.3).

Figure 8 shows a sample cut from the insulator model filled with P1-EPA foam, in an early stage of cooking (pre-exposing). As shown, the sample stay afloat (floats) in a volume of water. Also, samples of filled with foams P2-RTV and P3-RTV "floated" during cooking. This state was observed throughout the whole 100 hour period of exposure. When it comes to P4-LSR foam sample it dropped to the bottom of the vessel and throughout the time of exposure was only slightly raised by bubbles of boiling water. After cooking, the samples were removed from the vessel with boiling water and placed for 15 minutes in another container filled with tap water with an ambient temperature. The voltage test was to be carried out in 3 h after removal of samples from the cooking vessel.

![Figure 8](image1.png)

**Figure 8.** A sample with P1-EPA foam filling, in the early stage of cooking.

After 15 minutes of conditioning in tap water (with an ambient temperature), it was found that the P2-RTV and P3-RTV foam samples contracted and partially detached from the composite tube which illustrate examples of images in Figure 9.

![Figure 9](image2.png)

**Figure 9.** View a sample with P3-RTV foam filling, after test for diffusion of water.

It was also found that the pores in the P2-RTV and P3-RTV foams comprise macroscopic water. In view of these the facts, the verifying voltage test for P2-RTV and P3-RTV samples of foams was pointless.

Samples of the P1-EPA and P4-LSR foams (after exposure by cooking and conditioning in water with an ambient temperature) were designed to verifying voltage test. The scheme and view of measuring system is shown in Figure 10.

![Figure 10](image3.png)

**Figure 10.** The view and scheme of measuring system used in high-voltage test.

In accordance with the procedure specified in EN 62217: 2013 standard, section 9.4.2.4, directly before...
voltage trial the surfaces of the samples were dried with filter paper. The samples were then placed between electrodes and test voltage with a value of 12 kV (RMS, AC 50 Hz) was applied. Voltage test time was 60 seconds and was calculated from the moment of achievement of the required testing voltage. According to evaluation criteria (section 9.4.2.5 of the PN-EN 62217: 2013), while applying testing voltage any puncture or surface jump cannot occur. Also during the entire test, the leakage current cannot exceed 1 mA (RMS).

In the case of the sample filled with P1-EPA foam during the test voltage, while the required test voltage was attaining, the throughout puncture occurred, and a visible dark path (charring) appeared on the surface of the foam which shows the photograph in Figure 11.

![Figure 11. The view of the dark path (charring) at the surface of P1-EPA foam, after the voltage test.](image)

But for sample with P4-LSR foam filling, while attaining the required value of the test voltage, the current flowing through the sample exceeded 1 mA. After reaching the voltage of 12 kV the current flowing through the sample (leakage current) exceeded 30 mA and the trial was stopped. There was not fired path. Table 3 shows the water diffusion test results for the all tested dielectric foams.

| Lp | Type of foam | Leakage current mA | Voltage, kV | Observations | Evaluation |
|----|--------------|-------------------|-------------|--------------|------------|
| 1  | P1-EPA       | > 1,0             | 12,0        | Through breakdown, visible dark path (charring) | negative   |
| 2  | P2-RTV       | -                 | -           | Breakage of filling, macroscopic water in the pores of the foam | negative   |
| 3  | P3-RTV       | -                 | -           | Breakage of filling, macroscopic water in the pores of the foam | negative   |
| 4  | P4-LSR       | >>1,0             | 12,0        | Excessive leakage current | negative   |

In accordance with the evaluation criteria set out in the PN-EN 62217: 2013 section 9.4.2.5, none of the tested dielectric foams, intended as light fulfillment to the composite insulators of tube structure, passed the test for diffusion of water with positive result.
5. Summary
As a result of conceptual works, design and technological developments, the novel construction of high-voltage hollow composite insulator has been developed.

As electrical insulation foams to fill the supporting structure of the developed insulator it was decided to use the commercially available materials (epoxy resin foaming, two expansive foams based on RTV silicone and a foam obtained by our own method of foaming LSR silicone). For each of the selected material the technique of filling the interior of the tubular structure of the insulator with the expanding foam was developed.

On samples taken from the full-size models of insulators filled with the produced foams, the penetration of the dye and water diffusion tests, which verify [5, 12] the quality of core of composite line and traction insulators, have been performed. The evaluation found that all of the dielectric foams passed the test for dye penetration positively. In contrast, none of the foams received a positive assessment in testing for water diffusion.

In summary, the carried out research has shown that foams made of the selected materials, despite their high dielectric properties and process parameters should not be used as an electrical insulation for tubular (hollow) insulator. Contraindications to the use is a negative test result for diffusion of water, and this attempt is contained in the standards [5, 6, 12] and falls within the scope of design quality qualification.

Basing on previous experience, the carried out works and technical examinations it is anticipated that the tested materials may be suitable for fulfillment of insulation pipes that should meet the requirements of the standard [13].

As an electrically insulating light fulfillment to insulators of tubular construction suitable are silicone LSR, as shown by the work of the authors at issue in the patent [14], and relatively new materials which are silicone gels.

6. References
[1] Usa1 S., Karthika V. P., Edison Selvaraj D., Kiruba Sankar M., Dinesh Aravind C., 2012, International Journal of Latest Research in Science and Technology, 1 (3) 247-253
[2] Mazurek B., Mączka T., Gmitrzak A., 2000, Proceedings of The 6th International Conference on properties and Applications of Dielectric Materials, Xi’an, China
[3] Chavez J.L.F., INMR November/December 2003 11 (6) 30-34.
[4] Świerzyna Z., Paściak G., Mazurek B., Olejnik J., 2009, Materials Science-Poland, 27, 4/2.
[5] PN-EN 62231:2008, Composite station post insulators for substations with a.c. voltages greater than 1 000 V up to 245 kV – Definitions, test methods and acceptance criteria.
[6] PN-EN 62217:2013-6 Polymeric HV insulators for indoor and outdoor use – General definitions, test method and acceptance criteria.
[7] PN-EN 60071-1: 2008, Insulation co-ordination – Part 1: Definition, principles and rules.
[8] PN-EN 06303: 1998, Exposure of outdoor insulation to pollution and selection of insulators under polluted conditions.
[9] PN-IEC 815: 1998, Guide for the selection of insulators in respect of polluted conditions.
[10] PN-IEC 60273: 2003, characteristics of indoor and outdoor post insulators for systems with nominal voltages greater than 1 000 V.
[11] Polymer vs porcelain suspension insulator equivalence - what to use, 2004, http://www.hubbellpowersystems.com EU1205-HR (as at year 2015).
[12] PN-EN 61952:2010 Insulators for overhead lines – Composite line post insulators for A.C. systems with a nominal voltage greater than 1000 V
[13] PN-EN 60855:1999, Insulating foam-filled tubes and solid rods for live working.
[14] P.412376, 2015, Patent Application, T. Mączka, G. Paściak, M. Piątek, A. Jarski.

Acknowledgments
Authors gratefully acknowledge the financial support received from: Operational Programme Innovative Economy 2007-2013, Priority 1 Research and development of new technologies, Section 1.4 Support for special projects, POIG.01.04.00-00-150 / 13 "Innovative technology for composite insulators of the Electrotechnical Institute"