APPLICATION NOTE
FIRE-RESISTANT CABLE SIZING

Sizing of conductors supplying electrical equipment that must remain functional during a fire

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CONTENTS

SUMMARY

The integrity and functionality of the electricity supply cables is vital for keeping safety services operational during a building fire. Choosing a cable that is tested and classified as ***fire resistant*** is a first step when designing an electrical circuit to supply equipment that must remain functional during a fire. The next step – equally important – is **to calculate the appropriate cable conductor cross section**. This requires particular attention because of the fact that electrical resistance increases sharply as temperature rises.

To calculate the electrical resistance under fire conditions, the **fire temperature** must be known. First, it must be determined for how long the safety services must remain operational. The standard durations of fire resistance classes are 30, 60, 90, and 120 minutes. When this time span is known, the fire temperature can be derived from the standard temperature-time curve as defined in ISO 834. The **electrical resistance under fire conditions** can then be obtained by applying the Wiedemann-Franz law. This will establish an electrical resistance correction factor which facilitates the calculation of the voltage drop under fire conditions.

The voltage drop over the entire length of the supply cables must be restricted to ensure that fire safety equipment will maintain functionality for the required length of time. Usually, the maximum voltage drop will be specified in the equipment's user guide. If this is not the case, one must consider a maximum voltage drop of 10%. Because buildings are often compartmentalised into fire zones, cables feeding fire protection equipment are rarely exposed to fire temperatures over their entire length. The part of the cable not affected by the fire will operate at normal temperature, while the part exposed to the fire will have increased resistance. The total resistance over the whole length of the cable is calculated by applying the electrical resistance correction factor only to that part of the cable affected. From the maximum voltage drop of the fire safety equipment, the electrical resistance correction factor and the compartmentalisation of the cable route, the maximum electrical resistance the cable is allowed to have at normal temperature (20°C) can be calculated. The minimum conductor cross section can then be derived from this using Tables 1 to 4 of the international standard EN/IEC 60228, or their equivalent in national standards.

The electrical insulation of fire-resistant cables is designed to withstand extreme temperatures, a fact which could lead to the false assumption that there is no limit to the **current-carrying capacity** of these cables. In reality, fire-resistant cables are not tested for the potential additional heat produced as a result of the increased electrical resistance at high temperature. Moreover, any additional temperature rise above that represented by the standard temperature-time curve (ISO 834, post-flashover fire) could bring the cable close to the melting temperature of copper. Laboratory tests have demonstrated that this additional heat production does not affect the cable performance up to the 90 minute mark of the ISO 834 temperature-time curve. For these cases, the conductor cross sections and associated current-carrying capacities can be chosen based on the IEC 60364-5-52 standard for cables working under normal service conditions. If the installation must remain functional beyond 90 minutes (safety class 120), measures should be taken to avoid a loss of integrity in the cable.

The cross-section to be chosen is the highest value obtained from the voltage drop and current-carrying capacity assessments.

INTRODUCTION

When there is a fire in a building, safety services should not fail. They can save the lives of occupants and emergency workers. The first objective is to provide safe evacuation routes from the affected areas and to ensure that all services required for firefighting are maintained for as long as necessary. Another objective may be to ensure that services in areas not directly affected by fire are secured to provide a safe environment for occupants who are evacuated, pending complete evacuation or the end of the incident. Preserving property is also at stake.

The length of time for which safety services are required to operate depends on the building's use, the number and type of occupants, and the specifications given by national regulation and insurance companies. While it may be feasible to evacuate a dwelling or a small office building quickly, larger or taller structures and many public buildings will take much longer. The longer safety services can remain operational, the better the chance of bringing a fire under control, avoiding injuries, and reducing property damage.

A prerequisite for keeping safety services operational during a fire is to maintain a reliable power supply. Choosing a power cable tested and classified as *fire resistant* is a first step when designing an electrical circuit supplying equipment that must remain functional during a fire. The second step – just as crucial – is to calculate the minimum cable conductor cross section, which is the main subject of this application note.

THE DEVELOPMENT OF A FIRE

How a building fire develops depends on many factors, of which *the fire load* is the most important. The fire load is the average calorific value of combustible material per square metre of fire zone and is expressed in mega-joules per square metre (MJ/m^2).

The key to being able to specify a suitable fire-resistant cable is having a sound knowledge of the temperature rise characteristics in areas affected by the fire. Although the exact process depends on the location and fire load, standard temperature-time curves that model typical fires have been developed. In this application note we will use the standard temperature-time curve of post-flashover fire as defined in ISO 834. This standard curve is the most common in the fire-testing of buildings and is used in construction products regulation (CPR) tests. For some application areas, alternative temperature-time curves, such as hydrocarbon or tunnel curves, must be used.

The ISO 834 standard temperature-time curve of a post-flashover fire is expressed by the formula:

$$T = 345 \log(8t + 1) + 20$$

where:

T is the temperature, in °C

t is time, in minutes

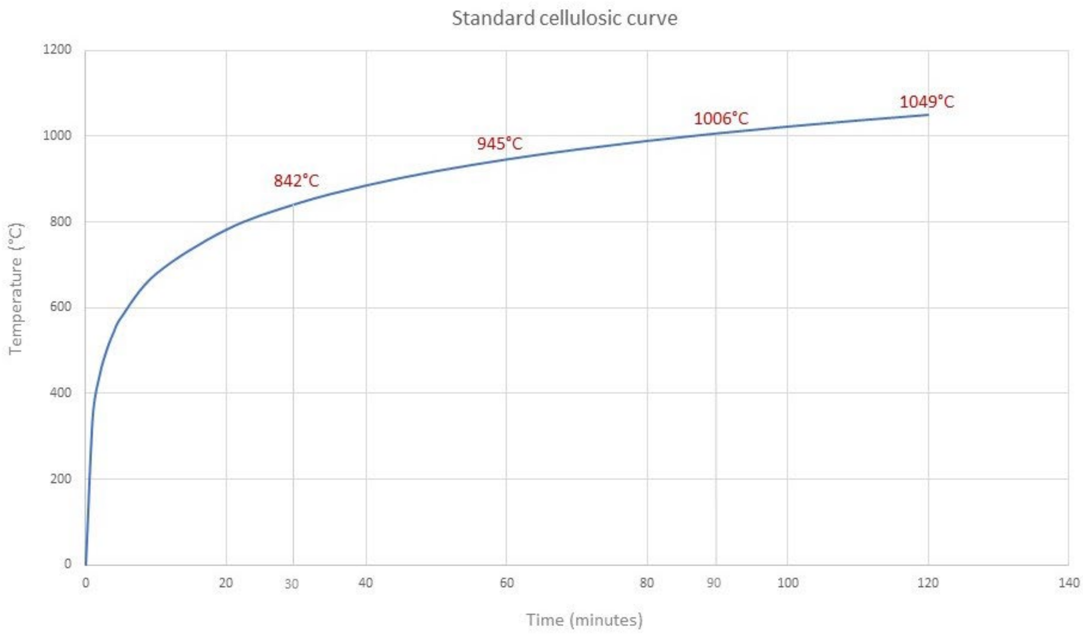

FIGURE 1 – TEMPERATURE-TIME CURVE FOR A STANDARD TEMPERATURE-TIME CURVE (ISO 834, POST-FLASHOVER FIRE)

After 30 minutes of fire, the temperature is already in excess of 800°C. It will continue to rise and reach more than 1000°C after 90 minutes.

FIRE-RESISTANT CABLES

There are a number of circumstances where high risk demands enhanced fire protection. These include buildings with high numbers of occupants, especially where they are unfamiliar with their environment. The need for enhanced protection can also depend on the nature of the activities, or risk in terms of loss of life, historic artefacts, or economic value.

Typical locations include:

- Public buildings and spaces – cinemas, theatres, hotels, museums, transport hubs, and shopping centres
- Buildings with vulnerable occupants – schools, hospitals, and day-care centres
- Where evacuation and rescue access may be difficult – mines, tunnels
- Hazardous locations – chemical manufacturing and storage, bulk powder storage
- Sensitive infrastructure – data centres, communications facilities, banks
- High-rise buildings, where fire could spread very quickly, hampering firefighting and evacuation

The types of equipment that must be available during a fire include:

- Smoke venting systems, including pressurisation and depressurisation fans
- Electrically operated fire shutters and smoke curtains
- Firefighting lifts
- Sprinkler and wet-riser pumps
- Equipment for explosion prevention and suppression
- Command and communications systems, including audible warning devices addressing the public
- Emergency lighting

Cables commonly used for electrical installations would already suffer damage at temperatures much lower than those experienced in a fire. For this reason, one of the following measures must be put in place:

- Protect the cables by installing them in a fire-resistant sleeve, conduit, or trunk, or
- Use cables with intrinsic fire-resistance, specifically designed for the purpose.

Cables with intrinsic fire-resistance can be used unprotected and are classified based on the minimum time they are able "to maintain a reliable form of power supply when exposed to the conditions of the standard temperature-time curve" (EN 13501-3 §5.1.6), expressed in minutes. The standard durations of fire resistance are 30, 60, 90, and 120 minutes – hereunder simply called "fire safety classes".

Calculating the minimum cable cross section for cables that must remain functional during a fire is different from the calculations for cables operating under normal conditions. Because of the high temperatures, the electrical resistance will be much higher. This must be taken into account when assessing the voltage drop and current-carrying capacity. This is discussed in detail in the following chapters.

Conductor sizing of fire-resistant cables

We will first calculate the electrical resistance under fire conditions, before relating it to the voltage drop and the current carrying capacity of the cable. The appropriate conductor cross section will follow from a combination of both assessments.

The conductor resistance under fire conditions

In normal electrical applications, the resistance of a copper conductor can be calculated using the following formula, which is valid up to about 200 °C:

$$R = R_{20}(1 + \alpha_{20}\Delta T)$$

where:

R_{20} is the conductor resistance at 20°C, in Ω

α_{20} is the temperature coefficient of resistance at 20°C, per °C. α = 0.0039 for copper

$\Delta T = T_k - 20$ is the temperature difference, in °C

T_k is the final temperature, in °C.

At temperatures higher than 200°C, the relationship between the temperature and the conductor's resistance becomes non-linear and is given by the formula:

$$R = R_{20}(1 + \alpha_{20}\Delta T + \beta_{20}\Delta T^2)$$

where:

$\beta_{20} = 6.0 \times 10^{-7}$ °C^{-2}

Alternatively, application of the Wiedemann-Franz law yields:

$$R = R_{20}\left(\frac{T}{T_{20}}\right)^{1.16} = R_{20}\left(\frac{T}{293}\right)^{1.16}$$

where:

R is the resistance at temperature T

R_{20} is the resistance at 20°C (293 K)

T is the temperature in K (i.e., temperature in °C + 273)

Neither formula are exact laws of physics, but they are both useful approximations. The minor differences in outcomes of the two formulae, and their slight variance with physical reality, are negligible compared to the range of uncertainties involved in modelling a fire situation.

Using the Wiedemann-Franz law, the correction factor *m* to be applied when calculating the electrical resistance at fire temperature T_y (in K) compared to the resistance at base temperature T_x (in K) can be obtained from:

$$m_x = \left(\frac{T_y}{T_x}\right)^{1.16}$$

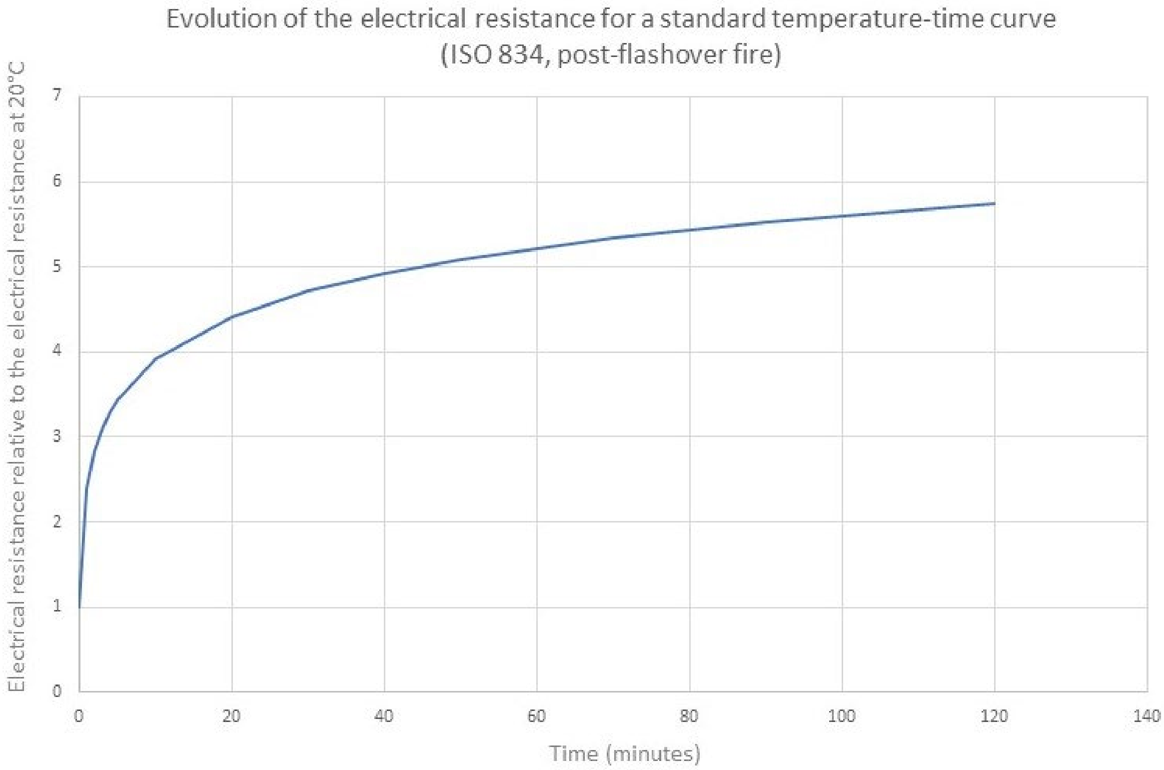

FIGURE 2 – EVOLUTION OF THE ELECTRICAL RESISTANCE, RELATIVE TO THE ELECTRICAL RESISTANCE AT 20°C, OF A CABLE SUBJECTED TO A STANDARD TEMPERATURE-TIME CURVE. AFTER 120 MINUTES, THE ELECTRICAL RESISTANCE IS ALMOST 6 TIMES HIGHER.

CALCULATING THE VOLTAGE DROP

To ensure that all fire safety equipment will maintain its functionality for the required length of time, the voltage drop in the cable supplying it must be restricted. Usually, the maximum voltage drop will be specified in the equipment's user guide. If this is not the case, one must consider a maximum voltage drop of 10%.

Since the voltage drop is caused by the energy losses over the entire length of the cable, those losses must be restricted. This can be done by choosing an adequate cable cross section.

The voltage drop can be calculated from the following formulae for single-phase and three-phase circuits:

1/ for a single-phase circuit:

$$\Delta U = 2\,.\,l_{tot}\,.\,(R_f\,.\cos\varphi +\ \omega\,.\,L\,.\sin\varphi\,)\,.\,I =\ 2\,.\,l_{tot}\,.\,(R_{20}\,.\frac{R_f}{R_{20}}\,.\cos\varphi +\ \omega\,.\,L\,.\sin\varphi\,)\,.\,I$$

2/ for a three-phase circuit:

$$\Delta U = \sqrt{3}\,.\,l_{tot}.\,(R_f\,.\cos\varphi +\ \omega\,.\,L\,.\sin\varphi\,)\,.\,I = \sqrt{3}\,.\,l_{tot}.\,(R_{20}.\frac{R_f}{R_{20}}.\cos\varphi +\ \omega\,.\,L\,.\sin\varphi\,)\,.\,I$$

where:

l_{tot} is the total cable length

R_f is the electrical resistance per cable length in case of a fire

Cos φ is the power factor

ω is the radial frequency

L is the inductance per cable length

R_{20} is the electrical resistance per cable length at 20°C

I is the rated current

The relation between the resistance at 20°C (R_{20}) and the cable cross section is given in national standards and in Tables 1 to 4 of IEC/EN 60228.

The quotient $\frac{R_f}{R_{20}}$ is given by the correction factor m_{20}.

APPLICATION IN BUILDINGS

Because buildings are often compartmentalised into fire zones, cables feeding fire protection equipment are rarely exposed to fire temperatures over their entire length. The part of the cable not affected by the fire will operate at normal temperature, while that exposed to fire will have increased electrical resistance. The task of the designer is to assess which areas may be simultaneously affected by fire in the worst-case scenario, and what proportion of the cable runs through those affected areas. The total conductor resistance is then calculated by assuming normal resistance for the length unaffected by fire and applying the correction factor m to the length that is affected by fire. This means the total correction factor q_{20} can be calculated from:

$$\boldsymbol{q_{20} = \frac{R_T}{R_{20}} = \frac{((100-y)+(y\ .\ m_{20}))}{100}} \quad \textbf{(EQUATION 1)}$$

where:

y is the percentage of the cable length estimated to be affected by fire

m_{20} is the electrical resistance correction factor, relative to the value at 20°C

The value of m_{20} at 30, 60, 90 and 120 minutes of the standard cellulosic curve are shown in Table 1.

TABLE 1

	Fire resistance class, standard temperature-time curve (ISO 834)			
	30' (842°C)	**60' (945°C)**	**90' (1006°C)**	**120' (1049°C)**
Electrical resistance correction factor m_{20}, relative to the resistance of a cable specified at 20°C	4.71	5.22	5.53	5.74

The resulting values of q_{20} are given in Table 2.

TABLE 2

Correction factor q_{20}	Fire safety class (minutes)			
Proportion in hot zone	30'	60'	90'	120'
10%	1.37	1.42	1.45	1.47
20%	1.74	1.84	1.91	1.95
30%	2.11	2.27	2.36	2,42
40%	2.48	2.69	2.81	2.90
50%	2.85	3.11	3.26	3.37
60%	3.23	3.53	3.72	3.84
70%	3.60	3.95	4.17	4.32
80%	3.97	4.38	4.62	4.79
90%	4,34	4.80	5.08	5.27
100%	4.71	5.22	5.53	5.74

With this, we can write the voltage drop formulae as follows:

1/ for a single-phase circuit:

$$\Delta U = 2\,.\,l_{tot}\,.\,(R_{20}\,.\,q_{20}\,.\cos\varphi + \ \omega\,.\,L\,.\sin\varphi\,)\,.\,I$$

2/ for a three-phase circuit:

$$\Delta U = \sqrt{3}\,.\,l_{tot}.\,(R_{20}\,.\,q_{20}\,.\cos\varphi + \ \omega\,.\,L\,.\sin\varphi\,)\,.\,I$$

The maximum electrical resistance at 20°C (R_{20}) that will limit the voltage drop to ΔU under fire conditions can be calculated from:

1/ for a single-phase circuit:

$$R_{20} = \frac{\Delta U}{2\,.\,l_{tot}.\,I\,.\,q_{20}\,.\cos\varphi} - \frac{\omega\,.\,L\,.\sin\varphi}{q_{20}\,.\cos\varphi}$$

2/ for a three-phase circuit:

$$R_{20} = \frac{\Delta U}{\sqrt{3}\,.\,l_{tot}.\,I\,.\,q_{20}\,.\cos\varphi} - \frac{\omega\,.\,L\,.\sin\varphi}{q_{20}\,.\cos\varphi}$$

For conductor cross sections less than 16 mm², the inductive part may be ignored.

For cross sections greater than 16 mm², $\omega\,.\,L\,.\sin\varphi$ can be approximated by the value 0.048 in all cases.

Following on from this:

1/ for a single-phase circuit:

$$R_{20} = \frac{\Delta U}{2\,.\,l_{tot}.\,I\,.\,q_{20}\,.\cos\varphi} - \frac{0.048}{q_{20}\,.\cos\varphi}$$

2/ for a three-phase circuit:

$$R_{20} = \frac{\Delta U}{\sqrt{3} \, . \, l_{tot} . \, I \, . \, q_{20} \, . \cos \varphi} - \frac{0.048}{q_{20} \, . \cos \varphi}$$

With q_{20} given by Table 2, or calculated by Equation 1 (and m_{20}, given by Table 1).

When the maximum voltage drop ΔU is known, the formulae above give the maximum electrical resistance R_{20}. The appropriate cable cross section associated with R_{20} can be obtained from national standards, or from Tables 1 to 4 of IEC/EN 60228.

Consulting the cable manufacturer is advised to validate these calculations. Depending on national regulations, some modification may be necessary.

MOTOR STARTING CURRENTS

Electric motors draw starting currents many times greater than the running current. Fire pump motors are not usually equipped with soft starters or variable speed drives to mitigate this phenomenon. Add to this the increased electrical resistance under fire conditions, and these currents could lead to a voltage drop that is too great for the motors to continue their start-up. Fire safety circuits must be designed to avoid such failures.

Squirrel-cage induction motors are often used to drive fire pumps because of their simple construction and good reliability. For this type of motor, and in the working conditions of a fire pump, the voltage drop must in no scenario exceed 10%. This figure is to be taken as an initial indication; the exact maximum permissible voltage drop value will be indicated in the motor's user guide and/or in the national regulation.

ASSESSING CURRENT-CARRYING CAPACITY

The IEC 60364-5-52 standard stipulates the maximum current-carrying capacity for cables working under normal service conditions, depending on the nominal cross-section of the conductor(s), the type of electrical insulation, and the installation method. The limiting factor is the maximum temperature the cable insulation can withstand – typically 70°C or 90°C. In the case of fire-resistant cables, the electrical insulation is designed to withstand extreme temperatures for a defined duration (30, 60, 90 or 120 minutes), which could lead to the false assumption that there is no limit in the current-carrying capacity of those cables.

In reality, Joule losses might cause fire resistant cables to reach higher temperatures than those they were designed for, since the prevailing testing protocols described in the standards do not fully take into account the potential additional heat production caused by the increased electrical resistance at high temperature combined with the reduced heat dissipation under fire conditions.

Indeed, the cable's thermal balance depends on:

- Internal heat production due to electrical losses (Joule losses), and
- Heating or heat dissipation through radiation, convection, and conduction.

The Joule losses are proportional to the square of the current. In fire conditions, their contribution to the cable's thermal balance will be more significant due to:

- The increased electrical resistance at high temperature, and
- The reduced heat exchange with the cable surroundings due to the high temperature of flames.

The Joule losses could consequently result in a cable temperature surpassing the maximum value it was designed for, in particular towards the end of the duration corresponding to the safety class under consideration. To investigate whether this could affect cable performance, laboratory tests were carried out at Nexans in Lyon, France in November 2022, while a second series of tests is due to be carried out in a different laboratory in the first half of 2023 to validate the results.

The tests were carried out on:

- 1.5 mm^2 fire-resistant cables carrying 25 A
- 4 mm^2 fire-resistant cables carrying 45 A

They followed the standard temperature-time curve of a post-flashover fire as defined in ISO 834.

The tests revealed that, up to 90 minutes, the Joule losses do not affect the performance of the copper conductors. After that time, they lead to a conductor temperature approaching the copper melting point, causing the conductor to break. If the installation must remain functional beyond 90 minutes (safety class 120), measures should be taken to avoid such a loss of integrity in the cable. It is highly recommended to consult cable manufacturers or fire engineers who can assist in modelling the thermal balance of the cable under fire conditions according to the IEC 60287-1 analytical method. Subsequently, the conductor cross-section can be increased until the impact of the Joule losses on the thermal balance is sufficiently minimized. This measure can be combined with the installation of additional support structures to reduce the mechanical stress on the cable.

Up to safety class 90, following the IEC 60364-5-52 standard for cables under normal working conditions is sufficient to guarantee the current-carrying capacity, with no further calculations required.

Conclusion

Just as cables used in normal operating conditions, fire resistant cables must have a minimum conductor cross section to ensure that the voltage drop is restricted and the current-carrying capacity guaranteed. When making calculations, however, the increased electrical resistance at high temperature must be taken into account.

1. **Limiting the voltage drop**

   The maximum voltage drop ΔU will normally be specified in the user guides of the fire safety equipment. If this is not the case, one must consider a maximum voltage drop of 10%. The associated maximum electrical resistance at 20°C (*R_{20}*) can be calculated from:

   For a single-phase circuit:

$$R_{20} = \frac{\Delta U}{2\,.\,l_{tot}.\,I\,.\,q_{20}\,.\cos\varphi} - \frac{0.048}{q_{20}\,.\cos\varphi}$$

   For a three-phase circuit:

$$R_{20} = \frac{\Delta U}{\sqrt{3}\,.\,l_{tot}.\,I\,.\,q_{20}\,.\cos\varphi} - \frac{0.048}{q_{20}\,.\cos\varphi}$$

   where:

   l_{tot} is the total cable length

   Cos φ is the power factor

   I is the rated current of the circuit

   q_{20} is the electrical resistance correction factor under fire conditions, compared to 20°C

   For cables smaller than 16 mm^2, the last term of the equation ($0.048/q_{20}\,.\cos\varphi$) can be ignored.

   The value of *q_{20}* can be obtained from Table 2 or from:

$$q_{20} = \frac{\big((100-y)+(y\,.\,m_{20})\big)}{100}$$

   where:

   y is the percentage of the cable length estimated to be affected by fire, taking compartmentalisation into account

   m_{20} is the electrical resistance correction factor, relative to the value at 20°C; see Table 1 for a standard cellulosic curve

   The maximum cross section associated with R_{20} can be obtained from national standards for cables operating under normal service conditions, or from Tables 1 to 4 of IEC/EN 60228.

2. **Ensuring the current-carrying capacity**

Up to 90-minute mark of the standard temperature-time curve as defined in ISO 834, the Joule losses do not affect the performance of the copper conductors. The IEC 60364-5-52 standard for cables under normal working conditions is sufficient to guarantee the current-carrying capacity.

After that time (safety class 120), the Joule effect, combined with the fire conditions, lead to a conductor temperature approaching the copper melting point, with the risk of cable breakage. If safety class 120 applies, it is highly recommended to consult cable manufacturers or fire engineers who can assist in modelling the thermal balance of the cable and formulating the required measures.

3. Determining the minimum cable cross section

The cross-section to be chosen is the higher of the two values from assessments 1 and 2.