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Bogotà, Colombia, 20 November - 1 December 1972

RECENT DEVELOPMENTS OF WIRE ENAMEL FOR MAGNET WIRES IN ELECTRONIC AND MOTOR APPLICATIONS 1/

by

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SUMMARY

RECENT DEVELOPMENTS OF WIRE ENAMEL FOR MAGNET WIRES IN ELECTRONIC AND MOTOR APPLICATIONS [1]

by

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The present situation and the future trend in the field of wire enamels is described. Following the requirements of the enamelling and electrical industry to reduce the numerous types of various wire enamels an attempt is made to give an outlook on the possibility of developing a universal wire enamel. The crowded field of wire enamels can be roughly divided into enamels for electronic applications and enamels for motor applications.

The field of electronics (television radio applications, telcommunications etc.) is dominated by polyurethane enamels. The possibility of a direct soldering of the polyurethane enamelled wires means great savings in terms of time and cost for these industries which handle millions of soldering points in production line operations every day. New types of polyurethane enamels with improved solderability which allow higher enamelling speed - up to 600 m/minute and faster - and are especially developed for fine wires are discussed.

Design and performance criteria during the past few years have placed ever-increasing demands on the physical electrical and thermal capabilities of electrical insulating materials in electrical motors. The families of aromatic polyimides polyamidimides, polyesterimides and polyhydantoins offer an overall balance of these properties

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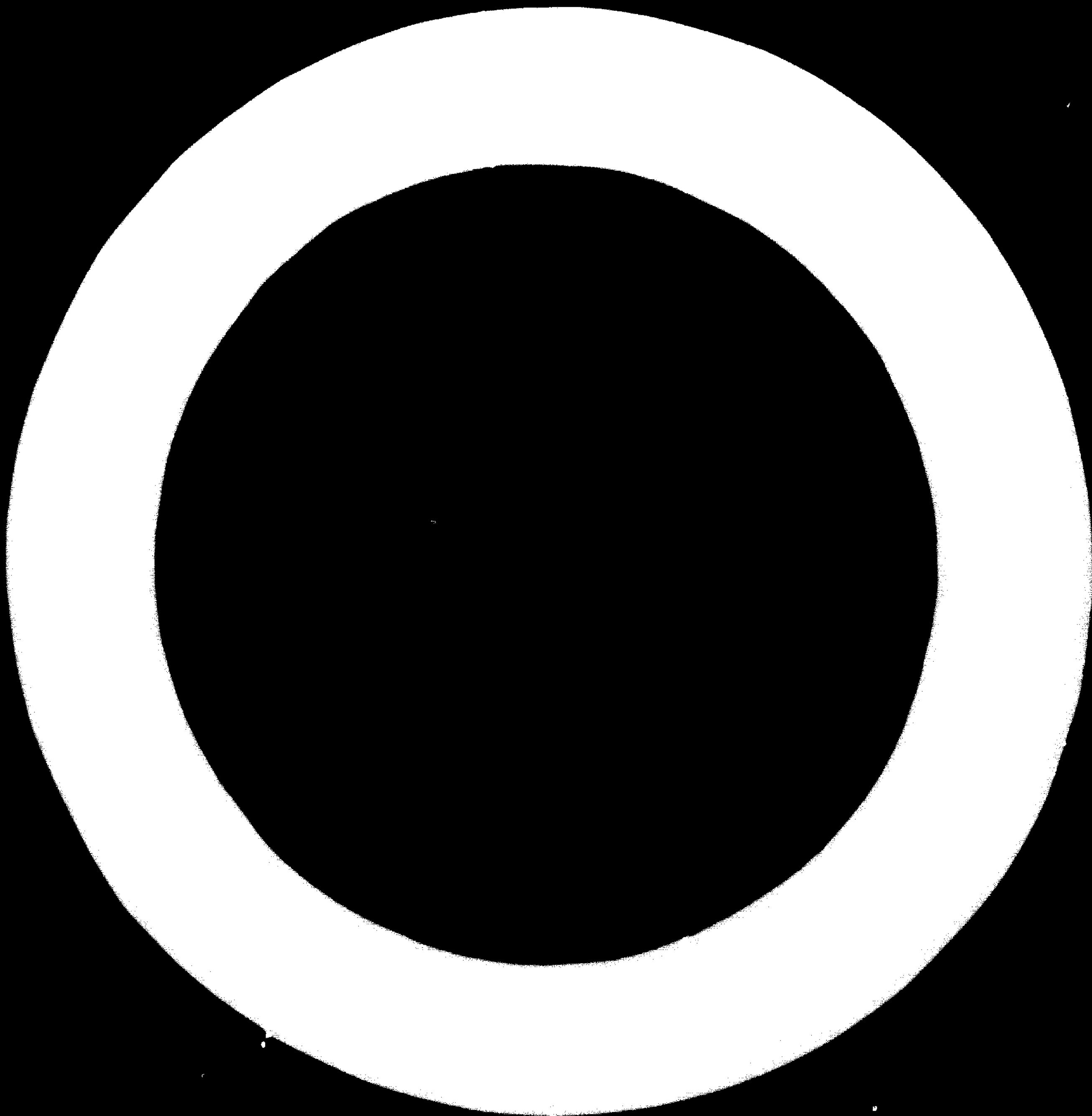
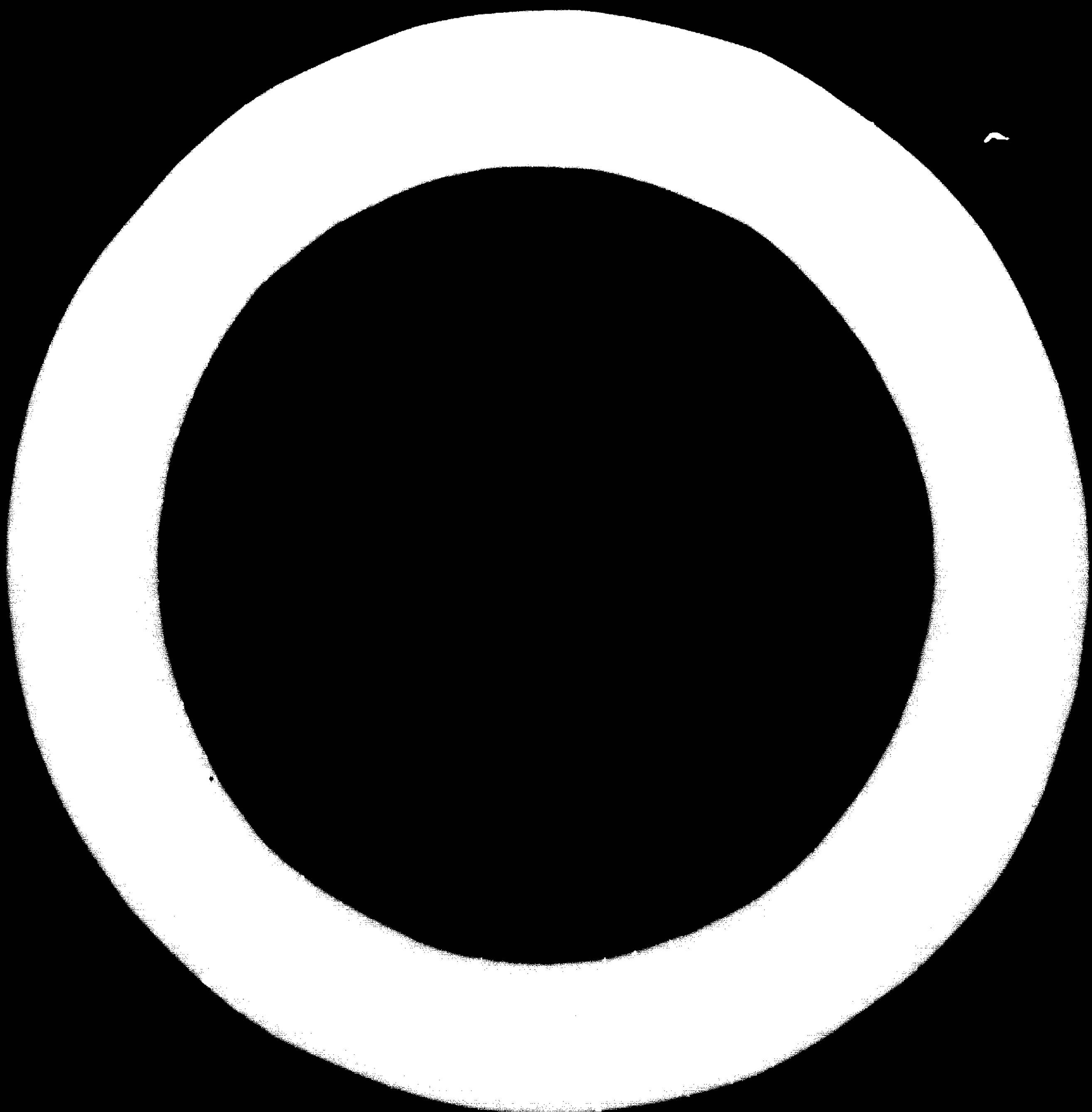


which have never before been available in organic materials. Since the price level of that type of wire enamels has dropped the polyesterimides and modified polyamid-imides in particular are likely to replace the well known polyvinylacetal enamels in the near future. The various types of enamels with high thermal rating are described. The most critical requirements and the application fields (houshold machines portable tool machines hermetic motors for refrigerators and airconditioners) are discussed.



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I. INTRODUCTION

Varnishes and enamels of differing composition have for decades played a substantial role in the various sectors of electrical engineering. Despite its very low proportion of the total weight of an electrical machine, the insulation of a motor winding, for instance, is of primary importance. The percentage of the wire insulation of the weight and volume of an electric motor can be considered inversely proportional to its significance.

The insulation of the enamelled wire is still applied from an enamel solution on specially designed machinery, using an appropriate application device. Until about 20 years ago, oleoresinous and polyvinylacetal based enamels were the basis of wire enamelling. In the meantime, miniaturization and higher service temperatures have led to the development of a wide variety of enamels. To the layman, this variety of existing wire enamels and enamelled wires must be bewildering. - Are all of these materials really needed?

The electrical industry has been demanding the universal wire enamel, which satisfies all requirements posed for the mechanical, electrical and thermal properties. However, this material will continue to be a wish-dream, at least in the near future. Nevertheless, there is indication of a trend toward reducing the great variety of widely differing wire enamels by selecting materials wisely under the aspects of quality and efficiency.

The sector of wire enamels can be roughly subdivided into materials for electronic equipment and materials for electric motors. While the electronics sector (television, radio, telecommunications, etc.) makes exclusive use of polyurethane enamels it is polyester imide, polyamide imide and polyhydantoin based wire enamels which seem to be the preferred materials out of a variety of new developments for motor construction.

II. POLYURETHANE ENAMELS FOR THE ELECTRONICS SECTOR

1. General

The development of the polyurethane wire enamels by Bayer AG introduced new aspects especially for mass production in the electronics sector; for the fact that the polyurethane bonds are split up at high temperatures permits polyurethane-enamelled wires to be tinned without prior removal of the insulating coat (either mechanically or by means of solvent). This fact, which is extremely favourable for rationalizing production processes, has opened up a wide range of applications for polyurethanes. Apart from the advantage of direct tinning, polyurethane wire enamels are notable for outstanding mechanical properties and excellent electric and dielectric data. The good resistance of these wires to humid atmospheres and water is particularly appreciated in telecommunications. In Europe, polyurethane-enamelled wires are given a thermal rating of 120° C. In the U.S.A., nylon-overcoated polyurethane enamel coats are permitted for use at service temperatures of 130° C.

2. Polyurethane enamels with improved tinning properties

The progress made in general development has led to the demand for solderability at lower temperatures, made with respect to other elements of the equipment. Originally, the polyurethane wire enamel resulted from the reaction of a polyfunctional isocyanate with the hydroxyl groups of the hydroxyl polyester used as the reaction partner. In the thermal splitting process, therefore, all urethane bonds are split up; thus, the isocyanate originally used is disintegrated into small fractions, which have much higher volatility than the polyester remaining structurally intact to a large extent. Considerably improved solderability could be achieved by replacing the ester groupings with urethane groupings as additional built-in sites of thermal splitting. Moreover, the enamel film so formed - a polyurethane in its purest form - allows a markedly higher enamelling speed than the conventional polyester based urethanes. In addition to a three to five fold reduction of the tinning time and the possibility of reducing the solder bath temperature to less than 320° C, these polyurethane enamels permit take-off speeds up to 600 m/min. and more with ultra-thin wires.

3. Prospects

In Europe and the U.S.A. the polyurethane enamels account for about 25 % of the total of wire enamels applied. The required quantity of polyurethane wire enamels will increase slowly but steadily as the general development of the electronics industry continues. The sales of pure polyurethanes will increase at the expense of the polyester-based urethanes. For special electronic components with very low thermal stability there are polyurethane enamels for enamelled wires which can be tinned at temperatures around 250° C but, unfortunately, do no longer show the mechanical, electrical and dielectric properties desired.

On the other hand, the demand of the electrical industry for a self-fluxing wire enamel for wires with relatively high thermal ratings could be met by the development of special polyester imides, which are dealt with in the section on motor wires.

III. WIRE ENAMELS FOR MOTORS

1. General

Electrical equipment and machinery is expected to have a long service life during which it operates troublefree and at full capacity as well as to be of the least complicated and smallest design possible. These requirements lead to ever higher service temperatures, which in the case of electrical machinery may be up to and above 200° C during a service life of many years. Apart from the increased demands made upon the thermal ratings of the enamelled wires, improved mechanical, electrical and dielectric properties as well as high chemical resistance are required. Polyimides, polyamides, polyester imides, polyester amide imides and polyhydantoins combine all these properties to an extent previously unthought of purely organic compounds. In addition to this variety of modern enamels with increased thermal ratings up to about 240° C - in the case of polyimide - the old-established polyvinyl acetal based enamels developed around 1940 are still being used, as are oleoresinous and epoxy enamels, though to a small extent only. As earlier indicated, the non-expert is not the only one bewildered by the variety of materials; the motor designer, too, is hard put selecting the best quality for his purpose from the great number of enamelled wires offered to him. Therefore, the demand made by the users of wire enamels as well as the electrical industry for reducing the wide variety of enamels and enamelled wires to a reasonable extent is quite understandable. However, can the demand for a universal wire enamel be satisfied in the near future?

2. Wire enamels with increased thermal ratings

An answer to this question cannot be given without briefly discussing the various new developments marketed worldwide.

Polyimides

Thanks to its outstanding thermal rating up to approx. 240° C, the polyimide definitely is the ideal polymer for wire enamels. Nevertheless, this product has not yet been successful in finding that extensive application as an electrical insulating material which would be expected when considering its outstanding properties. The stability of the enamel solution is limited. Reactions which occur at room temperature cause a viscosity decrease of the solution and reduce the flexibility of the stoved film. Owing to relatively strong acidity, polyimide wire enamel can only be applied on equipment in stainless steel. Finally, the high price of the material is an obstacle to its wider use.

Polyamide imides

Although polyamide imides do not fully attain the polyimides in thermal ratings, they are increasingly used on account of their long-term thermal ratings at and above 200° C and their outstanding mechanical, electrical and dielectric properties, their use as over-coating material in multi-coat enamelling having particularly ex-panded. The high price for the preferred solvent of polyamide imides, N-methyl pyrrolidone, led to the development of cresol -soluble grades. Despite the slightly lower thermal ratings of the modified polyamide imides, the wires coated with enamels on this basis are notable for an excellent property pattern and, thanks to improved hardness, abrasion resistance, cut-through temperature and chemical resistance, have become a fierce competitor of the old-established polyvinyl acetals.

Polyhydantoins

Polyhydantoins offer the advantages of high cut-through temperature, good resistance to thermal shock, outstanding hydrolysis re-sistance, very good application properties, i.e. excellent flow. The chemical resistance of polyhydantoin-enamelled wires can be controlled through the catalyst addition of the enamel solution. Thanks to the considerable flexibility reserve, the flexibility decrease accompanying the increase in the degree of crosslinking hardly reaches a critical level. As a result of its remarkably good compatibility with other organic compounds, polyhydantoin is often contained in wire enamels not so designated.

Polyester imides, polyester amide imides, polyester hydantoins

The terephthalic polyesters, which have been known since about 1955, offer good thermal ratings and, thanks to their wide range of applications, are offered at fairly reasonable prices. However, the materials have poor resistance to thermal shock. By incorporation of, or combination with, compounds that contain imide groups, amide-imide groups and hydantoin groups it was possible to give the terephthalic polyesters improved thermal rating (thermal shock, cut-through temperature) without affecting their good shelf life and application properties.

There is a great variety of modified polyester imides. Thermal ratings vary between 155° C and 200° C. A favourable influence on hardness, burn-out resistance, cut-through temperature and thermal stability can be exerted by incorporation of crosslinking compounds, especially tris-(2-hydroxyethyl)isocyanurate (THEIC). For the time being, however, these improvements can only be obtained at the expense of flexibility, especially after thermal ageing. The flow properties of the polyester imides are not yet satisfactory on the critical round wire diameters (< 0.22 and > 1.5 mm) as well as on flat wire and strip. What has been pointed out on the polyester imides is also roughly applicable to the polyester amide imides. The polyester hydantoins, which are a combination of terephthalic polyester and polyhydantoin, have a thermal rating of about 190° C and show outstanding flow properties, even on the critical wire diameters, and very good flexibility after ageing at elevated temperatures. However, their cut-through temperature is lower than that of the polyester imides modified with THEIC.

The demand in motor construction for a wire enamelled with a self-fluxing wire enamel and having a high thermal rating led to the development of polyester imide enamels with thermal ratings of 180° C to 190° C, which are solderable at temperatures above 450° C.

Multi-coat enamelling

Apart from the above mentioned possibility of improving the properties by modification of the chemical structure and combination of different materials, in the enamel solution, the same effect can also be obtained in the enamelling process by applying several enamel coats consisting of different enamel bases. In practice, the material normally chosen for the base coat is a terephthalic polyester or a polyester imide. The mechanical strength or the thermal and electrical properties can be improved by overcoating with polyethylene terephthalates or polyamide imides.

3. Requirements

For safety reasons, the electrical industry has made very exacting demands upon wire enamels, and the properties of these materials are often utilized to the very limit. Even under severe conditions like these, the troublefree operation of a machine or the function of an appliance must be ensured at all costs. This explains the necessity for very thorough testing, even of the raw materials to be used in the formulation of such enamels, as well as the fact that only such materials can be used as have proved their suitability.

Since increasing development has in the last few years resulted in the considerable extension of the range of demands made upon wire enamels and enamelled wires, an ever greater outlay on measuring and testing facilities has been required.

The rough handling of enamelled wires on winding machines calls for adequate hardness and high abrasion resistance of the enamel film as well as for good flexibility, i.e. good adhesion to the conductor coupled with adequate film elongation. The low friction of the wired enamel as demanded for the winding process is primarily governed by selection of the right lubricant. Regardless of whether winding is followed by an impregnation or trickling process, the enamel film should be resistant to solvents or general chemical reagents. This is particularly true for testing on suitability in the construction of refrigerating equipment. Here the wires come in direct contact with the refrigerant. The manufacturers of refrigerating equipment make particularly high demands, because this contact with the fluorinated/chlorinated aliphatic hydrocarbons, some of which are highly aggressive, and with the oil of the refrigerating unit takes place at elevated temperatures and under pressure.

In testing the electrical data of electrical machines, emphasis is placed on the breakdown voltage at room temperature and the temperature limit of the particular class of thermal ratings. The dissipation factor should be invariably low over a wide range of temperatures.

Naturally, the thermal data are of the greatest interest where thermal ratings above 155^{o} C are referred to. Thermal ratings are determined by ageing twisted specimens of enamelled wires at different temperatures in air, noting the failure of the insulation under a specified test voltage. There is a linear time/temperature relationship between the logarithm of the average life of the test specimen and the reciprocal of the absolute temperature, this relationship permitting extrapolation of substantially longer periods at lower temperatures.

The cut-through temperature of an enamelled wire is that temperature at which the enamel film softens to an extent at which it will sag under defined conditions, causing a short-circuit.

The thermal shock describes a complex behaviour of the enamelled wire stoved after mechanical exposure by winding round a mandrel of specified diameter. The parameters to be tested are the flexibility and adhesion of the enamel film under thermal and mechanical load.

Finally, enamelled wires are required to have good burn-out or overload resistance. This property is understood to be the resistance of the insulating capacity of an enamel coat to the thermal effect of a heavy current.

These thermal properties alone do not stand for the serviceability e.g. of a motor. Although being prerequisites, they are not the only requirements to be satisfied. An "ideal enamelled wire" for motors, which meets the increased requirements of today, should have the property data shown in column 1 of the table below. The property patterns of some of the wire enamels or enamelled motor wires discussed are included for comparison.

Tests as per DIN 46 453	1	2	3	4	5	6	7	8	9
Film hardness	5 H	4 H- 6 H	2 H- 3 H	≤ 2 H	6 H	4 H	3 H- 4 H	4 H	4 H
Abrasion resistance [HUbe]	150	>150	100- 120	< 50	>200	100- 120	100- 120	120- 150	100- 120
Elongation of the outer enamel fibres [%]	70	> 70	> 70	> 70	≥ 70	> 70	> 70	60	> [illegible]
Dielectric strength [V/μm] at room temperature at temperature limit	 100 75	 >100 > 75	 >100 > 75	 >100 > 75	 >100 > 75	 >100 > 75	 >100 > 75	 >100 > [illegible]	 >100 > [illegible]
Temperature limit [°C]	180	105- 120	170- 190	≥220	200- 220	180- 200	155- 190	1[illegible]- 200	20[illegible]
Cut-through temperature [°C]	330	180- 260	230- 290	>400	>400	385	260- 310	≥330	[illegible]
Thermal shock behaviour [°C] (single diameter)	210	180- 260	140- 150	>400	>300	280	200- 220	≥220	260

1. requirements
2. polyvinylacetal enamels
3. terephthalate enamels
4. polyimide enamels
5. polyamide-imide enamels
6. polyhydantoin enamels
7. polyester imides without THEIC
8. polyester imides with THEIC
9. polyester hydantoins

IV. CONCLUSIONS AND OUTLOOK

On the basis of the information reported, the question about whether there is a universal wire enamel can be clearly answered in the negative. Even the desire for getting along with two enamel systems in the sectors of electronics and motor construction, which comes very close to the ideal situation, appears to remain a wish-dream into the near future. Although there is a trend toward wire enamels for electronic equipment being exclusively based on polyurethane materials, selection of the right enamel for motor wires will continue to be difficult. The demands made upon enamelled wires are highly differentiated depending on the end-use. As for thermal ratings, for instance, users still require a level of 155° C in the majority of cases. The rating of 180° C, though desired for propaganda reasons, is not yet a must under technical aspects. Thus, the users of wire enamels will notice any increase in thermal ratings with great interest, unless it is accompanied by major reductions of other properties, but hardly honour it by paying higher prices.

It especially is the group of compounds modified by incorporation of, or combination with, imide, amide-imide and hydantoin groups which appear to be increasingly accepted. The properties of the polyvinylacetal wire enamels have become inadequate especially in high-speed motors such as used in household machines and portable machine tools as well as in motors used in the construction of refrigerating equipment. Since, in addition, the prices of these modified polyesters have been subject to heavy cuts, sales can be expected to increase at the expense of the polyvinyl acetals and, of course, particularly at the expense of the oleoresinous and epoxy enamels. In Great Britain, for example, a sales increase from 15 % (1970) to 35 % by 1973 is foreseen for these resins while sales for polyvinyl acetals, oleoresinous enamels and other wire enamels are expected to decrease from 65 % to 30 %. Likewise a sales increase from 20 % to 35 % is expected for polyurethane enamels. In the U.S.A. modified polyesters account for over 45 % of the total consumption of wire enamels while consumption of polyvinylacetal enamels has dropped to below 15 %.

Where the use of enamelled wires with even higher thermal ratings is indispensable, such as in automotive starter coils, an increasing use of wires enamelled with multi-coat systems is noticed. In this connection emphasis should be placed on the modified polyester resins overcoated with polyamide imides.

It especially is in view of future immission legislation that water-based dispersions or solutions have regained significance. There has been growing interest in the acrylic polymer dispersions which were, in fact, developed in the early sixties. New coating methods, which have been accepted in the paint sector at large, such as electrodeposition and electric powder spraying, are being discussed, and attempts are being made to adopt these new application techniques in wire enamelling. However, the raw materials offered for general paints are far from meeting the stringent requirements of wire enamelling. Although attempts are made to develop materials of adequate quality, there still is widespread uncertainty about whether the new machinery required for applying such materials will be constructed and installed. On the other hand, continuation of the methods currently applied in wire enamelling will not violate immission legislation if waste gases are eliminated by simple after-burning.

Bibliography

B. v. Bornhaupt and W. Rating, Kunststoffe Bd. 61 (1971)
W. Dünwald, Kunststoffe Bd. 62 (1972)
G.P. French, Insulation Engineer Bd. 1 (1971)
I.R. Poswick, The BEAMA Electrical Insulating Conference (1970)
B. Reichenbach, Vortrag auf einem Klasse F-Symposium, 28/29 Oct. 1970 in Frankfurt/Main

16. 7. 74