Wire Enamels – An Application for High Performance Polymers Unknown to Chemists

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Introduction

To build a functioning electrical machine, it is necessary to guide the electric current in defined ways. This is usually be done by electric wires consisting of a material that is able to conduct the electric current with a low resistance. These wires consist usually of a metal, mainly copper due to its low resistance to the electrical current. To force the electric current to run in a defined way, and not in the way of lowest resistance, it is necessary to avoid the bare conductors coming into contact with each other. The easiest way that this can be achieved is by leading the conductors at a distance from each other which is greater than the flash-over distance of the tension. This principle is still in use with printed circuits, but it can hardly be used in an electrical motor or generator. Such machines would be extremely large and very difficult to run effectively. Therefore the insulating material – air – in such constructions has been substituted with materials that are better insulators than air. This allows the conductors to be brought into very close contact, which makes the construction of machines much easier and more effective. Therefore, it is understandable that the development of the industry for electrical machines was strongly dependent from the improvement of the manufacturing of insulated winding wires.

A Short History of Wire Enamels

The first wires were insulated with fibrous materials, such as cotton, cellulose (paper) or silk. Such winding wires were very sensitive to mechanical impacts and, hence, difficult to handle in the manufacturing process of electrical machines. Therefore, since about 1900, the wrapping of such wires has been impregnated with air drying varnishes or mixtures of bitumen and air drying oils. Another reason for the impregnation was the high hygroscopicity of the insulating materials, which leads to a considerable reduction of the insulating capability. The normal humidity of air was enough to reduce the insulating properties. Since about 1915, varnishes based on natural resins were gradually substituted by varnishes based on synthetic resins, like phenolic resins. When using such synthetic varnishes it was possible to cover the copper wires directly without the necessity to first insulate the wires with fibrous materials.

Very successful in this respect was the use of poly(vinyl acetal) (PVA) based varnishes, developed from 1938 by the companies Hoechst and General Electric, mainly in the USA. In 1940, varnishes based on polyamide were introduced. Three years later (1943) terephthalic polyester based varnishes were simultaneously introduced by General Electric in the USA and Dr. Beck in Germany. Wires produced on this basis were superior in mechanical and thermal properties to the widely used PVA based coatings.

In 1950, varnishes based on polyurethanes invented in 1937 by Bayer were introduced. Today, polyurethane coated wires are used mainly in the communication and electronic industry. They allow high enamelling speed and direct soldering of the coated wire.

Based on the above mentioned terephthalic polyesters and primarily in the United States, during the 1960s the glycerol in the polyester formulation was replaced by tris-(2-hydroxyethyl)-isocyanurate (THEIC). The incorporation of THEIC into the polymer significantly improved the cut-through and flexibility and further enhanced the thermal performance of the coating.

From this development on, there was a marked divergence between American and European manufacturers of enamelled wires in their approach to producing magnet wires with a high thermal rating.

In the USA, the preferred route was to use dual coatings, applying the THEIC polyester enamel as a basecoat and aromatic poly(amide-imide) varnishes, developed by Amoco Chemicals in the USA in the mid-1960s, as an overcoat to improve the thermal endurance properties.

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In Europe, single coats were the order of the day and, in 1961, the poly(ester-imide) enamels were launched; initially these were THEIC-free, and later (1965) modified with THEIC. Poly(ester-imide)s were for decades the mostly used coatings for winding wires, having not only excellent thermal, mechanical and electrical properties but also good enamelling properties. Today poly(ester-imide)s are also used as base coats under poly(amide-imide) overcoats. The history of wire enamels is summarised in Table 1.

Besides these main types of wire enamels, for special applications other products are used:

- With the invention of the aromatic polyimide, by DuPont in 1959, having a temperature index higher than 240 °C and a cut-through above 500 °C, an outstanding resin for enamels was found. Polyimide wires, however, are normally used only in special applications, such as in the nuclear, aerospace and military sectors, due to the fact that the shelf life is limited and the high price puts the enamel out of court for conventional applications.
- Self-bonding wires are principally dual coat wires with a standard base coat and an overcoat of enamels based on solutions of aliphatic or partially aromatic polyamides. Wires with such enamel films can be bonded under pressure and temperature. In special cases the enamel can be crosslinked to improve the thermal properties of this type of secondary insulation. This technology has replaced the impregnation with an impregnating resin in small motors and in magnet coils.
- Wire enamels for glass fibre braided wires are, in fact, epoxy-, polyurethane- or poly(ester-imide)-based impregnating varnishes. After curing, they form a compound with the glass fibre, around the copper core. Manufacturing of such wires is very expensive. Therefore, they are used only in special applications like traction motors.
- For the use of wires in high-end motors wires wrapped with a polyimide film are sometimes used. These expensive high end motors are used in applications where extreme reliability over long times is necessary for safety reasons or where the access to the electrical machine for repair or its exchange is dangerous, difficult or impossible.
- As the application of inverter fed electrical motors became more and more common, it was necessary to improve the resistance of wire enamels against corona discharges. In the late 1980s, General Electric introduced such wires containing inorganic fillers.

A wire enamel does not only consist of a film building resin, but also solvents, catalysts and other components to influence the application and performance properties. Most of the wire enamel resins are dissolved in a mixture of cresol isomers and aromatic hydrocarbons. The poly(amide-imides) and polyimides use *N*-methylpyrrolidon as solvent. Polyester and poly(ester-imides) today use butyl- or cresyltitanates as curing catalysts. The polyurethanes use salts of tin, zinc or complex mixtures of amines to accelerate the formation of the urethane bonds. Poly(amide-imide) and polyimide wire enamels do not contain catalysts for curing. Besides these ingredients, flow additives and, sometimes, dyes to colour the enamelled copper wire are incorporated in the finished enamel. To improve the windability of the wires, they are coated with a slipping aid, mostly simply by applying solutions of paraffins.

Enamelling Technology Overview

Today's enamelling machines are the result of many optimisation steps made by the oven manufacturers. The first enamelling machine was run in 1907 by George Jacobs and his wife Ethel Mossman in Dudley, Massachusetts. The basic principle – coating of the wire with the enamel, curing in the oven and applying further coating layers – has not changed until today; Nevertheless, many improvements have been made over the years. Today, the wire enamel is applied on thin wires by felts and on thick wires by dies. By increasing the number of passes, from usually 5 to 10 up to a maximum of 20, the number of defects of the wire enamel film is made near to zero. In addition, thin films can be cured faster without blisters and therefore the enamelling speed can be increased significantly.

When the wire with the wet film enters the oven, the solvent is evaporated. The remaining enamel resin cures giving a highly crosslinked film. By using a catalyst for oxidising the solvents, the modern enamelling machines use the fuel value of the solvents to balance the thermal yield of the electrically heated ovens. In addition, the nearly quantitative oxidation of the solvents has solved the pollution issue, in spite of the need to use solvents being far away from being harmless. Incorporating the drawing process of the bare copper wire from copper bars into the enamelled wire manufacturing process further increases the economics of the whole process. Figure 1 demonstrates the construction of a typical wire enamelling machine as they are in use today.

Due to the problems with the supply of cresols in the 1970s, a need for alternative enamelling processes became obvious. At the same time, discussions started about substituting harmful materials in industrial use by less harmful ones. Although the manufacturing process of enamelled wires is economically and environmentally favourable, the enamels themselves are harmful because of the special solvents needed. There also began a

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Table 1. History of wire enamels.

Year	Chemical basis	Inventor	Properties	Importance today	Reference
1900	Oil-bitumen		Excellent humidity resistance, poor thermal properties	None	
1915	Tung oil, copal, phenolic resins		Improved hardness, flexibility and solvent resistance	None	
1938	Polyvinyl acetal	General Electric	Excellent mechanical properties and adhesion, low solids	Reduced	[1]
1940	Polyamide		Improved mechanical properties, flexibility, low coefficient of friction, self bonding	Overcoat, self bonding	
1950	Polyurethane	Bayer	Solderable, fast enamelling	Many	[2]
1954	Polyester (glycerine)	General Electric, Beck	Excellent solvents and humidity resistance, good thermal endurance	Reduced	[3,4]
1959	Polyimide	DuPont	Outstanding thermal resistance, high raw material costs	Special application	[5]
1961	Poly(ester-imide) (glycerine)	Beck	Improved cut through and thermal endurance, increased enamelling speed	Reduced	[6]
1965	Poly(ester-imide) (THEIC)	Schenectady	High cut through, hydrolytic stability, Freon resistance	Great	[7]
1966	Poly(amide-imide)	Amoco	Excellent thermal, mechanical properties	Great	[8]
1967	Polyester (THEIC)	Schenectady	Improved thermal endurance, adhesion, base coat in dual coat systems (PAI as overcoat)	Great	[9]
1968	Polyhydantoine	Bayer AG	Excellent thermal properties and adhesion, high raw material cost	None	[10]
1973–1980	Alternative enamelling technologies	Beck, Herberts,..	Hot melts, water and mild solvent enamels, dispersion, powders, extrusion resins, Electrophoretic enamels	None	
1988	Corona resistant wire enamels	General Electric	Resistant to partial discharges in inverter driven motors	Special applications	[11]

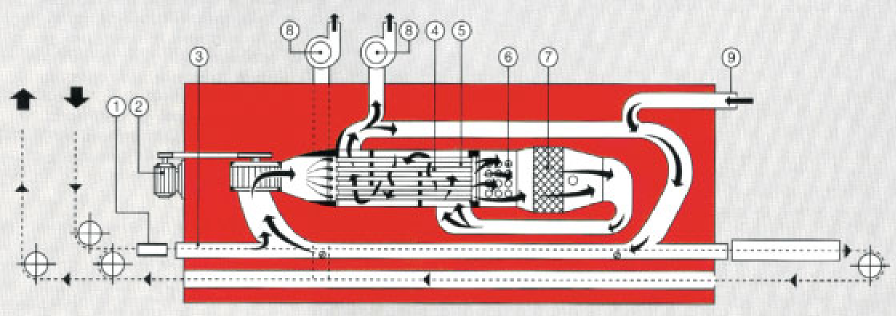

Figure 1. Sicme's NEM 400 wire enamelling machine: 1) Enamel applicator where the copper wire is coated with the wire enamel; 2) Blower motor for air circulation; 3) Oven for curing the wire enamel; 4)Heat exchanger pipes; 5) Heat exchanger; 6) Heater for the catalyst; 7) Catalyst for the evaporated solvent oxidation; 8) Waste air blower; and, 9) Fresh air intake

discussion about the greenhouse gases, mainly carbon dioxide, which, of course, is set free from the enamelling machines. The manufacturers of the wire enamels had to react on these requirements. They developed new wire enamels based on the well known resins with alternative solvents and application methods.

The first effort was to solve the problem with the cresol shortage by developing cresol free enamels and enamels with high solid contents. These materials could be applied by the standard wire enamelling machines, although in some cases it was necessary to substitute the lower energy output, due to the reduced content of solvents, by additional energy sources. This increased the production costs of the enamelled wires.

Many other technologies have been developed to cope with the actual requirements of the market, but they all needed more or less strong modifications of the existing equipment, or even completely new enamelling machines. In most cases, it was also necessary to use external energy sources for the curing process, instead of the solvent as an internal energy source.

The main requirement for all these new technologies was that the quality level of the final enamelled wire was the same or even better than the quality obtained by the standard enamelling process. In many cases this could not be fulfilled.

From all the alternative wire enamel technologies invented and listed in Table 2, only high solid wire enamels are universally applied. Hot melt resins, having no solvents at all, had insufficient thermal properties. Dispersions, having low viscosities at high solids content, frequently show surface defects. Water born wire enamels never reached the performance level of the standard cresylic products. Mild solvent based wire enamels are too expensive from the raw materials side. Electrophoretically applied enamels show extremely good edge coverage on profile wires but are thermally unsatisfactory. Electronic beam and UV-curing enamels are attractive due to the fast curing, but the properties are unsatisfactory. Powder coatings show an excellent build but are not pinhole free. Extrusion coating would be a very productive technology but the resins needed to get an acceptable property level are extremely expensive.

Table 2. Alternative wire enamel technologies.[12]

Technology	**Environment**	**Productivity**	**Quality of wire**	**Overall performance**	**Reference**
High solid wire enamels	Acceptable	Acceptable	Excellent	Acceptable	
Hot melt resins	Excellent	Excellent	Acceptable	Acceptable	[13]
Dispersions	Excellent	Acceptable	Insufficient	Insufficient	[14]
Water born wire enamels	Acceptable	Acceptable	Insufficient	Insufficient	[15]
Mild solvents based enamels	Acceptable	Excellent	Acceptable	Acceptable	[16]
Electrophoretic enamels	Excellent	Insufficient	Insufficient	Insufficient	[17]
UV curing enamels	Excellent	Acceptable	Insufficient	Insufficient	[18]
Powder coatings	Excellent	Acceptable	Insufficient	Insufficient	[19]
Extrusion coatings	Excellent	Excellent	Insufficient	Insufficient	[20]

When using one of the mentioned new technologies, the manufacturer of enamelled wires has not only to fight against costs for the installation of new equipment and energy but also with quality problems. Nevertheless, some of the technologies have survived for very special applications, for example the extrusion process with thermoplastic polymers for enamelled wires with hydrolytic stability or powder coating for special rectangular wires.

Properties of Enamelled Wires

Talking about ''enamel'' properties actually means talking about ''enamelled wire'' properties. Before application a liquid enamel is a mixture of polymeric molecules dissolved in solvents and characterised basically by solid content and viscosity. Once the enamel is cured on the wire, the resulting film or better conductor-coating system is characterized by specific properties, depending on the enamel applied and on the enamelling conditions. Once the enamel has been properly applied and cured, it can be checked for quality characteristics.

The properties of enamelled wires have been standardized by international standardization commissions, like the IEC (International Electrotechnical Commission),[21] UL (Underwriters Laboratories),[22] ISO (International Organization for Standardization), IEEE (Institute of Electrical and Electronic Engineers) and many national standards organizations, like NEMA (National Electrical Manufacturers Association), DIN, EN, BS, CEI, NF, AS, JIS, IS, etc. The standards adopted by winding wire manufacturers to describe wire properties reported on the datasheets are usually IEC, NEMA and JIS. Among these, the most widely accepted International Standards are those ones developed and approved by IEC.

The relevant standards developed by the Technical Committe 55 (TC 55) can be divided into three groups, one describing the methods of tests (IEC 60851), another reporting the specifications (IEC 60317) and the last one describing packaging (IEC 60264) of insulated wires. MW 1000 together with MW 757 and MW 760 are the equivalent standards to IEC standards developed and published by NEMA and preferably used in North America. MW 1000 is divided into three parts: Part 1 describes the wire dimensions corresponding to IEC 60317 Part 0; Part 2 defines the properties and requirements and corresponds to IEC 60317; and, Part 3 describes the test procedures and corresponds to IEC 60851.

Another important standard for magnet wires describes the test procedure for the determination of the temperature index (TI) and is coded IEC 60172; there is no direct NEMA equivalent but a parallel ASTM standard D2307 is referenced to in NEMA MW 1000.

The properties of enamelled wires can be divided into four categories – mechanical, thermal, electrical and chemical:

1. Mechanical properties describe the behaviour of the enamelled wire under the influence of different mechanical stresses. According to IEC 60317, they can be summarized into elongation (the increase in length before breaking, expressed as a percentage of the original length), springiness (the recoil, measured in degrees, after the wire is wound in the form of a helical coil or bent by a defined angle), flexibility and adherence (the potential of the wire to withstand stretching, winding, bending or twisting without showing cracks or loss of adhesion of the insulating film) and the resistance to abrasion (the maximum force which can be substained when a needle scrapes along the wire under a progressively increasing force). The test methods are described in the standard IEC 60851-3. These mechanical properties are important for the manufacturing process of the final electrical machine. The automatic winding processes lead to severe mechanical forces on the winding wires.
2. Thermal properties describe the capacity of the enamel to maintain its structure and properties at high temperatures. They can be summarized into heat shock (the potential of mechanically stressed wire to withstand high temperatures), cut through (thermoplasticity of the enamel at high temperature), thermal endurance (expressed as a ''temperature index'', the maximum temperature at which wire can be used for 20 000 h, determined in accordance with IEC pubblication 60172), high temperature failure test (indicates the performance of the insulating film at temperatures up to 450 °C, simulating overload conditions under voltage stress). Unless otherwise stated, IEC 60851-6 specifies the test methods. The thermal properties are of great importance for the reliability of the finally manufactured electrical equipment using the enamelled wires.
3. Electrical properties describe the behaviour of the enamel under the influence of electrical fields (electrical resistance, dielectric loss tangent) and voltage (breakdown voltage, continuity of covering). Other properties measured are the electrical resistance (the resistance of the wire expressed as the d.c. resistance at 20 °C), breakdown voltage (resistance of the insulating film to an a.c. voltage with a nominal frequency of 50 or 60 Hz), continuity of covering (uniformity of coating measured under a specified potential difference), dielectric loss tangent (steep rise of the dielectric loss showing the correct curing of the insulating film). IEC

60851-5 specifies related methods of tests. The electrical properties are of great importance for the reliability of the electrical equipment containing the enamelled wires.

4. Chemical properties describe the capacity of the enamel to withstand attack by chemicals. They can be summarized into resistance to solvents (the capacity of the insulating film of the enamelled wire to retain its hardness after immersion for a defined time in specified solvent mixtures), resistance to refrigerants (expressed as a percentage of remaining mass after treatments with refrigerants like Freon R22, R134, etc.), resistance to transformer oil (breakdown voltage and loss of adhesion of enamel after the enamelled wire has been heated in wet transformer oil in a sealed system). In reality, these tests are not real chemical tests, because the influence of the solvents principally is a physical effect of the solvent molecules on the dimensions of the network. Only in the case of hydrolysis is the molecular structure of the film building molecules changed by degradation. Also, the solderability found in this section is a chemical process in so far as the molecules are broken, but not under the influence of chemicals but heat; Therefore, solderability is more a thermal than a chemical property. IEC 60851-4 specifies to relevant test methods.

In order to get international recognition, the conformity of a product to the standard specifications is usually checked by a third party, an internationally accredited laboratory which certifies the compliancy of products to international standards. In the case of electrical/electronic products like wire enamels, such an organization is the UL (Underwriters Laboratories).

Although the tests mentioned above describe the enamelled wire very well, from the practical point of view the properties can be divided into two categories: properties related to winding conditions and properties related to electrical equipment performance.

Properties Related to Winding Conditions

Adhesion and Flexibility

After a given amount of elongation (5 to 20%), the wire is wound around a mandrel with stepwise defined diameters (1 to *x* times the wire diameter). The appearance of cracks and loss of adhesion are visually checked. These characteristics are directly related to the strain applied to the wire during the automatised winding of an electrical machine.

Sliding Property

This property is directly related to the capability of the wire to be applied on automatic high speed winding machines. A good positioning of the wires in the slot and a highly compact filling of the slot with wires are directly related to this property.

Abrasion Resistance

This characteristic is directly related to the mechanical strain the wire has to withstand during the winding process. A high abrasion resistance is a guaranty that no failure will be generated to the wire during the winding operations.

Properties Related to Electrical Equipment Performance

Electrical Resistance

This property is directly related to the standardized copper quality.

Elongation to Break and Spring Effect

The quality of the annealing process is controlled by these properties.

Heat Shock

The same test sample used to determine the flexibility is heated to 200 °C in an oven and then cooled to ambient temperature. Visually, no cracks must be identified. This property is related to the capability of the winding to resist to thermal shocks.

Thermo-Plasticity

A standardized pressure is applied on two wires crossing each other at one point. The temperature is progressively increased. When an electrical contact between the two wires occurs due to the softening of the wire enamel film, this temperature is recorded as cut through or thermo plasticity. This test demonstrates the flowing capability of the enamel under pressure. Modern enamels with thermal class of 200 °C have cut through higher than 320 °C. This value allows the estimation of the existing safety margin of a winding in case of a hot spot.

Breakdown Voltage

On a standardised wire sample, a rising AC current is applied at room temperature for 1 min, until electrical breakdown takes place. Values are generally more than ten times higher than the operating voltage of the proposed electrical windings.

Thermal Class

The thermal class defines the temperature at which the insulating film will withstand a defined voltage for 20 000 h. To avoid long test times an accelerated test procedure takes place. Wire samples are aged at different

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temperatures higher than the expected class temperature. The failure time is periodically checked at room temperature under a defined voltage (e.g., 1 000 V for a 1 mm diameter wire). These values are extrapolated to 20 000 h using the Arrhenius law to find the thermal index of the wire enamel.

Permittivity and Dielectric Losses (tg δ)

These electrical properties are directly related to the enamel formulation and correlate with the curing level of the polymer. These values are very important for high voltage applications, dielectric losses generating overheating in the winding.

Unfortunately, all these standard tests, except that for determining the thermal class, do not cover things like changes of properties under the operating conditions of the electrical machines. For example, after thermal aging the adhesion of a wire enamel film to the wire's copper surface can suffer drastic changes; By this, the performance of the equipment containing the enamelled wire is influenced. Standard tests done before and after aging can give significant different results. This shall be demonstrated in the following:

Wires enamelled with two batches of wire enamels [poly(ester-imide) as basecoat and poly(amide-imide) as overcoat] were submitted to a peel test showing the adhesion (higher figures show better adhesion). The two batches show the same adhesion, flexibility and heat shock. After 2 h at 180 °C, wires from Batch 1 show no loss in adhesion, while the wires from Batch 2 have a significantly lower adhesion.

The wires were analysed in detail. For this, samples from Batch 1 were aged at 180 and 200 °C for 2 h and wires from Batch 2 were aged at 130 and 150 °C. The adhesion was periodically measured by the standard peeling test. The results are listed in Table 3 and 4.

As Table 3 shows, the peel test values of Batch 1 drop below 50% of the initial value after 250 h of aging at 180 °C. At 200 °C, this aging occurs between 3 and 24 h. In Table 4, we see that wires from Batch 2 lose adhesion below 50% of the initial value between 24 and 72 h of aging at 130 °C, and even after 3 h at 150 °C.

The conclusion is that testing the enamelled wires according to the IEC standards is sometimes not sufficient. Taken into account the aging effect the wire is submitted under normal operation in an electrical machine, accelerated aging tests should be done to find out the long term properties of the enamelled wires.

Enamelled Wires in Electrical Machines

Enamelled wires are used in electrical machines like motors, generators, relays, transformers, ignition coils, and many others. These machines are, from a material point of view, complicated systems containing, besides enamelled wires as primary insulation, impregnating materials as secondary insulation, steel bodies, plastic sleeves, papers or polyester phase insulations and many others.

Table 5 shows that enamelled wires perform differently depending on the environment. Wires coated with different wire enamels (A to E) were assembled to test specimens and impregnated with different secondary insulating materials. The impregnated test specimens were submitted to a partial discharge test and the time, in minutes, was determined until the complete electrical insulation (wire enamel film plus impregnating

Table 3. Peel test results after aging the wires from Batch 1.

Temperature	**Peel test results after aging time**										
°C	**New**	**1 h**	**3 h**	**24 h**	**72 h**	**150 h**	**250 h**	**500 h**	**750 h**	**1 000 h**	**1 500 h**
180	104	–	89	87	63	50	62	19	34	25	23
	96	–	92	77	71	57	42	22	32	35	26
	95	–	89	76	76	56	57	23	37	32	21
	100	–	97	89	83	52	42	25	34	30	23
	95	–	90	89	66	60	48	28	29	23	17
Mean	*98*	–	*91*	*84*	*72*	*55*	*50*	*23*	*33*	*29*	*22*
200	104	92	88	24	–	–	–	–	–	–	–
	96	96	90	24	–	–	–	–	–	–	–
	95	86	94	27	–	–	–	–	–	–	–
	100	87	87	25	–	–	–	–	–	–	–
	95	86	91	28	–	–	–	–	–	–	–
Mean	*98*	*89*	*90*	*26*	–	–	–	–	–	–	–

Table 4. Peel test results after aging the wires from Batch 2.

Temperature	Peel test results after aging time					
°C	New	1 h	3 h	24 h	72 h	150 h
130	136	150	148	85	36	16
	142	143	136	89	18	24
	147	139	139	75	40	20
	141	145	135	79	25	22
	151	146	147	89	28	17
Mean	*143*	*145*	*141*	*83*	*29*	*20*
150	136	141	85	15	15	12
	142	143	85	14	9	12
	147	131	47	13	11	10
	141	140	59	13	10	8
	151	139	39	15	11	10
Mean	*143*	*139*	*63*	*14*	*11*	*10*
180	136	26	12	–	–	–
	142	25	13	–	–	–
	147	26	11	–	–	–
	141	26	16	–	–	–
	151	22	17	–	–	–
Mean	*143*	*25*	*14*	–	–	–

resin) had been destroyed by the corona discharge.

Table 5 shows some very interesting details. First of all, there are great differences in the actual corona resistance of wires enamelled with corona resistant enamels. The data show that a standard dual coated wire (MW 35) passes the test as well as a special wire, coated with a corona resistant wire enamel. Secondly, there exist impregnating materials that strongly reduce the performance of the enamelled wires. Thirdly, the performance of the enamelled wires can be greatly improved by some secondary insulating materials. At closer look, these systems are obviously able to impregnate the windings of the test specimens very well so that no corona discharges can occur due to the lack of voids. And by proper choice of the secondary insulating material, it is not necessary to use wires with a corona resistant enamel.

The properties of an enamelled wire, a system consisting of a copper conductor and an insulating enamel film, can be determined quite easily. Rating the performance of that wire in an electrical machine is more complex by far. The best way to determine the performance of the machine would be to test it in a long term test. Such tests are expensive and time consuming. Therefore, accelerated tests have been developed. This is possible because the film of the enamelled wire as the primary insulation is bearing the main burden of the insulation. Interactions with other components seldom improve the performance of the enamelled wire (not the whole system, see Table 5).

There are two tests to determine any influences on the enamelled wire. One is the motorette test according to IEC 61857. In this case, a model of an electrical machine containing all relevant insulating and construction materials used to build the equipment is tested. The advantage is that not only the interaction of the different materials can be evaluated but also the impact from the surrounding like climate (temperature and humidity), acceleration (for instance for traction motors) or industrial atmospheres. Figure 2 shows the construction of such a motorette.

Table 5. Effects of impregnation on corona resistance (in minutes) for selected wire enamels.[23]

Impregnation	A	B	C	D	E
	Standard MW 35	Corona resistant	Corona resistant	Corona resistant	Corona resistant
No resin	5.4	29.3	121.1	288.9	5.6
Epoxy resin	0.7	0.5	1.6	1.1	1.4
Unsaturated polyester resin thix	>6 000	>6 000	>6 000	>6 000	>6 000
Epoxy resin thix	4732.0	4.6	>6 000	>6 000	>6 000
Epoxy resin filled	>6 000	5.7	>6 000	>6 000	>6 000
Water based enamel 1	0.7	0.5	1.1	0.8	1.7
Water based enamel 2	7.6	15.9	63.8	177.9	10.6

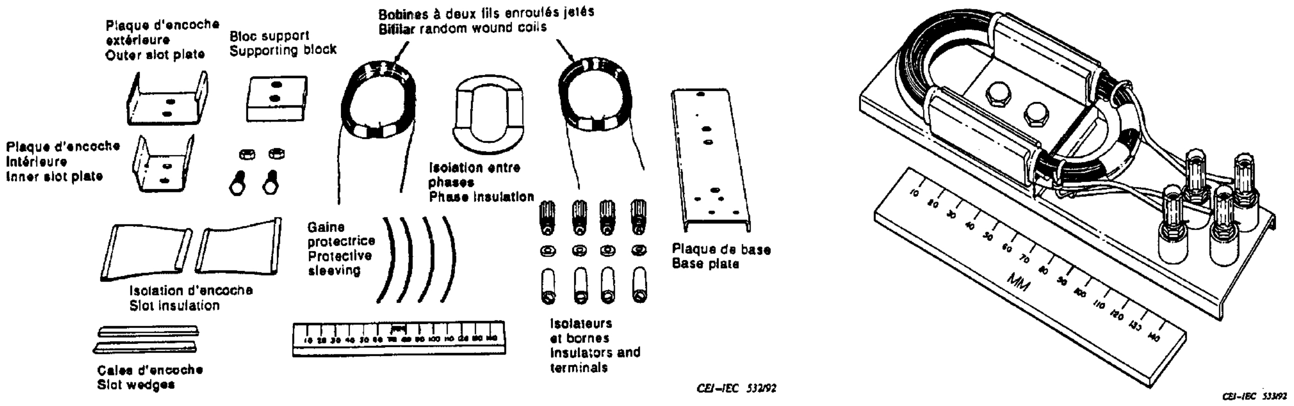

Figure 2. Parts necessary to build a motorette and a ready-to-test assembled motorette.

The second type of test is a mere compatibility test, the sealed tube test according to IEC 61858. The components of a system are placed in a sealed tube and aged. Then, electrical properties of the enamelled wire are tested. When components of the system are replaced, one of the components after the other is changed in the sealed tube test and aged again. The results of the tests of the enamelled wire are compared with those obtained from the original system.

Market for Wire Enamels

It is assumed that the worldwide production of wire enamels is around 200 000 Mt per year. The chemical bases are approximately: 30% THEIC modified polyesterimides, 20% polyurethanes, 18% polyesters, 10% THEIC modified polyesters, 10% polyamide-imides, 7% polyvinylformales, 4% selfbonding and 1% others. Wire enamels and also enamelled wires are manufactured around the world. In times of globalisation, the end-users for enamelled wires shift their productions around the world. Therefore, enamelled wires are traded worldwide. In some regions, such as the Far East, the demand for enamelled wires is strongly increasing; in other parts of the world the demand is constant, as in Europe.

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