The test methods for flame propagation of long elements of the electrical wiring system, in particular, cables, cable conduits and ducts, are analyzed, and differences in them are found in the test conditions and criteria for evaluating the resistance to flame propagation.

Using a substrate of a wooden board covered with a layer of tissue paper with an areal density of (21±9) g/m^2, adopted for testing other elements of the electrical wiring system, a cable was identified that is not resistant to flame propagation. It is proposed to use this substrate for testing the flame propagation of cables instead of a substrate made of a double layer of filter paper with a surface density of (80±15) g/m^2.

In one of three experiments, a cable that was not resistant to flame propagation was found based on the criterion of the presence of ignition of the substrate located under it. To reduce the risk of making an incorrect decision on compliance, it is proposed that the assessment of long elements of the wiring system be carried out according to the rules established for cable ducts, trays and ladders in EN 50085-1 and IEC 61537.

For the AVVG cable with an outer diameter of 10 mm to 60 mm, when it touches the blue flame cone of 1 kW, the correlation coefficient of the dependence of the length of the charred part on the diameter was 0.969. For a distance of 100 mm between the sample and the burner along its axis, a correlation coefficient of 0.985 was obtained. It is proposed to test cables under the second condition recommended in IEC 60695-11-2.

For two conduits, flame propagation was revealed when exposed to a 1 kW flame for 120 s and 240 s. However, for these conduits, flame propagation did not occur under standard conditions of exposure to such a flame for 20 s and 25 s. To identify long elements of the wiring system that are not resistant to flame propagation, it is proposed to test them at a duration of exposure to a flame of 1 kW, established for cables in IEC 60332-1-2

Keywords: electrical product, electrical and optical cable, conduit, fire safety, flame propagation, wiring system

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IMPROVEMENT OF TEST METHODS AND CRITERIA FOR EVALUATION OF RESISTANCE TO FLAME PROPAGATION OF LONG ELEMENTS OF THE WIRING SYSTEM

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1. Introduction

Electrical wiring systems are elements of power supply, power supply and control systems for various equipment and communication systems in buildings and vehicles. Fires associated with electrical wiring systems can spread the flame over a considerable distance from the source of the fire. In the process of their combustion, smoke, toxic and corrosive volatile combustion products can be released in a dangerous amount for people and property. Under certain conditions, the development of a fire from electrical wiring systems led to catastrophic consequences.

The main preventive measure to reduce the risk of fire from electrical products is the fire hazard test [1]. The priority is the testing of finished products [2].

In practice, fire hazard testing of all combinations of wiring systems is problematic. In this regard, the compliance of these systems with fire safety requirements ensures compliance with such requirements of each of their elements.

In electrical wiring systems, potentially fire hazardous elements are electrical and optical cables and wires (hereinafter referred to as cables), conduits, trunkings, ductings, trays, ladders, liquid tight sheathings and powertracks.

For long elements of the electrical wiring system, one of the measures to reduce the emission of hazardous volatile combustion products is to limit the spread of the flame.

Considering that fire hazard tests of long elements of the wiring system are performed separately, their test conditions, criteria for evaluating the results, as well as the rules for making a decision on compliance should not differ significantly.

At the same time, in standard methods, the specified characteristics, on which the results of assessing the resistance to flame propagation of long elements of the wiring system depend, are different, therefore, studies to determine the characteristics that significantly affect such an assessment are relevant.

2. Literature review and problem statement

In [3], a new model was developed for the rate of heat release during combustion of a horizontally located cable tray located at the side wall. The resulting model makes it possible to reduce the error in determining the peak rate of heat release during the combustion of the cable tray. However, it is advisable to identify discrepancies in the results obtained by the developed model and standardized test methods, for example, using the Steiner tunnel.

An extended model for estimating the speed of flame propagation during combustion of a vertically located cable tray, depending on the distance between the cables, is proposed in [4]. However, it is desirable to investigate the change in flame propagation speed for cables placed on a cable ladder. Testing of cables on cable ladders is accepted by international and European standards.

The work [5] presents the results of studies of the effect of the distance between cables and their layers on the height and width of the flame when burning cables laid in the tunnel. The paper also presents data on the speed of horizontal flame propagation along the cables. At the same time, it is advisable to determine the dependence of the horizontal flame propagation on the transverse dimensions of the cables.

The results of studies of the influence of the angle of inclination of the cable (0–20°) laid in the tunnel and the speed of longitudinal air flows (0.35–0.65 m/s) on the heating temperature of the tunnel ceiling from a burning cable are presented in [6]. But the work does not provide important data on the influence of these parameters on the speed of propagation of the flame of the cables.

In order to reduce the risk of fire in buildings associated with cables, methods for testing cables laid in bundles for flame propagation have been improved [7]. These methods make it possible to additionally determine the indicators of heat release and smoke production. On the basis of these and other methods, a new classification of cables for reaction to fire has been developed. This classification is implemented in EN 13501-6 [8] to fulfill the requirements of Regulation (EU) No 305/2011 [9]. At the same time, the disadvantage of this classification is not taking into account all the criteria for assessing the resistance to flame propagation of single-laid cables. The lack of an estimate for the duration of self-combustion and the flammable ability of particles separated from single laid cables can affect their classification.

To reduce the cost of testing cables of the same brand with different transverse dimensions, a procedure for extended application of the results for fiber-optic cables has been developed [10]. Such a procedure has been proposed for the classification of electrical cables according to their reaction to fire.

At the same time, work [11] did not find a clear relationship between fire hazard indicators and the main parameter χ of the extended application procedure for electrical cables. Therefore, further research is advisable to improve the procedure for the extended application of cable test results.

To meet the requirements of technical regulations [9, 12], The International Electrotechnical Commission (IEC) has developed methods for determining the length of the charred part of samples [13] and the incendiary ability of particles separated from them [14]. For these methods, the procedure for measuring the outer diameter of the samples was determined and the requirements for the duration of the application of a flame source of 1 kW to samples of flat cables were improved [15, 16]. At the same time, the distance between the torch and the sample was not given in accordance with the distance recommended by the basic IEC standard.

The European Committee for Electrotechnical Standardization (CENELEC) for the method [13] has defined an additional criterion for assessing the length of the carbon part of the cable [17]. However, with the introduction of an additional classification criterion [8], other important criteria for assessing the length of the carbon part of the cable were excluded.

Also CENELEC for method [13] has improved the requirements for test equipment to ensure constant exposure to a flame source for a specified duration of its application [18]. At the same time, such an improvement has not been proposed for the method [14].

The research results presented in [19] established a significant variance in the test results according to the method [13] of samples of identical cables obtained in different laboratories. The author notes that if the obtained length of the charred part of the sample is more than 152 mm, the testing laboratory runs the risk of making an incorrect decision on the conformity of the cables. However, the factors that influenced the reproducibility of the comparative test results have not been identified.

When using a 1 kW flame source, the International Electrotechnical Commission has developed methods for testing the flame propagation of other long elements of the wiring system [20–24]. At the same time, these methods differ in terms of test conditions and criteria for evaluating the results, which can influence the decision on the conformity of such elements. This applies to standardized methods for testing cables with a 1 kW flame.

It should be noted that in practice, standardized test methods for products compared to non-standardized ones are those, based on the results of which, a decision is made on its compliance and use at facilities. The perfection of these methods is an important influential factor in ensuring the fire safety of both the product itself and the facilities on which it is used.

At the same time, for economic reasons, improvements in such methods, especially in terms of significant changes in the design of test equipment, are slowly being introduced into practice.

The complex of factors influencing the assessment of the fire hazard of electrical products is defined in [2]. Their influence on the assessment of resistance to flame propagation of long elements of the wiring system has not yet been adequately studied.

All this leads to research on the resistance to flame propagation of long elements of the electrical wiring system under conditions of exposure to a 1 kW flame source.

3. The aim and objectives of research

The aim of research is to ensure the fire safety of facilities by improving test methods and criteria for assessing the resistance to flame propagation of long elements of the wiring system. This will help to reduce the number of people killed and injured and the amount of damage from fires.

To achieve the aim, the following objectives were set:

– to analyze the standardized test methods for flame propagation of long elements of the wiring system;

– to determine the influence of the characteristics of the bases, placed under the sample of long elements of the wiring system, on their flammability;

– to determine the influence of the characteristics of the base, placed under the sample of long elements of the wiring system, on the assessment of resistance to the propagation of flame of the cable;

– to determine the influence of the duration of application of the flame source to the sample and the distance between the burner and the sample on the assessment of the resistance to flame propagation of cables;

– to determine the effect of the duration of application of the flame source to the sample on the assessment of resistance to flame propagation of cable conduits trunkings and ductings.

4. Materials and methods of research

4. 1. Experimental conditions

Research methods of testing and criteria for assessing the resistance to flame propagation of long elements of the wiring system [8, 13–17, 20–24] were carried out using analytical and experimental methods.

To eliminate the influence on the results of experimental studies of the conditions of air conditioning and the environment and the size of the samples:

1) samples and bases for assessing the inflammatory capacity of particles separated from them were kept for at least 48 hours at a temperature of (23±2) °C and a relative humidity of (50±10) %;

2) the experiments were carried out at a temperature of (23±2) °C, a relative air humidity of no more than 75 % and an air flow rate of no more than 0.1 m/s;

3) samples of length 600_{0}^{+25} mm were subjected to tests.

4. 2. Methodology for studying the effect of the characteristics of bases on their flammability

To study the influence of the characteristics of the bases placed under the sample of the long elements of the electrical wiring system on their flammability, two bases were used.

The first base consisted of a white pinewood board 700_{-25}^{0} mm long, 300_{-25}^{0} mm wide and 10 mm thick, covered with tissue paper with an areal density of (21±9) g/m^2.

The second base was a double layer of filter paper with an areal density of (80±15) g/m and a square shape with a side of (300±10) mm.

The source of the formation of burning drops was a telephone wire with polyethylene insulation TRP 2×0.5.

The bases were placed under a horizontally located wire at distances of 150 mm, 200 mm and 600 mm.

Five experiments were performed at each distance.

During the experiments, the number of drops at which the base ignited was recorded, and the time from the beginning of the fall of the first burning drop until the base ignited.

4. 3. Methodology for studying the influence of the characteristics of the bases on the assessment of resistance to the flame propagation of the cable

To study the influence of the characteristics of the foundations under the sample on the assessment of resistance to flame propagation of the cable, a test method was applied according to IEC 60332-1-3 [14, 16]. During the experiments, let's additionally use a base made of a white pinewood board 700_{-25}^{0} mm long, 300_{-25}^{0} mm wide and 10 mm thick, covered with tissue paper with an areal density of (21±9) g/m^2.

The distance between the base and the point of application of the 1 kW flame was 200 mm.

Samples for each experiment were six lengths of 4×240 AVVG cable, 54.6 mm in diameter each.

The duration of the application of the test flame to the cable samples was 240 s.

In the course of the experiments, the length of the charred part and the duration of self-combustion of the samples were additionally determined.

4. 4. Methodology for studying the influence of flame application conditions on the assessment of resistance to flame propagation of cables

To study the influence of the duration of application of the flame source to the sample and the distance between the burner and the sample on the assessment of resistance to flame propagation of cables, test methods and criteria for evaluating the results were used according to standards [13–17].

Additional experiments were carried out on the distance between the burner and the sample, which is measured along the axis of the burner, equal to 100 mm.

In all experiments, the distance between the base and the point of application of the 1 kW flame was 200 mm.

The samples for the experiments were six cable sections AVVG 4×2.5, AVVG 4×16, AVVG 4×35, AVVG 4×120 and AVVG 4×240 with diameters of 10 mm, 19 mm, 26 mm, 42 mm, and 61 mm.

In the course of the experiments, the duration of self-combustion of the samples was additionally determined.

4. 5. Methods for studying the effect of the duration of the application of the flame on the assessment of resistance to flame propagation of cable conduitstrunkings and ductings

To study the effect of the duration of the application of the flame source to the sample on the assessment of resistance to flame propagation of cable conduits trunkings and ductings, test methods and criteria for evaluating the results were used in accordance with the standards [21, 23].

Additionally, experiments were carried out on the duration of the application of the flame source, established for cables [13].

The samples for the experiments were:

a) six segments:

1) corrugated cable conduit made of polyamide with an outer diameter of 16 mm and a wall thickness of 0.5 mm;

2) corrugated polypropylene cable conduit with an outer diameter of 50 mm and a wall thickness of 0.8 mm;

3) rigid PVC cable conduit with an outer diameter of 52 mm and a wall thickness of 4.1 mm;

4) corrugated cable conduits made of polyethylene with an outer diameter of 62.5 mm and a wall thickness of 1.4 mm;

b) three segments:

1) blind cable ducting with transverse dimensions 50×20 mm, complying with EN 50085-1 [21];

2) cable trunking with transverse dimensions 60×40 mm, which complies with EN 50085-1 [21].

5. Results of experimental studies on resistance to flame propagation of long elements of the wiring system

5. 1. The results of the analysis of standardized test methods for flame propagation of long elements of the wiring system

Tables 1, 2 give the characteristics of test methods and criteria for assessing the resistance to flame propagation of long elements of the wiring system.

According to the Table 1, for cable conduits and liquid tight sheathings, more stringent conditions for the conditioning of samples are specified compared to other long elements of the electrical wiring system. The temperature and relative humidity of the air of such elements is consistent with the conditions for the conditioning of electrical products [25, 26].

The duration of conditioning samples of cable conduits, liquid tight sheathings and cable trunkings, ductings, trays, ladders (Table 1), respectively, is 5 and 3.5 times longer than the duration of conditioning samples of electrical products established in the fundamental standards [25, 26]. For cables, this duration is 2 times less.

Table 1

Characteristics of test methods and criteria for evaluating the resistance to flame propagation of long elements of the wiring system

Characteristics	Value or description				
	Cables [13–17]	Powertracks [20]	Cable trunkings, ductings, trays, ladders [21, 22]	Cable conduits [23]	liquid tight sheathings [24]
Sample length (E^*), mm	600±25	675±10			
Conditioning conditions for samples	(23±5) °C; (50±20) %; ≥16 h	not defined	≥168 h after manufacturing	(23±2) °C; (50±10) %; ≥240 h	
Conditioning conditions of the base to determine the flammability of particles separated from the sample	(23±2) °C; (50±10) %; ≥4 h	not defined			
Temperature during testing, °C	23±10	20±5			
Chamber volume for protection against air flows, m^3	≥1	not used			
Dimensions of the metal fence, mm×mm×mm	(1200±25)× ×(300±25)×(450±25)	$(1300\pm 25)\times$ $\times 700_0^{+25}\times 450_0^{+25}$	$(1300\pm 25)\times$ $\times 300_0^{+25}\times 450_0^{+25}$		
Clamp width (support) (A^*), mm	not defined (≈25 mm according to IEC 332-1:1979)	25			
Distance between clamps (resistors) (D^*), mm	550±5	550±10			
Distance between the lower clamp and the point of application of the flame source to the sample (C^*), mm	75±10	100±5			
Distance between the upper edge of the lower clamp and the bottom of the guard (F^*), mm	≈75	500±10; 550±10 (for trays and ladders)			
Width of white pine board covered with tissue paper, mm	not used	700^0_{-25}		300^0_{-25}	
Distance between burner and sample (B^*), mm	62±16 (blue cone height)	100±10			
Duration of application of the flame source to the sample, s	t±2 (Table 2)	60±2		t_0^{+1} (Table 2)	
Distance between the point of application of the flame source to the sample and the upper limit of the rounded zone of the sample (L_1), mm	<425±5 1)	<400±15			
Distance between the point of application of the flame source to the sample and the lower boundary of the carbon zone of the sample (L_2), mm	≤65±5 1)	not defined		<50±5	
Length of the carbon part of the sample (L_3), mm	≤425 2)	not defined			
Standard base condition	double layer of filter paper 3) does not ignite 1)	tissue paper 4) does not ignite and the wood board is not heated		the tissue paper does not ignite	
Duration of self-combustion of the sample (t_{af}), s	not defined	≤30			
The number of samples that must withstand the test, pcs.	1 or 2 additional	1 or 12 additional	1 or 3 or 2 additional	3	

*See Fig. 1:
1) The criterion does not apply for cables covered by EN 13501-6 [8].
2) The criterion applies only to cables that are subject to EN 13501-6 [8].
3) Filter paper with a basis weight of (80±15) g/m^2 and a square shape with a side of (300±10) mm.
4) Packing with surface density (21±9) g/m^2.

Table 2

Duration of application of a flame source of 1 kW to samples of long elements of the electrical wiring system

<table>
<tr><th colspan="3">Cables [12, 13]</th><th colspan="3">Cable conduits, liquid tight sheathings [22, 23]</th></tr>
<tr><th colspan="2">Outer diameter, mm</th><th rowspan="2">t, s</th><th colspan="2">Wall thickness, mm</th><th rowspan="2">t, s</th></tr>
<tr><th>more</th><th>no more than</th><th>more</th><th>no more than</th></tr>
<tr><td rowspan="9">–</td><td rowspan="9">25</td><td rowspan="9">60</td><td>–</td><td>0.5</td><td>15</td></tr>
<tr><td>0.5</td><td>1.0</td><td>20</td></tr>
<tr><td>1.0</td><td>1.5</td><td>25</td></tr>
<tr><td>1.5</td><td>2.0</td><td>35</td></tr>
<tr><td>2.0</td><td>2.5</td><td>45</td></tr>
<tr><td>2.5</td><td>3.0</td><td>55</td></tr>
<tr><td>3.0</td><td>3.5</td><td>65</td></tr>
<tr><td>3.5</td><td>4.0</td><td>75</td></tr>
<tr><td>4.0</td><td>4.5</td><td>85</td></tr>
<tr><td>25</td><td>50</td><td>120</td><td>4.5</td><td>5.0</td><td>130</td></tr>
<tr><td rowspan="2">50</td><td rowspan="2">75</td><td rowspan="2">240</td><td>5.0</td><td>5.5</td><td>200</td></tr>
<tr><td>5.5</td><td>6.5</td><td>300</td></tr>
<tr><td>75</td><td>–</td><td>480</td><td>6.5</td><td>–</td><td>500</td></tr>
<tr><td colspan="3">* For cables with a non-circular cross-section in which the ratio between the length of the longer and shorter axis does not exceed 3, the nominal value of the length of the shorter axis is chosen as the outer diameter. For cables with a non-circular cross-section, in which the ratio between the length of the longer and shorter axes is in the range from 3 to 16, the sum of the lengths of the longer and shorter axes, divided by 3.14 (π), is chosen as the outer diameter. For cables in which the ratio between the longer and shorter lengths exceeds 16, the test criteria are defined in the product standards, and if they are not available, in the agreement between the manufacturer and the buyer.</td><td colspan="3">–</td></tr>
</table>

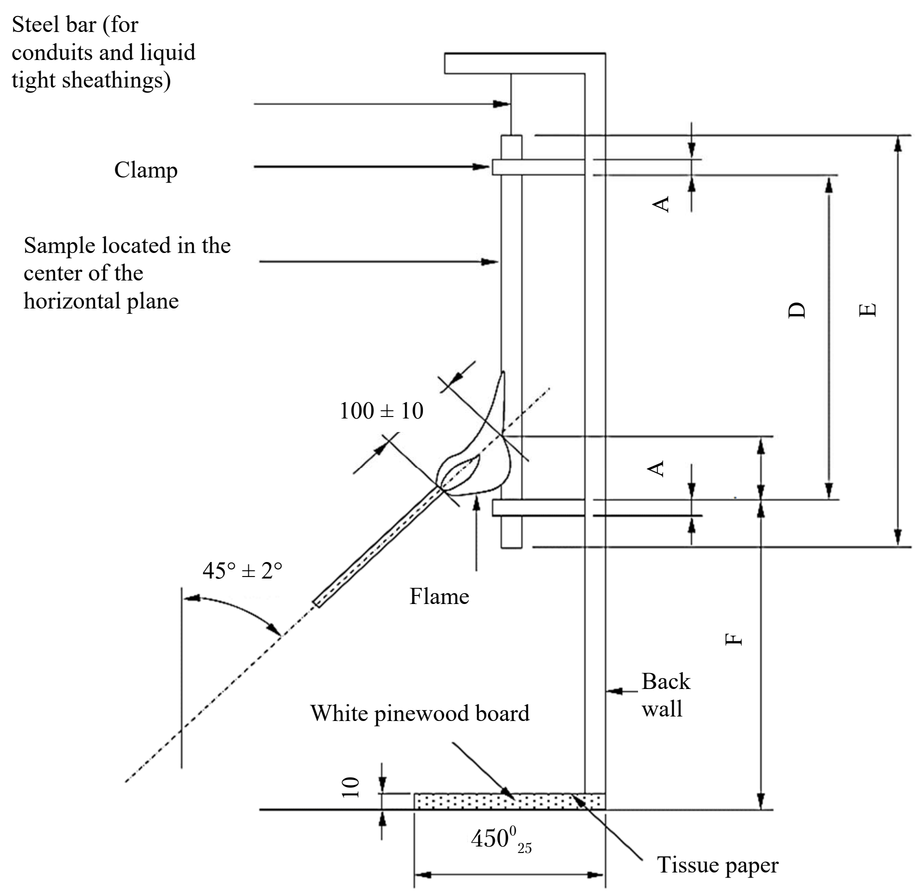

Fig. 1. Scheme of testing long elements of the wiring system for flame propagation (legend — according to Table 1)

Regarding the conditioning of the bases for assessing the inflammatory capacity of particles separated from the samples, such conditions are determined only for cables (Table 1). Moreover, such conditions for the base are not consistent with the conditions of sample conditioning.

To prevent the influence of extraneous air currents on the combustion process, the cables are tested in a protective chamber (Table 1). Also for these purposes, such a chamber is used to test other electrical products in accordance with fundamental standards [25, 26]. No such chamber is provided for testing powertracks, cable trunkings, ductings, trays, ladders and liquid tight sheathings.

When testing all elements of the wiring system, the total ambient temperature is (23±2) °C. At this temperature, it is customary to test electrical products in accordance with standards [25, 26]. According to these standards, the relative humidity should not exceed 75 %.

For all long elements of the wiring system, the distance between the clamps is 550 mm (Table 1). Taking into account the width of the clamps, a specimen length of 600 mm is sufficient.

According to the Table 1, the distance between the torch and the sample, which is not recommended in IEC 60695-11-2 [27], is set for cables to ensure reproducibility of results. The results of the study on the influence of this factor on the assessment of resistance to flame propagation of cables are presented in clause 5. 4.

According to the Tables 1, 2 for long elements of the wiring system, different durations of application of the flame source are determined. The results of the study on the influence of this factor on the assessment of resistance to flame propagation of cables, cable conduits trunkings and ductings are presented in clauses 5. 4 and 5. 5.

For cables other than those intended for use in buildings, the permissible length of the charred part of the sample can be in the range from 425 to 490 mm (Table 1). At the same time, for cables intended for use in buildings, the spread of the flame downward from the point of application of the flame source is not limited.

For other long elements of the wiring system, a stricter permissible flame spread of 400 mm upward from the point of application of the flame source is set than for cables.

A stricter permissible level of flame spread of 50 mm downward from the point of application of the flame source is established for liquid tight sheathings. When this level is selected for all elements of the electrical wiring system, with the permissible length of the carbon part of 425 mm, there is an admissible level of flame propagation upward from the point of application of the flame source of 375 mm.

For cables and other elements of the electrical wiring system, various bases have been determined for assessing the flammability of particles separated from samples and (Table 1). Also, different distances are set between the point of application of the ignition source and the base. The results of the study on the influence of these factors on the flammability of the bases and the assessment of the resistance to flame propagation of cables are presented in clauses 5. 2 and 5. 3.

For long elements of the wiring system, in addition to cables, such a criterion as the duration of self-combustion of samples, not exceeding 30 s is used. To obtain additional data on the fire hazardous properties of cables, such a criterion was applied during experimental studies.

According to the Table 1 rules for deciding on the compliance of all three samples for cable conduits and liquid tight sheathings with more stringent ones. Less stringent rules are established for powertracks when a decision on the test data of one or an additional sample is sufficient. At the same time, more samples have been identified for cable trunkings, ductings, trays and ladders for testing, which contribute to obtaining more reliable results.

5. 2. Influence of the characteristics of the bases placed under the sample of long elements of the electrical wiring system on their flammability

The data of experimental studies on the ability to ignite standard bases for determining the igniting ability of particles (drops) separated from a burning cable TRP 2×0.5 are presented in Table 3.

Table 3

Experimental data on the inflammatory capacity of standard bases

Basis characteristics	Distance between cable and base, m	The number of burning particles at which the base ignited *	Duration from the beginning of the fall of the burning particles to the base ignition*, s
Double layer of filter paper	150	6	3.7
	200	7	5.5
	600	9	7.9
White pinewood board covered with a layer of tissue paper	150	2	1.1
	200	2	1.5
	600	3	2.6
*Average value over five experiments.			

The research results presented in Table 3 prove that:

1) standard white pinewood board base covered with a layer of tissue paper is more flammable than a double layer of filter paper;

2) ability of standard bases to ignite does not significantly decrease with an increase in the distance between them and the source of the formation of burning particles according to the distance between the source of formation of burning particles and the base in the range from 150 mm to 600 mm.

5. 3. Influence of the characteristics of the bases under the sample on the assessment of resistance to flame propagation of the cable

The data of experimental studies on the influence of the characteristics of the bases under the sample on the assessment of resistance to flame propagation of the AVVG 4×240 cable are presented in Table 4.

The research results presented in Table 4 prove that:

1) application of an additional criterion for assessing resistance to flame propagation – the flammability of particles separated from the sample increases the efficiency of detecting unsuitable cables;

2) standard white pinewood board backing covered with a layer of tissue paper is more effective in locating unsuitable cables than a double layer of filter paper;

3) assessment of the resistance of cables to flame propagation based on test data from only one sample may lead to an incorrect decision on the conformity of the cables.

Table 4

Data of experimental studies on resistance to flame propagation of AVVG 4×240 cable samples using various standard bases

Sample number	$L_1/L_2/L_3$, mm	t_{af}, s	Combustion of the standard base placed under the sample
Double layer of filter paper			
1	166/7/173	15	no
2	175/8/183	19	no
3	176/11/187	27	yes
White pinewood board covered with a layer of tissue paper			
4	158/9/167	10	yes
5	170/7/177	26	yes
6	172/10/182	20	yes
Note: Legend – according to Table 1			

5. 4. Influence of the conditions of use of a flame source on the assessment of resistance to flame propagation of cables

The data of experimental studies on the influence of the duration of the application of the flame source to the sample and the distance between the burner and the sample to assess the resistance to flame propagation of cables are presented in Table 5.

The duration of the application of the flame source to the sample increases with an increase in the outer diameter of the cable (Table 2). But it is constant for certain ranges of the outer diameter of the cable. Therefore, to analyze the results, it is better to consider the curves of the dependence of the resistance to flame propagation on the outer diameter of the cable.

According to the Table 5, linear dependences of the average values of the length of the charred part and the duration of self-combustion of cables on their outer diameter (d) are plotted, which are shown in Fig. 2, 3.

Table 5

Experimental data on the influence of the duration of application of the flame source to the sample and the distance between the burner and the sample on the assessment of the resistance to flame propagation of cables

Sample number	Duration of the ignition source type, s	$L_1/L_2/L_3$, mm	t_{af}, s	Combustion of the standard base placed under the sample
1	2	3	4	5
AVVG 4×2,5 cable				
Blue cone of flame touches the sample surface				
1	60	60/12/72	3.6	no
2	60	65/15/80	4.2	no
3	60	70/13/83	4.0	no
The distance between the torch and the sample, measured along the torch axis – 100 mm				
4	60	93/13/106	3.0	no
5	60	90/14/104	4.0	no
6	60	100/12/112	5.4	no
AVVG 4×16 cable				
Blue cone of flame touches the sample surface				
1	60	90/11/101	1.0	no
2	60	88/13/101	1.0	no
3	60	95/12/107	1.4	no
The distance between the torch and the sample, measured along the torch axis – 100 mm				
4	60	110/11/121	3.0	no
5	60	109/14/123	4.0	no
6	60	105/13/118	3.8	no
AVVG 4×35 cable				
Blue cone of flame touches the sample surface				
1	60	99/15/114	1.0	no
2	60	100/18/118	4.0	no
3	60	103/17/120	3.6	no
The distance between the torch and the sample, measured along the torch axis – 100 mm мм				
4	60	115/11/126	13.6	no
5	60	110/18/128	6.0	no
6	60	108/15/123	8.4	no
AVVG 4×120 cable				
Blue cone of flame touches the sample surface				
1	120	123/10/133	7.4	no
2	120	113/18/131	1.2	no
3	120	115/15/130	1.0	no
The distance between the torch and the sample, measured along the torch axis – 100 mm				
4	120	125/14/139	14.4	no
5	120	115/16/131	15.0	no
6	120	129/13/142	19.0	no

Continuation of Table 5

1	2	3	4	5
AVVG 4×240 cable				
Blue cone of flame touches the sample surface				
1	240	131/10/141	20.0	no
2	240	145/15/160	25.4	no
3	240	135/15/150	21.2	no
The distance between the torch and the sample, measured along the torch axis – 100 mm				
4	240	151/11/162	25.8	no
5	240	155/15/170	24.2	no
6	240	148/12/160	21.4	no

Note: Legend – according to Table 1

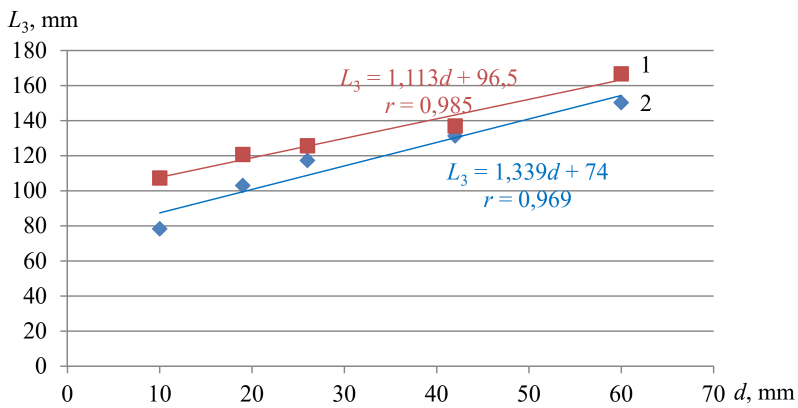

Fig. 2. Linear dependences of the length of the charred part of the cables on their outer diameter (d): 1 – distance between the torch and the sample, measured along the torch axis – 100 mm; 2 – blue cone of flame touches the sample surface; r – the correlation coefficient

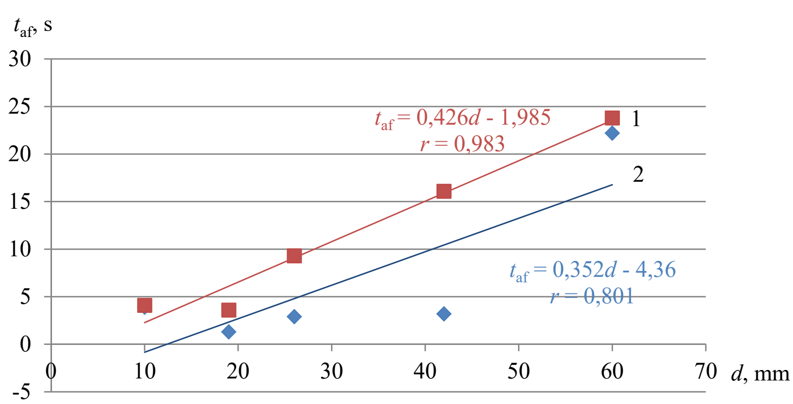

Fig. 3. Linear dependences of the duration of self-combustion cables on their outer diameter (d): 1 – distance between the burner and the sample, measured along the axis of the burner – 100 mm; 2 – blue cone of flame touches the sample surface; r – the correlation coefficient

Also, at a distance of 100 mm, a better correlation was obtained between the results of testing different diameters of the AVVG cable than when the blue cone touched the sample surface.

To assess the effect of the distance between the burner and the sample on the convergence of the results according to the Table 5, the rms values of the length of the charred part and the duration of self-combustion of the investigated AVVG cables are calculated, presented in Table 6.

Table 6

The value of the standard deviation of the length of the charred part and the duration of self-combustion of cable samples of the AVVG brand

Cable mark size	RMS			
	B=62 mm		B=100 mm	
	L_3, mm	t_{af}, s	L_3, mm	t_{af}, s
AVVG 4×2,5	5.68	0.306	4.16	1.206
AVVG 4×16	3.46	0.231	2.52	0.529
AVVG 4×35	3.06	1.528	2.52	5.69
AVVG 4×120	1.629	3.64	3.89	2.5
AVVG 4×240	9.5	2.84	5.29	2.23

Note: Legend according to Table 1

From Table 6, there is in four out of five cases better convergence of the results at a distance of 100 mm than when the blue flame cone touches the sample surface. As for the standard deviation of the duration of self-combustion of the samples, the best convergence at a distance of 100 mm between the burner and the sample was obtained only in two out of five cases.

In Fig. 2, 3 it is possible to see that with an increase in the duration of application of the ignition source, the length of the charred part and the duration of self-combustion of the AVVG cable with an outer diameter from 10 mm to 60 mm increase. At the same time, the values of these indicators do not exceed the threshold values of 425 mm and 30 s, respectively.

At a distance of 100 mm (curve 1), larger values of the indicators were obtained than when the blue cone touched the surface of the sample (curve 2).

The convergence of the results of the duration of self-combustion of the samples was influenced by the properties of the insulating materials placed under the shell, and the size of the zones of oxygen access to the place of combustion of such materials, formed as a result of damage to the shell.

As a result, it can be considered that the use of the recommended distance of 100 mm [2] will improve the convergence and reproducibility of the results of testing cables for flame propagation.

5. 5. Influence of the duration of the application of the flame on the resistance to flame propagation of conduits trunkings and ductings

The data of experimental studies on the influence of the duration of the application of the flame source to the sample on the assessment of resistance to flame propagation of cable conduits and ducts are presented in Table 7.

Table 7

Experimental data on resistance to flame propagation of cable conduits trunkings and ductings

Sample number	Duration of the ignition source type, s	$L_1/L_2/L_3$, mm	t_{af}, s	Combustion of the standard base placed under the sample
Corrugated polyamide cable conduit with 16 mm outer diameter and a 0.5 mm wall thickness				
1	15	115/15/130	5	no
2	15	125/14/139	7	no
3	15	122/18/140	9	no
4	60	190/23/213	108	yes
5	60	154/21/175	84	yes
6	60	170/24/194	97	yes
Corrugated polypropylene cable conduit with 50 mm outer diameter and 0.8 mm wall thickness				
1	120	burned out (Fig. 4)	≥30	yes
2	120	burned out	≥30	yes
3	120	burned out	≥30	yes
4	20	62/18/80	16	no
5	20	65/19/84	21	no
6	20	74/23/97	26	no
Rigid PVC cable conduit with 52 mm outer diameter and 4.1 mm wall thickness				
1	85	99/18/117	0	no
2	85	105/13/118	0	no
3	85	102/13/115	0	no
4	240	118/11/129	0	no
5	240	123/18/141	0	no
6	240	126/17/143	0	no
Corrugated polyethylene cable conduit with 62.5 mm outer diameter and 1.4 mm wall thickness				
1	25	136/28/164	22	no
2	25	129/27/156	18	no
3	25	138/29/167	24	no
4	240	burned out (Fig. 5)	≥30	yes
5	240	burned out	≥30	yes
6	240	burned out	≥30	yes
Blind cable ducting with cross dimensions 50 mm×20 mm, which complies with EN 50085-1 [19]				
1	60	185/37/222	0	no
2	60	148/27/175	0	no
3	60	131/31/162	0	no
Cable trunking with cross dimensions 60mm×40mm, which complies with EN 50085-1 [19]				
1	120	125/29/154	0	no
2	120	127/36/163	0	no
3	120	149/35/184	0	no

Note: Legend according to Table 1

Fig. 4. Corrugated polypropylene conduits that spreads the flame

Fig. 5. Corrugated polyethylene conduit that spreads the flame

The results of experimental studies presented in Table 6 prove that the duration of the ignition source seems to be a significant factor that affects the compliance of long elements of the wiring system with the requirements for resistance to flame propagation.

The duration of the operation of a flame source of the type specified in IEC 61386-1 [23] may not ensure that the conduits reach thermal energy sufficient to maintain stable combustion and flame propagation. This was revealed using the duration of application of the ignition source of the type set for cables in IEC 60332-1-2 [13].

This also applies to the test method for flame propagation of liquid tight sheathings [24].

For cable trunkings and ductings, an increase in the duration of the ignition source like this revealed their inconsistency. At the same time, additional testing of these products, cable trays, ladders and powertracks with a flame source duration of more than 60 s will provide confidence in the decision on their proper resistance to flame propagation.

6. Discussion of research results on resistance to flame propagation of long elements of electrical wiring systems

According to the principles set forth in [2], the conditions for the impact of a 1 kW flame source on long elements of the electrical wiring system and the criteria for evaluating the results, as far as possible, should be the same.

According to the results presented in Tables 4, 5, it is advisable to evaluate the resistance to flame propagation of cables according to such criteria as the presence of particles capable of ignition and the duration of self-combustion no more than 30 s. Assessment by such indicators is necessary for making a decision on the introduction of additional fire protection for cables at facilities.

The results are presented in Tables 3, 4, found that the generally accepted basis for evaluating the flammability of particles separated during the combustion of electrical products is more effective than that selected for cables. Therefore, the use of a base consisting of a white pine board covered with tissue paper will help reduce the risk of making the wrong decision about cable compliance.

Also, the results presented in Table 3, enable all elements of the wiring system to establish the same distance (200±5) mm between the point of application of the flame source and the base. Since the thermal energy of burning particles becomes less when falling from a greater height, determining such a distance will help to reduce the risk of making an incorrect decision in assessing the resistance to flame propagation of these elements.

It is not possible to determine the specified distance less than the overall dimensions of the burner [27] and the established distance between it and the sample (Table 1).

Also, reducing the specified distance allows to test all the long elements of the wiring system in a metal fence with the same height of 1200 mm (Table 1). This will help to minimize the number of pieces of test equipment.

Evaluation of the resistance of cables to flame propagation only according to the test data of one sample can lead to an incorrect decision about their compliance (Table 4). This also applies to powertracks.

To obtain reliable results, the decision rules established for cable trunkings and ductings, trays and ladders can be considered optimal (Table 1). At the same time, it is advisable to conduct experimental studies on the number of samples exceeding six.

With an increase in the duration of the application of the flame source to the samples of long elements of the electrical wiring system, an increase in the length of the charred part and the duration of self-combustion of the samples was obtained (Tables 5, 7 and Fig. 2–5). This is due to the transfer of more thermal energy from the ignition source to the samples, which helps to maintain their combustion.

At the same time, the levels of these indicators, as it is known, depend on the properties of the used insulating materials, their dimensions, the energy of the ignition source, oxygen availability and environmental conditions.

If materials that are not resistant to flame propagation are used, the short duration of the application of the flame source to them is not enough to initiate stable combustion. An increase in the duration of the application of the flame source to the samples made it possible to identify combustible conduits (Table 7).

In this regard, for all elements of the wiring system, it is advisable to take the most stringent requirements for the duration of the application of the flame source to the samples set for cables (Table 2).

If flame-resistant materials are used, damage to such elements occurs directly in the zone of influence of the ignition source. In this case, an increase in the duration of the application of the flame source will only lead to the burnout of materials in the zone of influence of this source. At the same time, the duration of self-combustion can reach a peak and further decrease.

Taking this into account, it is promising to evaluate the long elements of the wiring system by the speed of flame propagation.

Also, according to the test results provided in Tables 5, 7 and Fig. 2, 3, it is advisable to choose for the cables the distance between the torch and the sample recommended in [27]. This is due to the need to ensure the convergence and reproducibility of the results, since at a distance of about 100 mm, the parameters of the 1 kW flame source are checked.

The permissible distance between the clamps for the sample (Table 1) allows for all elements of the electrical wiring system to use for testing samples with the same and smaller length mm, adopted for cables. This makes it possible to eliminate the influence of the effects associated with the longitudinal heating of the samples under the influence of the ignition source. The specified dimensional tolerance will avoid the problems of fixing specimens due to the short length.

It is provided that the length of the samples is the same, eliminating the influence on the results of their transverse dimensions allows to choose the optimal duration of application of the ignition source to the samples. Therefore, it is promising to conduct relevant studies.

The content of excess moisture in the samples and the base, which is located under them, in excess of that which may be contained in electrical products during use, can negatively affect the process of their combustion.

For the elements of the electrical wiring system, the conditions of sample conditioning are different (Table 1). To eliminate the effect of this factor, for all elements of the wiring system, equal conditioning conditions for the samples and the base can be determined, established in the fundamental standards [25, 26]. Such conditions are holding the samples and the base for at least 48 hours at a temperature of (23±2) °C and a relative humidity of (50±10) %. At the same time, for safe and economic reasons, it is advisable to conduct experimental studies to determine the optimal duration of conditioning samples of long elements of the wiring system.

The combustion processes of electrical products can be affected by ambient temperature, relative humidity and atmospheric pressure. In this regard, it is advisable to test long elements of the wiring system under conditions that give the worst result, but are limited by actual operating conditions. Therefore, it is promising to carry out studies to identify the influence of such factors on the resistance to flame propagation of long elements of the wiring system. At the same time, such studies are difficult in terms of maintaining stable environmental parameters.

The combustion processes of samples of electrical products can be influenced by air currents. To limit their impact, protective chambers are used [25, 26]. Among the long elements of the wiring system, such chambers are intended for testing only cables (Table 1).

The disadvantage of using protective chambers is the depletion of oxygen during combustion of samples in a confined space. This affects the course of the normal combustion process. Therefore, for the use of protective chambers for testing elements of the wiring system, their internal dimensions should be justified.

The results obtained were discussed at the International Scientific and Practical Conference [28].

7. Conclusions

1. It was proposed to assess the resistance to flame propagation of long elements of the wiring system to meet the requirements of IEC 60695-1-30 [2], according to the same criteria:

– the length of the carbon part up and down from the point of application, the value of which does not exceed 375 mm and 50 mm, respectively;

– the presence and absence of ignition of the base located under the sample at a distance of (200±5) mm;

– the duration of self-combustion, the value of which does not exceed 30 s.

2. It was found that at a distance of 200 mm below the source of the formation of burning particles, the base of a wooden board covered with a layer of tissue paper with a surface density of (21±9) g/m^2 was occupied by 2 burning particles, and the base was made of a double layer of filter paper with a surface density (80±15) g/m^2 – from 7 burning particles. At the specified distance between the point of application of the 1 kW flame source to the cable and the first base, its ignition was detected, and when the second base was used, it did not occur. The use of the first base, which is accepted for testing other elements of the wiring system, increases the efficiency of detecting cables that are not resistant to flame propagation.

3. In one of three experiments, a cable was found that was not resistant to flame propagation, based on the criterion of the presence of a base fire located under the cable. To reduce the risk of making an incorrect decision on compliance, it is proposed to evaluate long elements of the wiring system according to the rules established for cable trunkings, ductings, trays and ladders in the standards [21, 22].

4. It was found for the AVVG cable in four out of five cases a better convergence of the results along the length of the charred part of the samples at a distance between the burner and the sample, which is 100 mm along the burner axis, than when the 1kW thief flame cone touches the sample surface. But in three out of five cases, the best convergence of the results of the duration of self-combustion was obtained under the latter condition. Under the first condition, the maximum values of the length of the carbon part of 170 mm and the duration of self-combustion of 25.8 s were obtained, and under the second condition, respectively, 160 mm and 25.4 s. Under the first condition, for the linear dependence of these indicators on the diameter of the AVVG cable within the outer diameter from 10 mm to 60 mm, the correlation coefficients were 0.985 and 0.983, respectively, and under the second condition, 0.969 and 0.801, respectively. Based on the generalization of these results and the recommendations of IEC 60695-11-2 [27], it was proposed to test cables under the first condition.

5. For two cable conduits that meet the requirements of IEC 61386-1 [22], for the duration of the application of a flame of 1 kW for 20 s and 25 s, it is found that they spread the flame for the duration of the application of such a flame source for 120 s and 240 s. To increase the efficiency of detecting long elements of the wiring system that are unstable to flame propagation, it was proposed to test such elements with a flame application duration of 1 kW, set for cables in IEC 60332-1-2 [13].

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