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Polymers as Core Materials in Power Engineering

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A brief overview on the growing impact of polymers, in their different forms, playing a critical role in the power transmission and distribution is presented. The selection criteria of conventional and specialty polymers as matrix material in power devices depends on their specific properties and the ability to mix with property enhancing additives under passive or active states of electrical stress. Recent advances on nanodielectrics are reviewed. The importance of polymers in switchgears, overhead lines, power cables, transformers and substations are indicated.

1.0 INTRODUCTION

Polymers are giant organic materials. In general, they are plastics. Under specific conditions and due to functional features, they may be called rubber, resin or a high molecular weight species. Technologically, we are in the age of plastics. We use vehicles with plastic and rubber parts. We look through spectacles made of unbreakable plastic glasses. We prefer to furnish our home, interior and exterior with polymers. We use plastics for kitchenware and furniture. Our drinking water comes in crystal clear plastic bottles. Attractive design features of computers, mobile phones and other gadgets are the marvels of polymer properties. Material designs, either for commodity items or for engineering parts, are plastics selected from a wide range of polymers that could provide opportunities to employ thinner and lighter body structure at conventional or greater operating stress conditions.

In power engineering, reliable operation of electrical system is essential for meeting power transmission and distribution needs and the nucleus of this requirement is the subject of materials that focus on issues relating to insulation, structural and environmental concerns. Polymers are entering into new avenues of power technology as advanced materials for cables, switchgears, transformers, substations and overhead lines. Polymers with superior properties could potentially facilitate numerous improvements for utility equipment, lower system cost, enhanced equipment performance, increased safety and in making compact components solving many issues related to product design.

2.0 MATERIAL DEVELOPMENT

Polymers as core materials in electrical devices should meet specific criteria such as provide solutions to increase the life of equipments, improve operations under emerging conditions, be explosion resistant, have high power rating with reduced losses and superior replacement options for ceramic insulation. Polymers play a critical role in the equipment performance chain and reliability. Hence, the need for application of new and improved polymers is quite strong. Polymer insulation materials used in electrical equipment may vary widely in the nature of

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polymer and in its application. They may be thermoplastics like polyethylene and polypropylene, thermosets like phenolic resins or epoxies, or rubbers like EPDM and silicone rubber.

2.1 Polyolefines

Polyolefines are a class of polymers produced from simple alkene monomers such as ethylene and propylene and their copolymer derivatives. Polyethylene in its cross-linked form (XLPE) is used as the insulating material for power cables for its excellent dielectric strength, volume resistivity and other dielectric properties. Manufacturing techniques of polyethylene involve conventional high pressure process, Ziegler Natta catalytic method and the more recent method of using metallocene catalyst. Among these processes, Metallocene Catalysed Polyethylene (MPE) is superior in respect of controlling the structure at molecular level, maintaining narrow molecular weight distribution, leaving lower catalytic residue after polymerisation. However, due to high crystallinity and structural property, the melt processing of MPE is highly complex and the better choice is to blend it with other polyethylenes without sacrificing compatibility. It was found that the dielectric strength of LDPE improved from 372 kV/mm to 520 kV/mm with 1% addition of MPE [1].

Copolymers of polyolefines that are important in electrical applications are Ethylene-Vinyl-Acetate (EVA) polymer, Ethylene-Propylene rubber and Ethylene-Propylene-Diene (EPDM) rubber. In EVA, the vinyl-acetate content usually varies from 10 to 40 weight % as copolymerised with ethylene. EVA has good clarity and gloss, barrier properties, low temperature toughness, stress-crack resistance, hot-melt adhesive, water-proof properties and resistance to UV radiation. Hot melt sealants, recommended for gas and water-blocked cable constructions, are stabilised blends of EVA based thermoplastic elastomers and functional fillers.

2.2 Polyvinyl Chloride

Polyvinyl chloride is a halogen containing polymer available in the form of high hardness, rigid grade or with plasticiser in a flexible form. Plasticised PVC is conventionally used as sheathing material or as insulation layer in power cables for its good electrical properties, desirable flexibility with tensile and tear resistance and flame retardant behaviour. Due to the polar nature of PVC, it is miscible with other polar polymers or fluids acting as plasticiser [2, 3]. As PVC is inherently flame resistant, incorporation of plasticiser drastically increases the burning characteristics. In order to compensate for flammability, plasticised PVC is processed with flame retardant additives [4, 5]. The particulate morphology of the PVC resin contributes to unique rheological characteristics and final properties of rigid and plasticised PVC [6, 7].

2.3 High temperature polymers

High temperature polymers are usually polymers with a benzene ring in the molecule such as Polyamide, Polyimide, Polyphenylene Sulphide (PPS), Polyetheretherketone (PEEK) and Polycarbonate . Polyimides are incredibly strong, astoundingly heat and chemical resistant polymers capable of replacing glass and metals such as steel, in many demanding industrial applications. Due to their excellent heat resistance and electrical properties, they are useful in coating insulation in electrical devices such as transformers and circuit boards. Polyamides or Nylons contain monomers of amide formed by the condensation reaction of amino group and a carboxylic acid or acid chloride. Polycarbonate, a heat resistant and transparent polymer, gets its name from the carbonate groups in its backbone chain. It is produced by the reaction between the sodium salt of bisphenol A and phosgene. The bulky structure of this polymer provides high impact resistance suitable for making bullet-proof materials. Glasses in lightweight spectacles are made of polycarbonate lenses. They are also used as casing for electrical meters. Polytetrafluoroethylene (PTFE) is a perfluorinated ethylene polymer with unusual flame resistance, non-sticky and hydrophobic characteristics. Hence PTFE is a specialty insulation material in many electrical and electronic devices.

2.4 Thermosetting polymers

Thermosetting resin undergoes exothermic curing during processing under the application of heat. Curing is an exothermic reaction taking place between the functional groups producing a three dimensional network of chemical bonds. The most popular thermosetting resin used in electrical power industry is epoxy resin for insulating components such as spacers, insulating frames, insulators and mould transformers from low voltage to high voltage level. Development of epoxy moulding compounds for semiconductors as microelectronic encapsulation has greatly improved the performance of heavy electrical devices. Laminates based on unsaturated polyesters reinforced with glass fibres are applied to the insulating frames of electromagnetic contactors and vacuum circuit breakers in the distribution field. The compounds may be in the form of sheet moulding compounds, bulk moulding compounds and wet moulding compounds with processing methods of injection moulding, compression moulding, transfer moulding, or pultrusion. When the application is for the purpose of high temperature resistance, high mechanical strength, high dielectric strength, wear resistance and low coefficient of friction, the choice of thermosetting polymer is polyamides. Polyamide resin is mixed with epoxy resin to improve workability or rheological behaviour during processing. They are used for rotating machines as heat insulation for outdoor application or when the components need a hydrophobic surface to perform as water repellant; the resin is based on silicone rubber containing a curing agent. As a coating agent, it may be applied on ceramic insulating surfaces in the form of fluoro-silicone elastomers. For low voltage applications and as an economical substitute, phenolic resin with fillers, additives and colourants are used. Other thermoset resins such as polyurethane and melamine may also be used in the reliable functioning and handling of power system equipments.

2.5 Polymer composites

Polymers may be mixed with other polymers to form polymer blends or incorporated with additives, fillers, reinforcing agents and other chemicals to obtain functionally useful products in the form of polymer composites. For a polymer blend to be functional, it must be structurally sound and have desirable physico-mechanical properties that are ideally better than those of the components of the blend.

Adding fillers to a polymer matrix is a well established way for improving performance in the context of electro-technical applications. Composite insulators based on epoxy resin are used as indoor high voltage devices. Even in indoor conditions, surface degradation of epoxy insulators can take place through dry band arcing under the conditions of variations of humidity and temperature. The mechanism of dry band formation is through leakage current and temperature rise under electrical stress. Aluminium trihydrate (ATH) is the filler used with insulating polymers to reduce leakage current induced degradation [8]. Polymer composites in the form of polymer concrete are used in electrical insulation or as enclosures and pads for electrical equipments. Polymer concrete is made from selectively graded aggregates in combination with a polymer resin system. When combined through a process of mixing, moulding and curing, an extremely powerful cross-linked bond is formed. Precast polymer concrete is reinforced with fibreglass for exceptional strength and rigidity. Another benefit of polymer concrete is the ability to precast enclosures according to the customer's specifications. Compared to the ordinary concrete mixes, polymer concrete has better resistance to water absorption [9].

2.6 Rubber materials

A wide range of rubber compounds are specifically formulated for use in transformer and switchgear applications. Silicone rubber is used in outdoor insulation for its weather resistance and hydrophobicity. The hydrophobicity is restored in time by a mechanism involving the migration of low molecular weight species to the surface. The two common grades used in electrical insulation are High Temperature Vulcanisable (HTV) and Room Temperature Vulcanisable (RTV) silicone rubbers. HTV is preferred for solid insulations and RTV is limited to coating insulations. Their surfaces have high contact angle with water droplets. A variation in polymer surface energy alters the shape of the water droplets as measured by contact angles [10]. Under electrical stress, surface hydrophobicity has obvious effects on the wetting state of polymer insulators and on the surface discharge during the pollution flashover [11].

Nitrile rubber gaskets are available in different degrees of shore D hardness in the form of mouldings, extrusions or press-cut gaskets. Nitrile compounds are designed to seal successfully in mineral oil applications at temperatures of upto 120°C. Typical applications will include cover gaskets, handhole gaskets, bushing washers and also extruded 'O' ring cord for cover gaskets which seal in a machined groove and welded specification. Electrical grade EPDM compounds, ranging from black commercial EPDM for relatively low specification application, to a Peroxide-cured EPDM which has been specifically formulated for use with SF_6 gas (sulphur hexafluoride) are commercially available.

2.7 Polymer nanodielectrics

Polymer-nanoclay composites are reinforced lightweight composite materials in which organically modified nanoclay is dispersed in a thermoplastic or thermoset matrix. In these composites, the organically modified hydrophobic clay can impart remarkable changes in the mechanical, thermal, flame resistance and barrier properties even at smaller loading levels (12, 13). Nanoclays such as montmorillonite incidentally have a large aspect ratio with their layered silicate structures. Nanosized montmorillonite clay dispersed in small amounts in polymer, results in polymer nanocomposites having superior engineering properties compared to those of the native polymer. These nano inclusions are created by treating clay with an organic modifier which makes clay into an unusually long carbon chain with alkylammonium or alkylphosphonium cations.

The most popular polymer-nanoclay composites are based on a thermosetting polymer matrix like epoxy resins due to its strong binding capability with materials such as glassfibres. It can provide enhanced compressive strength and resistance against corrosion. Epoxy resin with organophilic montmorillonite, significantly increases the tensile strength and modulus over the original value of epoxy due to the possible exfoliation of clay platelets in the epoxy matrix. As a consequence of exfoliation, the cross-linking between the epoxy resin and hardener inside the clay galleries was expected to take place at a faster rate than the curing reaction outside the galleries.

From a general point of view, filler-aspect ratio is a pertinent parameter to distinguish between various types of nanocomposites. Spherical silica particles are an example of isotropic nanoparticles which either provide increased composite stiffness while retaining matrix transparency, or exhibit novel optical properties by forming colloidal crystals. Among the variety of composites that display a unique structure and behaviour at the nanometer level, as compared to the classical micrometer scale particulate filled materials, the use of layered silicates as a reinforcing phase is by far the most successful way of designing polymer nanocomposites with markedly modified properties. Layered silicates comprise natural clay minerals such as montmorillonite, hectorite and saponite and also synthetic layered mineral, fluorohectorite, laponite, or magadiite. Stacking of layers leads to a regular van der Waals gap called gallery or interlayer. Cations located in the galleries counterbalance the excess layer charges.The interlayer space can be penetrated by organic cations or polar liquid as well. A key parameter of the stacking is the basal spacing or d-spacing, which ranges from 0.96 nm (i.e., the layer thickness) to about 2 nm, depending on the nature of the interlayer cation and the amount of adsorbed water. Nanofillers such as TiO_2 and Al_2O_3 at 5% or above levels have been found to increase dielectric properties in epoxy resin. However, they tend to decrease the dielectric constant at very low loading of less than 1% in epoxy matrix [14, 15]. In layered clay-epoxy systems, the type of curing agents strongly affect the dielectric properties. Among the amine cured samples, the permittivity was lower than the base resin, whereas acid anhydride cured sample values are equal or closer to the base resin [16].

Water molecules can diffuse into the epoxy molecules to interact with polar groups or cluster into the free volume space. The diffused water in the matrix facilitates dissociation of long chain structure of polymer and filler de-bonding due to free radical formation [17, 18]. This hydrophilic property in epoxy composite is reduced by incorporation of nanofillers. The improved hydrophobicity was noted with higher contact angle between a water drop and the polymer surface. This feature is accompanied by reduction in surface roughness [19].

Partial discharge resistance is significantly improved by adding small amount of nanofillers such as nanoclay in epoxy resin [20]. Resistance of a nanodielectric surface to corona discharge was found to be greatly enhanced as compared to surface formed by polymer microcomposite [21]. Resistances to partial discharges as well as oxygen plasmas were found to have improved with nanofiller in Polyamide-6. The growth of surface cavities due to partial discharges was impeded with the use of mica nanofillers [22]. Nano structured composites modified with polyetherimide have low dielectric constants with potential application as protective and insulating materials in microelectronic devices [23].

Inorganic fillers such as MgO, SiO_2 and Al_2O_3 are used as useful fillers in XLPE and LDPE for AC and DC cables. When these fillers are used as nanoparticles great improvement in properties are expected. Nanosized MgO has increased DC breakdown strength and volume resistivity in low density polyethylene, LDPE [24]. By the inclusion of a small number of nanoparticles, the suppression of space charge formation in the LDPE/MgO nanocomposite film was improved due to an amendment in surface area facilitating dipole moment induced by MgO nanoparticle subjected to a high electric field [25]. Functionalised montmorillonite in LDPE has significantly enhanced the breakdown strength accompanied by an increase in dielectric loss [26]. Similar increase in breakdown strength was noted with silica, titanium dioxide and clay nanoparticles in XLPE and Epoxy resin [27].

To improve nanoparticle dispersion with polymers, certain selected surfactants are gaining recent attraction. A surfactant molecule is a surface active agent that can reduce surface energy or interfacial tension in heterogeneous systems. Its adsorption is determined by two principal factors: the interaction of the surfactant with the surface and the hydrophobicity of the surfactant. A non-ionic surfactant based polyethylene oxide has been proved to be effective in improving dispersion of nano-particles of fumed silica with silicone rubber with evidence of improvement in resistance to heat ablation [28].

Advanced solid electrical insulation is expected from nanocomposite technology. The interface of a composite has a strong influence on its physical properties. In nanodielectrics, the interfacial region between nanoparticles and the matrix has a high volume fraction. Hence, in polymer nanocomposites, the dielectric properties shall be controlled by large interfacial contributions.

2.8 Flame retardation

Flame retardant, low smoke materials have gained considerable importance in our country due to frequent fire accidents at public utilities, school buildings, cinema theatres, high rise buildings etc. In view of this, there is a greater necessity to use flame retardant and low smoke components including wires and cables. In order to meet this requirement, PVC based flame resistant and low smoke compounds are introduced especially in the power sector. Though PVC formulations have the advantage of cost effectiveness, they have the inherent drawbacks of having acid producing halogen and emitting smoke. Hence, in advanced countries, improved FRLS compounds with zero halogens and lesser smoke generation have been replaced with PVC compounds. They are based on polymers such as EPDM rubber, silicone rubber or EVA thermoplastic elastomers and are costlier than conventional PVC based FRLS compounds. In India, stringent stipulations on quality control may be necessary to use zero halogen based FRLS compounds completely eliminating PVC.

3.0 POWER SYSTEM DEVICES

3.1 Switchgears

Switchgears are electrical distribution devices that convert incoming electrical power into several smaller circuits and provide overload protection in the form of fuses or circuit breakers. Switches are devices that allow electric current to flow when closed and prevent current flow when opened. In switchgears, polymer materials of different types are found in insulation spacers, nozzles, capacitors, composite insulators and bushings. Spacers with improved toughness are made from advanced epoxy formulations that are comprised of resin and hardener along with hard inorganic and soft organic particles as fillers. High temperature resistance and low permeability systems are also needed for the future. To improve interruption performance, polytetrafluroethylene (PTFE) filled with heat resistant filler is used in nozzles. This has the advantage of minimising the penetration of arc energy and reducing the susceptibility to cracking.

Capacitors are used as metallised thin films of polyolefines. They operate under very high electrical stress combined with low mechanical stress. Insulators and bushings of ceramic material as heavy components are now replaced with lightweight polymer or rubber composites based on silicone and EPDM rubber. Although silicone rubber has superior performance as outdoor components, EPDM rubber components are cheaper material for pollutionless environment. The performance of EPDM rubber can be further improved by the incorporation of reinforcing and non-reinforcing chemicals. The recent emergence of silicone polymers for switchgear applications has meant that both SF_6 and mineral oils can be successfully sealed in temperatures of -50°C to +200°C. Silicone is a particularly good performer in low temperature applications.

Cycloaliphatic epoxy castings are used to eliminate the need for insulating fluid, gas or foam in a vacuum interrupter. Requiring no maintenance throughout the life of a product, the unit has polymer casing that resists UV radiation. It maintains self-cleaning, unblemished surface with low adhesion to contaminants. Polymer also resists tracking, reducing flashovers.

Utilities are discovering that switchgear box pads made of polymer concrete are easier to install, stronger and last longer than traditional concrete box pads because they are lighter than the regular precast concrete alternative and no extra equipment is needed for installation. They have three to five times the compressive, flexural and tensile strengths compared to traditional concrete enclosures. They are also highly resistant to corrosion, so their lifecycle is extended. The polymer concrete box pads have less than 1% water absorption, are non-flammable and non-conductive; hence do not require grounding.

3.2 Cables

Polymers for wires and cables provide excellent performance and functionality that meet or exceed the demanding requirements of the wire and cable industry. These functions include flame retardancy, high temperature resistance, light weight (low specific gravity), excellent low temperature flexibility, insulation resistance, semiconducting property and clean stripping abilities.

FIG. 1 POWER CABLE WITH XLPE INSULATION AND PVC SHEATHING

Cables require polymer materials for sheeting, insulating layer and conducting screens. Cables operate under low voltage stress but higher mechanical stress and are used as much thicker layer than capacitor films. Although PVC is a common material for sheeting, XLPE of selected grades is a potential material for high voltage AC and DC extruded cables. The XLPE insulated cable consists of a copper or aluminium conductor as the core, a semiconducting layer extruded over the conductor, an XLPE insulation layer, an outer semiconducting layer, a metallic wire screen or aluminium sheath and an outer polyethylene sheath. The semiconducting layer influences the partial discharge.

The new generation XLPE made of metallocene technology has the superior properties of treeing resistance and space charge less. For conducting screens, XLPE or EVA polymer is filled with conducting carbon black. Progress has also been made in the use of conducting polymers such as polyaniline in place of carbon black. Heat shrinkable polymer insulation offers an extensive range of cable installation materials for all known cable types upto 36 kV. Heat shrinkable polymers are processed from polyolefines, silicone rubber, PVC, neoprene and fluoropolymers.

3.3 Transformer insulation

Transformer insulation operates at the lower end of the voltage stress range but under much higher mechanical stress, the design is complex. Opportunities in polymer materials area are relative to transformer needs. Synthetic polymer substitutes for paper, modification of cellulose and cellulose-paper blends are potential areas in this regard. Cellulose is a natural polymer. Transformer insulation based on polyimides has special significance due to its high temperature resistance and good dielectric properties. Polyacrylonitrile fibres have been studied and considered as an option for the future. Blends of Nitrile and Neoprene give excellent sealing properties against all transformer oils and protection against ozone ageing, which is a major factor with all large electrical machines.

3.4 Overhead lines

In overhead lines, polymeric materials are gaining ground internationally as replacements for traditional insulating materials such as glass and porcelain. Insulators made from polymeric materials are called non-ceramic insulators. If appropriately used, polymeric materials can offer advantages such as more compact products, reduced maintenance and lower total operating costs. With compact products, it is possible to optimise the construction of overhead lines to decrease electromagnetic field. The trend is also to increase the system voltage in order to be able to increase the transmitted power. Rubbers or elastomers like silicone rubber, Ethylene-Propylene Rubber (EPR) and Ethylene Propylene-Diene Monomer (EPDM) rubber are considered today to be the best suited for ceramic insulation.

A break down of insulation in high voltage devices can lead to catastrophic damage in the electrical network. The lifetime of insulators in power system devices is expected to be 30 years. The insulating properties of the materials are a combination of their physical parameters and their response during ageing to temperature, humidity and mechanical stress.

Although silicone rubber has been proved to be a superior insulation in polluted environments, it is prone to biological contamination. Hence the need exists for developing or modifying silicone rubber materials which could offer resistance to microbial growth. Long time performance than that of silicone rubber may be achieved by using fluorosilicones in outdoor application but these materials are very expensive today.

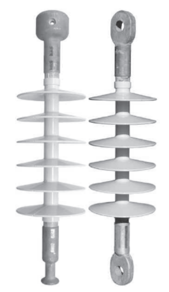

FIG. 2 POLYMER INSULATORS WITH FIBREGLASS REINFORCED FRP ROD AS THE CORE AND SILICONE RUBBER AS WEATHER SHED

Hydrophobicity loss on polymer insulation causes the development of leakage current and dry band arcing on insulators under high voltage stresses. The loss of hydrophobicity of RTV coating on ceramic insulators occurs with time through weathering and natural washings and is accelerated by acid rain which often causes depolymerisation of polydimethyl siloxane molecules [29].

Composite towers based on epoxies are used in construction of line towers. A range of solutions have been tested both as temporary replacement for standard towers and as permanent construction to replacing, for example, wooden towers. The integration for components of substitution of metallic parts of composite components result in compact, low weight and cost efficient design. In future, composite towers should make room for use as not only mechanical elements, but also as insulating ones in the transmission and distribution lines. The relations between process technology, fibres and matrix properties, and the resulting mechanical and electrical properties of the composite are important areas of ongoing research activities.

3.5 Substations

The design of future substations needs to take into account the changing load pattern much more rapidly. Substations should thus be transportable so that they can be adapted to ensure maximum flexibility of the changing power systems' needs. They should be small, visually compact and designed to blend in with the local environment. They should have very low lifetime losses and all components utilised in assembly and manufacture must be environmentally compatible and readily recyclable at the end of the equipment's lifetime. Porcelain has traditionally been used as the main mechanical and insulating structure for circuit breaker support insulation. Over recent years, there has been a gradual introduction of polymers in the typical forms of epoxies, EPDMs and silicone rubbers. Gas insulated switchgears with SF_6 gas as insulation medium have contributed to a significant downsizing of substation equipment.

Modern polymers now allow the production of mechanically robust structures for supports and enclosures. Moulded structures show considerable savings over fabricated metallic structures. Similarly, one could envisage the possible use of new mechanically robust polymers for pressurised enclosures for GIS applications. Transformer tanks could also be a further application for mechanically resistant polymers. The anti-vibration mountings are based on two cork/rubber materials.

Polymer-housings type surge arresters are compact and lightweight. They have been in service for twenty years and have shown significant advantages compared to porcelain-housed arresters especially with respect to performances under polluted conditions, seismic stresses and short-circuit currents. Polymer-housed surge arresters mixed with silicone or EPDM rubbers are useful as external insulations. A number of environments i.e. inland, coastal and semi-desert have indicated that a significantly shorter specific creepage is usable for silicone rubber insulators compared to porcelain insulators. Surge arrester housings made of materials other than silicone rubber are shown to age more rapidly. They also require greater creepage distance than silicone rubber to maintain equivalent watts loss levels in multistress tests. Polymer-housed arresters in general show a better damping against seismic stresses. The risk of a total collapse of the arrester structure is very low and hence the risk of arresters falling down damaging other insulators/equipment is negligible. This feature of polymer-housed arresters in addition to their low weight can also be used to avoid seismic stresses.

FIG. 3: SILICONE RUBBER HOUSED SURGE ARRESTER

4.0 CONCLUSIONS

Polymers are increasingly accepted as advanced materials in power engineering devices. Missions on innovations based on polymers as core materials in electrical technology can only be accomplished by a unified approach of lateral thinking among design engineers, material scientists and manufacturing engineers with industrial focus of polymers and composites. The goals may be to achieve, but not limited to, superior conductor-insulation integration, weight and size reduction, field shielding, antistatic protection, explosion resistance, fire resistance, energy source and environmental measures due to problems related to materials.

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