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Fire hazard of MV/HV cables installed in tunnels

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ABSTRACT

The fire performance of MV and EHV cables in a tunnel fire has been demonstrated using a modified FIPEC horizontal reference test scenario. The results revealed that a cable tunnel fire can have catastrophic consequences. An EHV cable without flame retardant technology exhibited a dramatic fire growth rate with very high heat release. In a real tunnel installation fire fighter access would be impossible and the fire would consume completely the installed cables. The heat release would result in severe structural damage. In contrast, it can be demonstrated that the potential risks might be largely mitigated by the use of sheathing materials with improved reaction to fire performance for the outer layer of the cable.

KEYWORDS

Tunnel fire, flame retardant, FIPEC horizontal reference scenario, EHV, HV, MV

INTRODUCTION

The principal issues when studying the cable tunnel fire scenario are the risk of such an event occurring and the resulting human and economic losses. Basically, the risk can be deemed as very low. However, as can be seen from the examples below, on the occasion that a fire does occur the consequences will often be catastrophic. Risk and prevention becomes a delicate balancing act.

In recent years, tunnel fires in both road tunnels and rail tunnels have claimed the lives of many people. In addition, they have caused severe structural damage and resulting economic loss. The fire in the Mont Blanc road tunnel (France/Italy - 1999) cost the lives of 39 people and caused severe structural damage resulting in a closure of the tunnel for 3 years. A similar scenario was seen from the St. Gotthard road tunnel fire (Switzerland - 2001), claiming 11 deaths and severe damage to the tunnel, with closure for 2 months. The most recent big road tunnel fire (France – 2005) in the Fréjus road tunnel left 2 people dead and 21 injured while 10 km of equipment needed to be repaired.

Besides the possible loss of human lives, the structural damaged caused by a fire can be devastating. The corrosive impact of the fire gases can cause serious malfunctioning of other utilities present, thereby initiating major service disruptions, e.g. power outage, loss of communication etc.. Fire-related non-thermal damage can be categorised according to various criteria. There is the time-scale aspect relative to the fire event such as short term and long term effects of corrosion caused by combustion products. The nature of the exposed materials and their sensitivity towards heat and effluent composition plays an important role in fire development. Within a cable tunnel the essential components are the metal and/or concrete infrastructure and the cabling [1].

An EHV cable typically has a heat capacity of 1000 MJ/m. Fires involving such cables can develop very high energy releases (150 – 600 MW) causing severe damage and rendering futile any effort to extinguish the conflagration. The materials used in the construction and contents of the tunnel are a crucial parameter determining the severity of the fire and the resulting tunnel damage [2].

Our paper concerns the consequence of a fire in an underground EHV or HV cable tunnel. Such a fire is unlikely to involve people and so here the principal concern is loss of function and physical damage. However it will become clear that fire behaviour and prevention are key issues when dealing with power cable tunnel installations. The paper reports the study of the fire performance of MV and EHV cables in a tunnel fire simulated using the FIPEC horizontal reference scenario test set-up. The main focus will be on the effect of using sheathing materials with improved reaction to fire performance (FR) for the outer layer of the cables.

EXPERIMENTAL

Materials

The test programme focussed on the performance of EHV and MV power cables. Five different cables were tested. Their main characteristics are presented in the table 1. The EHV cable is sheathed with a standard black HDPE (no flame retardant properties). MV1 is sheathed with black LLDPE (no flame retardent properties). The other MV cables have flame retardant jackets. MV2 is sheathed with Si-gum, $CaCO_3$ filled LDPE. The jackets of MV3 and MV4 are based on hydrate filled LSZH (Low Smoke Zero Halogen) technology, according to the respective manufacturers´recipe.

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Code	Voltage (kV)	Conductor	Diameter (mm)	Sheath	Insulation
EHV	231/400	1 x 1600RMS/320	128	HDPE	XLPE
MV1	6/10	Al- 3 x 150 #+25#	52-53	LLDPE	XLPE
MV2	6/10	Al- 3 x 150 #+25#	52-53	Si-gum, $CaCO_3$ filled LDPE	XLPE
MV3	6/10	Al- 3 x 150 #+25#	52-53	LSZH	XLPE
MV4	38/66	Cu 1x185# + 95#	57	LSOH	XLPE

Table 1 : Characteristics of the tested cable samples

FIPEC Horizontal Reference Scenario

The horizontal reference scenario has been chosen as the most representative large scale scenario for the testing of cables installed within corridors/tunnels. Figure 1 gives a schematic overview of the experimental set-up. It is a corridor configuration with no forced ventilation. The cables are mounted on three horizontal ladders. A sand burner is positioned at one end, below the lowest ladder. The reaction to fire performance of the cables can be assessed upon exposure to flames directly impinging on the horizontal cable trays. Different kinds of flame spread can be quantified : along one cable tray, from one cable to another as well as the observation of falling debris or molten droplets onto the lower cable trays.

The number of cables per ladder is described in the FIPEC Reference Scenario test method but basically requires each ladder to be filled with a single layer of cables with a space equal to half the cable diameter between each cable [3]. This installation would be totally inappropriate for EHV cables where one cable per tray and maybe a total of 6 or 8 cables within the tunnel would be normal. After some discussion it was decided to maintain the FIPEC geometry but to reduce the loading to 1 cable in the middle of each ladder, regardless of the actual cable diameter. Despite this discrepancy from the FIPEC proposed mounting, it results in a very realistic test set-up with the cables positioned directly on top/below each other (see figure 2). The cable length is 4 m.

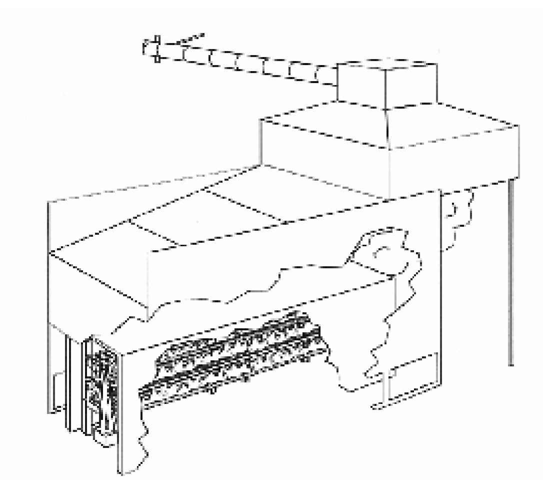

Figure 1 : Schematic presentation of the horizontal reference scenario [2]

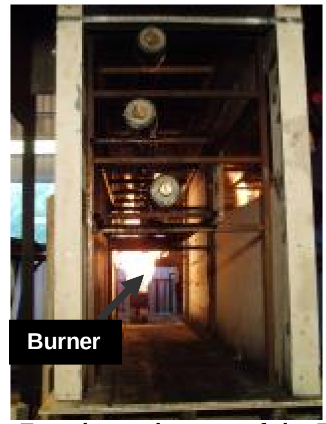

Figure 2 : Experimental set-up of the EHV cable in the horizontal reference scenario (front view)

A heat source programme is used according to the following scheme [3] :

Time (min)	Heat source (kW)	Criteria for next heat source level
0-5	40	No increase to 100 kW if flame spread > 2 m on the highest ladder or HRR* > 190 kW
6-15	100	No increase to 300 kW if flame spread > 2 m on the highest ladder or HRR > 250 kW
16-25	300	

The results obtained from the horizontal reference scenario test are both visual (flame spread and cable damage) as well as numerical , i.e. Heat Release Rate (HRR), Peak HRR, Total Heat Release (THR), Fire Growth Rate index (FIGRA), Smoke Production Rate (SPR), Total Smoke Production (TSP) and SMOke Growth Rate (SMOGRA).

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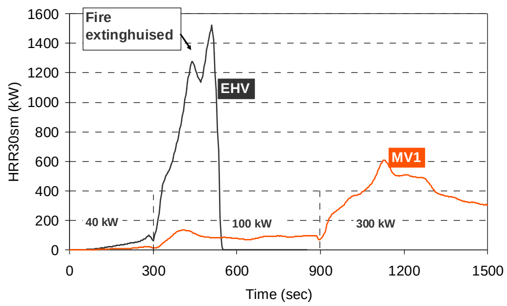
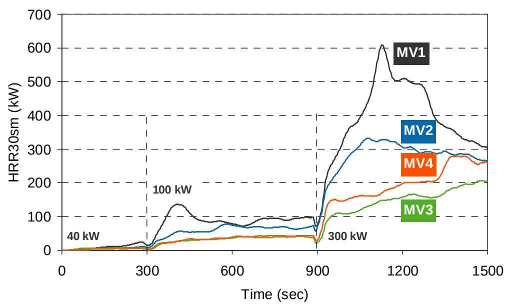
RESULTS

Heat generation

The modified FIPEC horizontal reference scenario test provides a powerful means for differentiating the fire performance of the five different cables. Figure 3 provides an overview of the heat release rates as detected during the fires, illustrating the course of the fire.



(a)



(b)

Figure 3 :
(a) Heat release rate (smoothed over 30 sec.) of the non FR sheathed cables (EHV and MV1)
(b) Heat release rate of the MV cables

The most immediate observation to be made is the overwhelming impact of cable size. A burner capacity of 40 kW is too low to initiate a quick fire development, regardless of the size or nature of the jacket. However, increasing the burner capacity to 100 kW results in an extremely rapid fire growth of the HDPE sheathed EHV cable. This phenomenon is also demonstrated by the very high FIGRA value (Table 2), expressing the rate of the fire growth. With FIGRA 5 times greater then the respective MV LLDPE cable, the EHV cable displays a considerably stronger fire growth. The rapid fire growth is accompanied by a rapid flame spread, reaching 3,5 m (top ladder) within 4 min of increasing of the burner capacity to 100 kW. The EHV cable reached a HRR level of close to 1,6 MW at which time the fire had to be extinguished by external means (water hose). This was due to the heat release and the violent character of the fire being close to the safety limit of the experimental test set-up. The result is unexpected as normally we find that large cables are more difficult to ignite and exhibit a slower fire growth. For the test under consideration the mounting and the potential for thermal transfer and dripping between the three cables clearly played a significant role. In the case of the MV cable based on LLDPE the fire growth was much reduced and we believe that the smaller cables limited the scope for interaction between the ladders thus reducing the scale of the fire.

The reaction to fire performance of the non flame retardant sheathed cables is different compared to the power cables having a flame retardant jacket. All MV cables only start to show increased burning when the burner capacity is increased to 300 kW. However, the LLDPE sheathed MV cable (MV1) displays the strongest reaction to fire as expressed by its distinctly higher FIGRA and peak heat release rate when compared to the FR sheathed MV cables. The latter cables clearly display the lowest FIGRA values.

	EHV	MV1	MV2	MV3	MV4
FIGRA (W/s)	**2983**	539	308	140	203
SMOGRA (cm^2/s^2)	227	47	46	44	30

Table 2 : FIGRA and SMOGRA values of the different power cables

The LLDPE sheathed MV cable generates a significantly higher (double) amount of heat compared to the FR sheathed MV cables, displaying much more moderate peak HRR levels (200 -300 kW). As expected the less flame retardant Si-gum, $CaCO_3$ filled LDPE (MV2) sheathed cable exhibits performance somewhere between the respective LSZH/LSOH sheathed cables (MV3/4) and the LLDPE sheathed MV cable (MV1).

The nature of the jacket material used to sheath the power cables, obviously has a significant impact on the resulting fire performance. To visually illustrate this effect, figure 4 shows the fire progress for the EHV, MV2 and MV3 cables at a specific moment during the experiment. The HDPE sheathed EHV cable shows a fully developed fire with complete flame spread over the top ladder shortly after increasing the burner capacity to 100 kW. The Si-gum, $CaCO_3$ filled LDPE sheathed cable displays a flame spread of ~ 2 m (top ladder) after an elapsed test time of 19 min (highest burner capacity – 300 kW). The fire performance of the LSZH sheathed cable (MV3) is clearly better, reaching the 1,7 m mark after ~ 22 min, also at a burner capacity of 300 kW.

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(a)

(b)

(c)

Figure 4 : Pictures illustrating the fire growth and flame spread for :
(a) EHV 100 kW 6 minutes
(b) MV2 300 kW 19 minutes
(c) MV3 300 kW 22 minutes

Temperature

The effluent temperature was measured in the exhaust duct approximately 8m from the collection hood. At this point the effluent had been diluted with make-up air from the hood and as such it is not directly related to the actual temperature in the vicinity of the fire. However, it is believed that the temperatures in the plume above the fire must have exceeded 1000°C. Despite this discrepancy in measuring distance, the temperature provides an indication of the fire temperature which would be experienced by the people and structures within a 10 m radius of the fire. The MV cables generate clearly lower temperatures and at a much later stage of the experiment compared to the EHV cable. The presence of an FR sheath does not seem to significantly reduce the fire temperature.

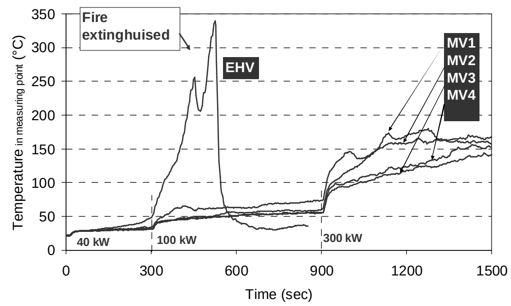

Figure 5 : Temperature measured in the fumes at approximately 8 m from the fire source

Damage

The physical damage to the cables is summarised in Table 3.

	L1 (upper)	L2 (middle)	L3 (lower)
EHV	3,5	2,8	1,3
MV1	3,3	3,2	3,0
MV2	3,2	3,0	2,9
MV3	2,6	1,9	1,6
MV4	2,6	1,7	1,5

Table 3 : Damaged cable length (m) measured after the fire

The most important observation to be made is the fact that the EHV cable fire had to be extinguished after less than 10 minutes whereas the MV cables were allowed to progress to the full extent of the test period. The flame spread of the later took much longer as the fire only had a real impact at the highest burner capacity (300 kW). There is a start-up period during which the fire consumes all material present in the initial part of the upper cable, before spreading. Although the flames do not pread that far along the lower ladders, a significant part of the lower MV1 cables is damaged as can be seen from table 3. This is mainly due to falling debris and burning droplets initiating local fire spots before the actual fire has reached that location. The MV3 and MV4 cables also display falling debris but to a lesser extent than the (less flame retardant) MV2 cable, hence less cable is damaged.

Visibility

The visibility is largely determined by the smoke generation and the smoke growth rate. Figure 6 illustrates the smoke production rate of the different tested cables. The SMOGRA values are given in table 2.

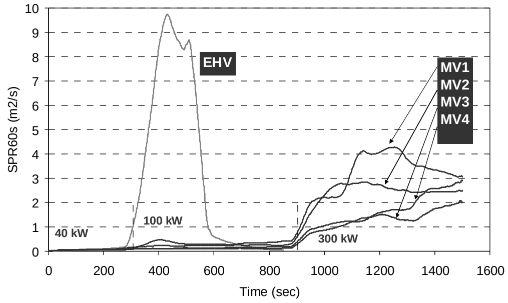

Figure 6 : Smoke production rate (smoothened over 60 sec) for the tested cables

In accordance with the heat release rate results, the smoke production displays a similar course of development. The HDPE sheathed EHV cable clearly has a very strong (black) smoke production even before the cable is subjected to a fully developed fire (shortly after 300 sec.) (see figure 7). Given sufficient ventilation the combustion of PE will result in the formation of CO_2 with very little smoke. However, in the case of a violent fire there is insufficient oxygen, resulting in an increase in partially combusted product, i.e. smoke and CO. This is seen by the lower vitiation factor (CO_2/CO) as illustrated in Figure 8. The reduced vitiation factor is only reached when the burner capacity is switched to 100 kW and the cables really catch fire. The FR sheathed cables burn more slowly, produce less smoke and display a significantly higher vitiation factor (lower CO production). Also for the MV cables, the vitiation factor only becomes of interest when the cables start to burn more extensively. The LLDPE sheathed MV1 cable reaches earlier a more vitiated stage.

Figure 7 : Illustration of the smoke production of the HDPE sheathed EHV cable approximately 8 minutes after the start of the test.

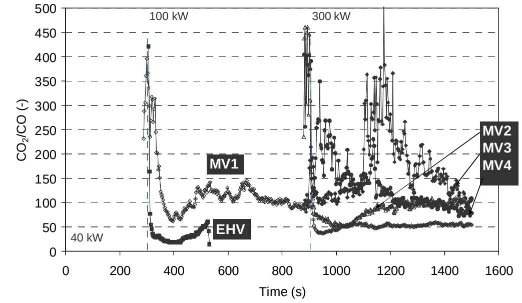

Figure 8 : CO_2/CO ratio as a function of time for the energy cable tested. No values are reported from the initial phase of the testing as the CO level (too low) could not be detected accurately.

DISCUSSION

The different fire performance of the five cables is striking. A simple comparison is to consider the key fire properties FIGRA and SMOGRA which in a conventional hazard analysis would clearly enable the potential impact of any fire to be considered (Table 2).
However for the current application we are less concerned with hazard and more with the impact of the fire in terms of damage and fire fighter access to the fire.

<u>Tunnel structural damage</u>

Structural damage encompasses the damage to the tunnel infrastructure like the concrete lining, cabling, etc. The initiation of cracking of concrete is very dependent on the actual surrounding environment (i.e. humidity and temperature) but in general it can be stated that concrete cracking will start when in contact with hot fume gases having a temperature of 600-700 °C [4]. It is quite obvious that the high temperatures reached during the burning of the non flame retardant EHV cable will cause structural damage to occur at a very early stage after the initial outbreak of the fire. In the case of the MV cables the temperature is clearly much lower and the scope for structural damage is reduced. Although not seen in the measured temperature, the lower energy release for the FR cables would certainly result in lower temperatures in the immediate vicinity of the fire. The most important question (which is one we are unable to answer) is to understand the benefit that an FR sheath could confer on a large MV or EHV cable. Based on the MV experiments we could anticipate a FIGRA reduction of 40 – 60% but it could be more important if the runaway fire identified in the current study could be avoided.

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Cable damage

Although it is assumed that the primary source of the fire will be the principal power cable, damage to the secondary cabling present in the tunnel can have severe consequences for the general functioning of the tunnel infrastructure. Specifically the access of any fire fighter team will be strongly hampered due to malfunctioning of the cabling , e.g. loss of power, loss of lightening and shutdown of the ventilation system. The latter can also have a devastating effect on the fire progress as good ventilation can ´drive´ the fire away from any critical point in the tunnel as well as decrease the presence of toxic gases in the available air.

Fire fighter access

Figure 9 illustrates the flame spread along the 3 different ladders during the fire progress for the EHV, MV2 and MV3 cable. The flame spread of the EHV cable along the top ladder is very fast. Within a short period of time, the complete cable is on fire. Also the middle ladder gets severely damaged during the fire whereas the lowest cable is relatively intact after the fire. From these results it is clear that after 10 minutes there is no realistic possibility of any fire fighter gaining access to the EHV fire. As a result the fire will develop unchecked with the total destruction of the tunnel + contents.

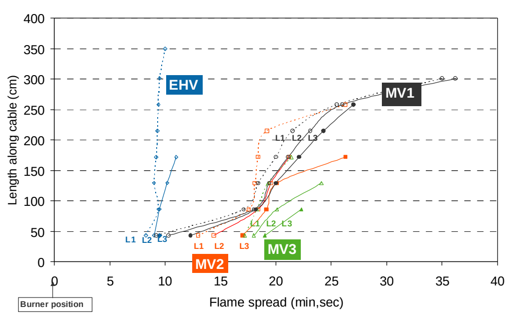

Figure 9 : Flame spread (min:sec) (X-axis) along the cable length per ladder :
L1 : upper ladder (open symbol, dotted line), L2 : middle ladder (open symbol, full line) and L3 : lower ladder (close symbol).

As already indicated, the flame spread of the MV cables is much slower and real structural and cable damage can only be expected after a significant amount of time has elapsed. In addition, the cable damage is only initiated at the highest burner capacity. The delay in the fire growth minimizes damage (cable and tunnel), increases the fire fighter access and potentially delays the loss of the functional tunnel cabling (lighting etc).

CONCLUSIONS

A cable fire involving a non FR sheathed EHV cable could result in a massive fire with limited opportunities for fire fighter access.
The consequence of such a fire could be the complete destruction of the tunnel contents + significant structural damage to the tunnel.
The effect of a FR sheath on an MV cable is to reduce FIGRA to between 40-60% of the value demonstrated for an equivalent cable having a non FR polyolefin sheath. There is a key need to quantify the benefit of an FR sheath on an EHV/HV cable.
The utility of the modified FIPEC Horizontal Reference Scenario to evaluate the fire performance of cables installed within tunnels is demonstrated.

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