

Study of Empirical Analysis of Cable and Passive Fire Protection of Cable Fire.

Dr.A.R.Sontake¹, Atharv Tivale², Harsh Chaurasiya², Aditya Diwate², Kamlesh Kumar Yadav², Sanjay M²

1. Professor , National fire service college, Nagpur

2. B.Tech Students , National fire service college

1.Introduction

1.1 Overview:-

Electrical cable fire is major reason in modern day to day life for fire incident in structural fire. Electric cable is fundamental components of modern infrastructure and used to transmit the electrical power and communication signals in residential, commercial, industrial system. Their reliability is essential for continuous operation and for the continuous use of the system. Yes, this integration brings the vulnerability: the polymer insulated cable have risk of ignition and possible fire hazard in associated area, this can lead to the catastrophic incident which result in loss of material and sometimes life. Cable consist of underestimated fire load that can serve as both ignition and fuel for flame spread.

The main reason behind the cable fire is degradation of cable insulation, exposed to excessive heat, electrical fault or external fire sources. Once cable fire is initiated it can spread rapidly along the cable routes. When these cables ignited adjacent cable can ignite in approximately 40 seconds when exposed to arc- generated flames.

Fire spread in cable is a complex phenomenon driven by the nature of the material fuel and thermal feedback. The empirical reality in cable fire behaviour is governed by complex, non-linear interaction between thermal degradation and environmental ventilation.

1.2 Scope:-

A primary focus with in this review is the empirical analysis of ignition thresholds for various cable configurations. The investigation of flame propagation kinetics, comparing vertical and horizontal spread divers cable tray systems. This investigation also helps to give idea about how fire spread in cable and combustion phenomena in cable. Combustion is very essential phenomena which supports the fire growth or fire spread in cable. By knowing this study, we can predict the severity of fire in different infrastructure like industry, data centre. It covers the performance of passive fire protection technologies which includes the effectiveness of intumescent coating. This analysis evaluates how material composition, geometric configuration, and environmental variables influences structural cable survivability. It identifies the discrepancies between standardized qualification testing and actual system survivability, which is essential for accurate risk assessment

1.3 Objective :-

The objective of this review is to establish a unified empirical taxonomy of cable fire behaviour and protective performance. This study seeks to reconcile the observed disparities between standardize laboratory testing protocol and non-linear thermal dynamics inherent in high consequence industrial fire events. By critically evaluating the failure threshold of intumescent system and fire stop barrier. The aim of the review is to develop predictive framework that enhance the accuracy fire resilience modelling in complex multi- conduit electrical infrastructures.

2. Literature review:-

2.1 Study of cable construction and material composition:-

Cable construction is vary according to need and cost material in different structures like in industry we required the high conductive metal core and more effective insulation because of the high voltage is used in the industrial facility.

2.1.1 Cable configuration:

The study state that commercial cable differ significantly from laboratory scale fire because they have multiple layers of insulation, because of that they have complex combustion phenomena. There are different types of layers surrounding the core of the cable. Typically there are three layers inner sheath, insulation and outer sheath.

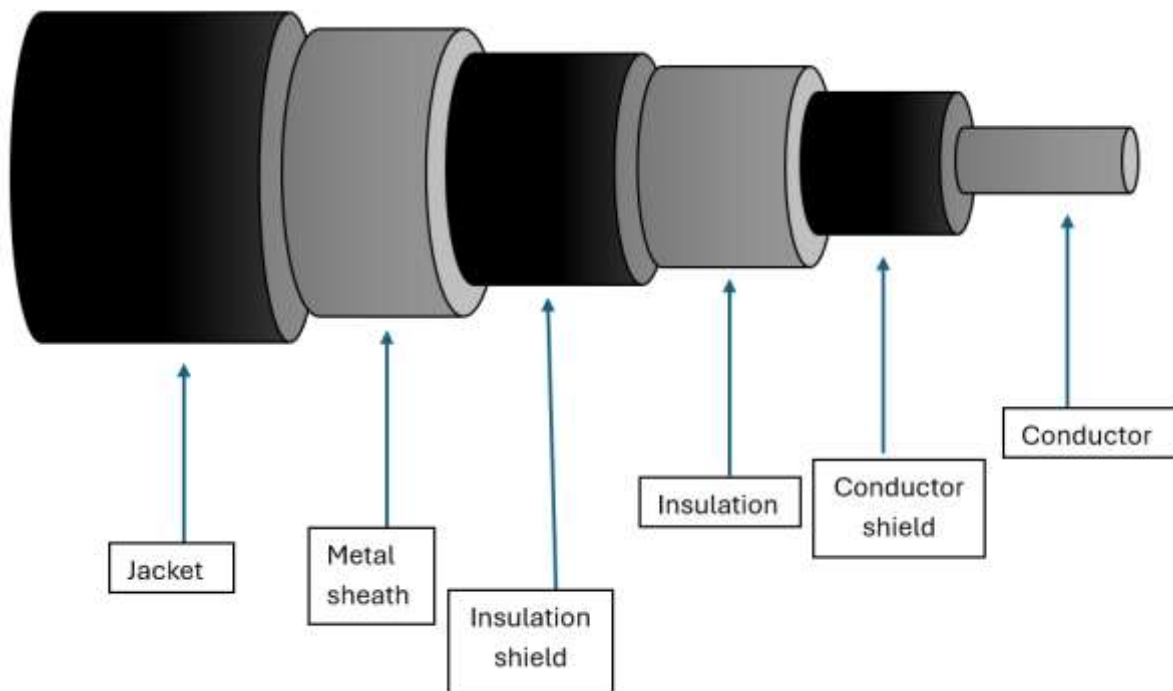


Figure 1. The above figure represent the basic structure of cable, which includes layers like conductor, conductor shield, insulation, outer shield, metal sheath, jacket.

Main part of the cable conductor which transmit the electric load to the specific destination. The layers around the core is not fixed it will vary according to the use of the cable and environmental condition.[1]

For Example:-the cable used have 3 layers of outer flame-retardant polyvinyl chloride (PVC) sheath, a cross-linked polyethylene (XLPE) insulation layer, and an inner copper conductor.

Like for above study they have not used the metal sheath because it is not mandatory to use the metal sheath, the metal sheath can be used in the high risk area where risk of ignition from outer side is more.[2]

2.1.2 Types of core:

There are mainly two types of conductor used in the cable i.e. aluminium and copper. The study show that the copper conductor have lower heat release rate than aluminium conductor, high thermal conductivity of copper allows copper to spread heat along the conductor effectively hence the copper conductor acts as heat sink. It will maintain the lower

temperature along insulator preventing from ignition. Hence it has slower heat spread than the aluminium.

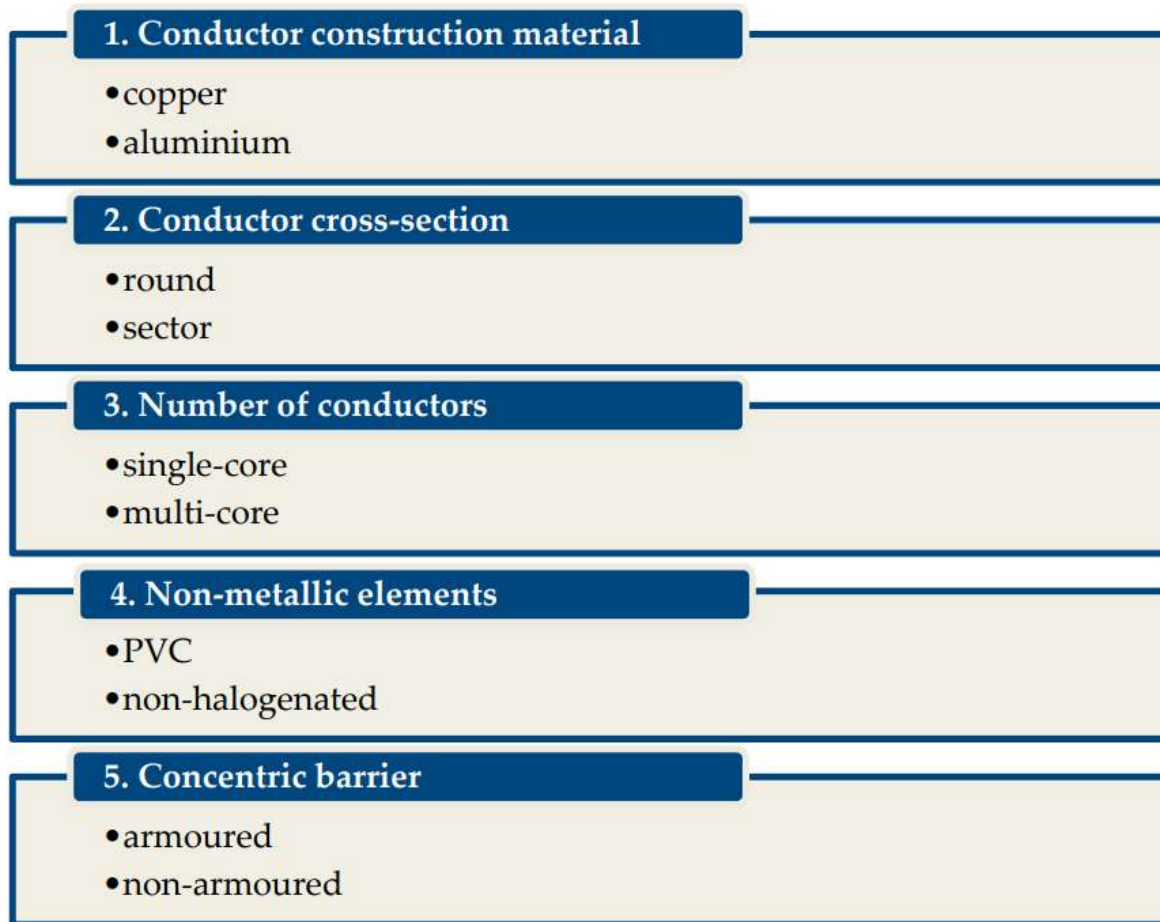


Figure 2. Identified constructional-material parameters of cables.[3]

2.1.3 Cable insulation material:-

There are several types of insulation systems for cables. Several factors have to be considered while making the choice of the choice of the insulation system. Trade-off is necessary between performance, processibility and cost of material. These Synthetic Rubber-like Insulating Materials are classified in four Classes: Elastomeric, Thermoplastics, Fluorocarbons, Thermosetting.[5]

Elastomers are materials that can be compressed, stretched, or deformed like rubber and yet retain their original shape. Elastomeric compound returns rapidly to initial shape and dimensions after deformation, at room temperature and with small stress. Under similar conditions, thermoplastic compound shows permanent deformation, Conventional elastomers need be cross linked with rubber by vulcanization generally by chemical methods. Thereby the resultant compound gets familiar characteristics like Rubber.

Examples of Elastomeric compounds are:

Natural Rubber (NR), Polychloroprene (PCP), Ethylene Propylene Rubber (EPR), Chlorosulfonated Polyethylene (CSP) Silicone Rubber.

The most common and popular synthetic rubber-like compounds in use today are :

EPR: Ethylene Propylene Rubber an Elastomers Compound.

EPDM: Ethylene Propylene Diene Monomer

PVC: (Polyvinyl Chloride), is a Thermoplastic Compound

PE: Polyethylene is a Thermoplastic Compound

PTFE: (Poly Tetra Fluoroethylene), is a fluorocarbon compound.

SEMICON: Semiconducting polymer compound.

XLPE: Cross linked Poly Ethylene, XLPE is Thermosetting Compound.[1]

Parameter	XLPE	EPDM	SiR	Semicon
Relative permittivity (ϵ_r)	$\epsilon_r=2.30$	$\epsilon_r=2.90$	$\epsilon_r=3.50$	$\epsilon_r=2.30$
Thermal conductivity (λ)	$\lambda=0.38$ W/m/K	$\lambda=0.30$ W/m/K	$\lambda=0.20$ W/m/K	$\lambda=0.34$ W/m/K
Specific heat	$C_p=1.90$ J/g/K	$C_p=0.73$ J/g/K	$C_p=2.25$ J/g/K	$C_p=1.90$ J/g/K
Electrical conductivity (σ)	$\sigma=4.7 \times 10^{-17}$ S/m	$\sigma=1.0 \times 10^{-15}$ S/m	$\sigma=9.2 \times 10^{-15}$ S/m	$\sigma=6 \times 10^3$ S/m
Temperature coefficient	$E_a=1$ eV	$E_a=0.44$ eV	-	-
Field coefficient /30°C Field coefficient /60°C	$B_E=1.38 \times 10^{-7}$ m/V $B_E=1.12 \times 10^{-7}$ m/V	$B_E=0.95 \times 10^{-7}$ m/V $B_E=1.08 \times 10^{-7}$ m/V	$B_E=4.1 \times 10^{-16}$ m/V	
Field power law	$a=-0.15$	$a=1.42$	-	-

Table 2 :Thermal and electrical parameters for various materials.[1]

2.2 Ignition and fire propagation:

Ignition and fire propagation plays the critical role in fire cable fire. By investigating the research paper we can understand the “How cable behaves during the fire and how it plays the major role”.

2.2.1 Ignition :-

The ignition in the cable can occur mainly through two reasons.

- The metal core produces the Joule heat, which heats the insulation and may even directly lead to an ignition during the event of the short circuit.
- The metal core changes the heat transfer process, if the wire is exposed to an external heat source from the environment or an internal heating from the core.

Figure 3. Illustrates three basic heating protocols relating to the ignition of electrical wire,

- the convective or radiant heating from the external source such as the flame or the hot smoke, (b) the local heating from the core to insulation, if core is directly heated by the flame or by the Joule heating at the poor connection point, and (c) internal heating from core due to the Joule heat during the short circuit or overload.

For the heating protocol,

- the core acts as the heat sink because of its large thermal inertia ($\rho c \lambda$) and the cooling effect along the longitude direction.

On the other hand, for the heating protocols (b) and (c), the core acts as a heat source to assist the heating of insulation. In reality, the wire could be heated under all three heating protocols at the same time, and the heating process could be transient.[4]

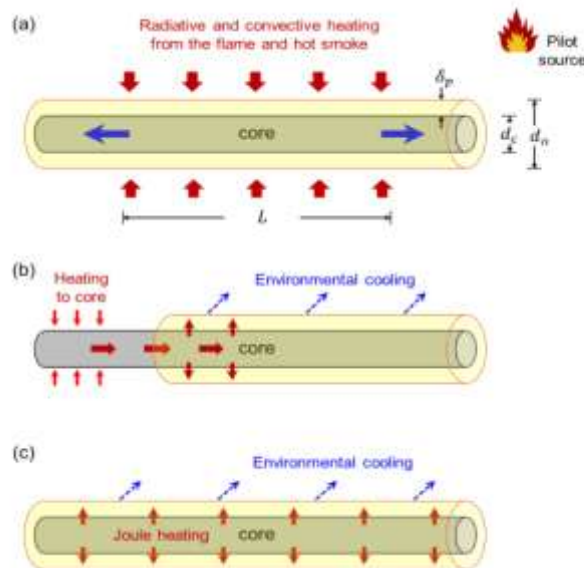


Figure3:- The schematic diagram for the ignition of wire under (a) the external heating, (b) the end heating from the core to insulation, and (c) the Joule heating during a short circuit.[4]

Since metal core has high thermal conductivity it tends to have uniform temperature along the wire.

Under the heating protocol (a), the ignition source could be local or not strong enough. Then, even if flaming ignition occurs, the ignition may not be sustained to stabilize a flame spread due to the cooling of the core. To ensure the transition from ignition to flame spread, additional external heating may be required, because core acts as a heat sink to cool down the ignition zone and quench the weak flame.[4]

2.2.2 Fire spread :-

Flame spread in cables is the process by which fire propagates along the length of an electrical cable after ignition. It occurs when the cable's combustible materials (such as insulation and outer sheath) ignite and continue to burn, allowing the flame to travel from one section of the cable to another.

Unlike normal flat substance the wire has cylindrical cross sectional area, hence the convective heat transfer through the wire is more than the normal material. Therefore the flame spread is influenced by the wire diameter, insulation thickness, metal conductivity. The study states that the flame spread is more in case of horizontal wires than the vertical cable.

Flame will not sustain in case where heat released during combustion is not sufficient for the pyrolysis of the insulation material and metal core acts as heat sink. The dripper material is also removed from the combustion zone, hence flame will not sustain for longer duration and weakens the combustion.[4]

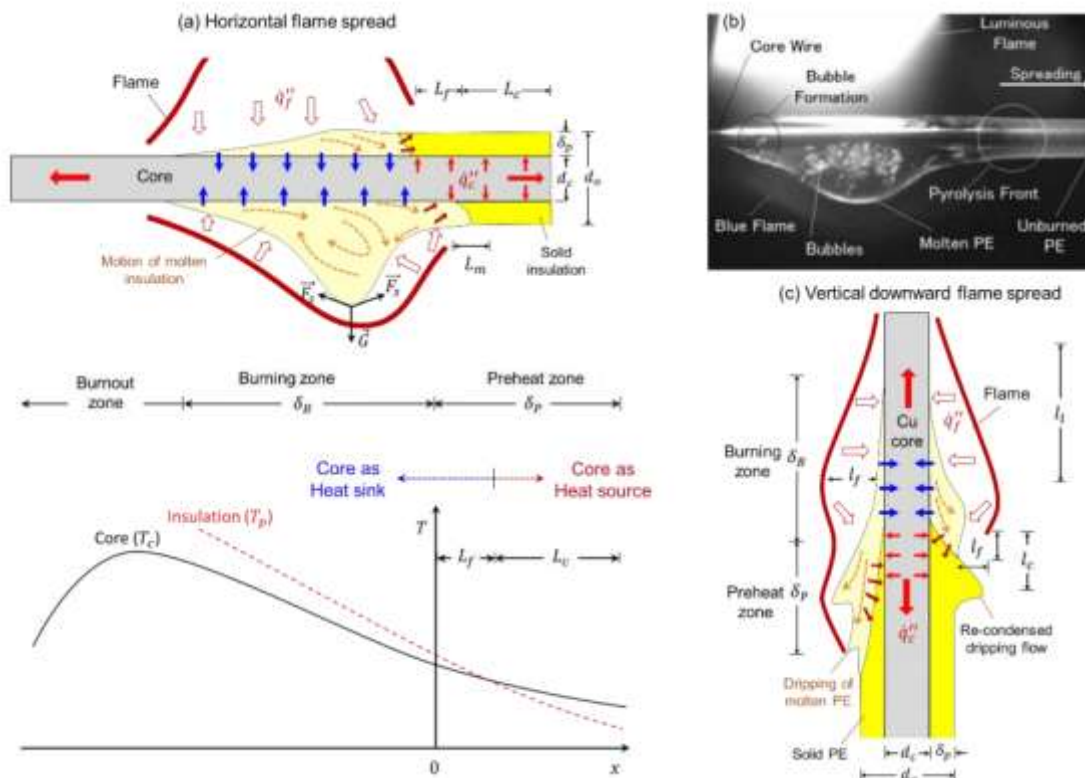


Figure 4. The schematic diagram for (a) the flame spread over the horizontal wire, together with the photo (b), and (c) the vertical downward flame spread [4]

2.2.3 Different phenomena in cable during fire:-

• Swelling:-

Cable swelling is the increase in the diameter or volume of an electrical cable when it is exposed to high temperatures or fire. It occurs because the materials inside the cable (insulation, sheath, fillers, and bedding) undergo physical and chemical changes such as thermal expansion, softening, gas formation, and decomposition.

They give increasing heat flux to the cable to test this cable, the cable they have used here is 3 layers of outer flame-retardant polyvinyl chloride (PVC) sheath, a cross-linked polyethylene (XLPE) insulation layer, and an inner copper conductor. Initially, no changes were observed in the cable, when heat flux rises the external layer begins to decompose and starts to expand. When gases are released with in external layer its diameter increases the twice of its original diameter. The gas released during these are accumulated inside this soft layer.[2]

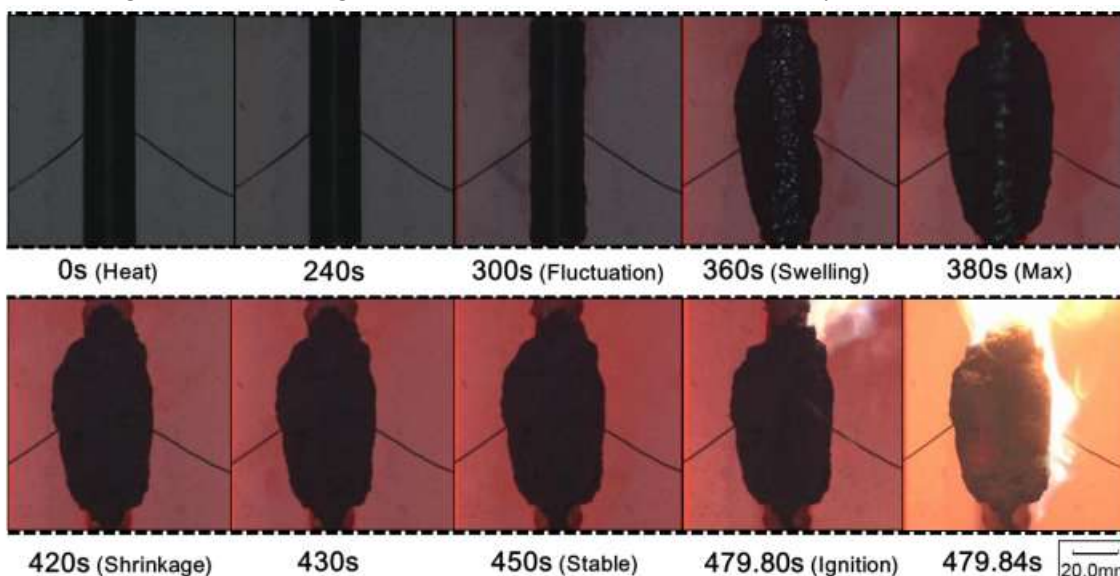


Figure 5. Snapshot series of the swelling and spontaneous ignition of flame-retardant cables sample for 70% full heating level in the chamber, where two wires on both sides are thermocouples.[2]

• **Spontaneous ignition:-** Alone external layer is not sufficient to start the ignition, when external pvc layer formed char layer and inner XLPE layer decompose during heating and release gas, when these gases are come into contact with the charred layer this can lead to the spontaneous ignition. The cable will be ignited without spark or flame. The time for ignition is depend upon the intensity of external heat flux, higher the external heat flux lower the time of ignition. Because the external heat flux increases the decomposition of insulation material and hence responsible for rapid spontaneous combustion.

In observation the measured temperature of surface of the cable sheath is 500 C independent the external heat flux , so 500 c can be threshold temperature for the spontaneous combustion of pvc sheath. [8]

Mechanism of Spontaneous Ignition

1. Self-heating
 - Slow oxidation or chemical reactions generate heat within the material.
2. Heat Accumulation
 - If the heat cannot escape, the material's temperature continues to increase.
3. Thermal Runaway
 - Higher temperatures accelerate the chemical reactions, producing even more heat.
4. Ignition
 - Once the material reaches its auto-ignition temperature, combustion starts without any external ignition source.[7]

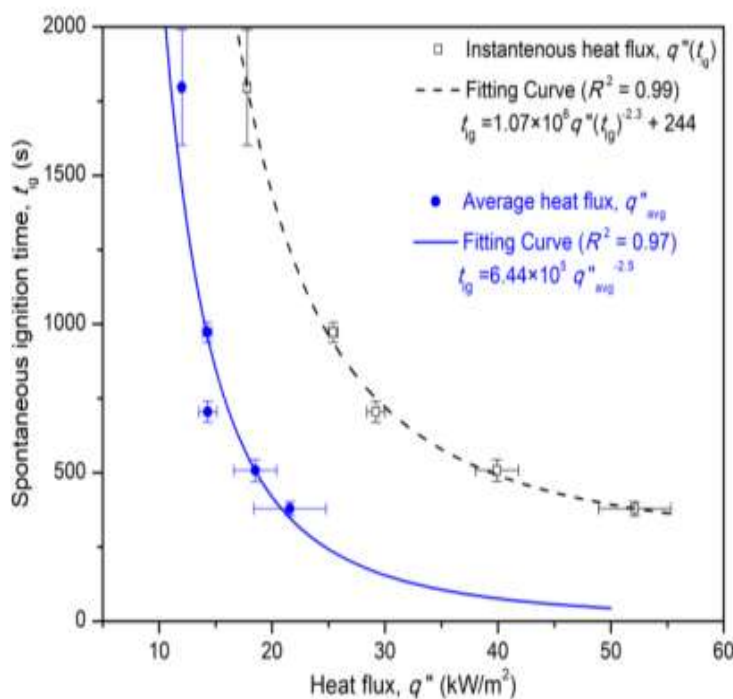


Figure 6. The spontaneous ignition time as a function of instantaneous heat flux (q_{ig}'') and time-average heat flux (q_{ig}''). [2]

3. Insulation electrical behaviour:

3.1 Temperature effects on the DC field distribution

The electric field distribution in high-voltage DC cables is a dynamic process that shifts from an initial geometric state to a steady-state resistive distribution, primarily controlled by thermal gradients within the insulation. Because electrical conductivity is highly temperature-dependent, the heat generated by the conductor creates a non-uniform conductivity profile that forces the electric field to redistribute, often leading to field enhancement near the outer screen.

Engineers model this behaviour using either empirical methods, such as Eoll's exponential rule, or more physically grounded approaches like the Arrhenius-based model, which accounts for thermally activated transport processes in polymers.

These conductivity gradients, along with potential variations in permittivity, result in space charge accumulation. To determine if field distortion is caused by these material property gradients rather than charge trapping, analysts use the criterion of polarity symmetry, as property-driven charge profiles remain symmetric when voltage polarity is reversed.[6]

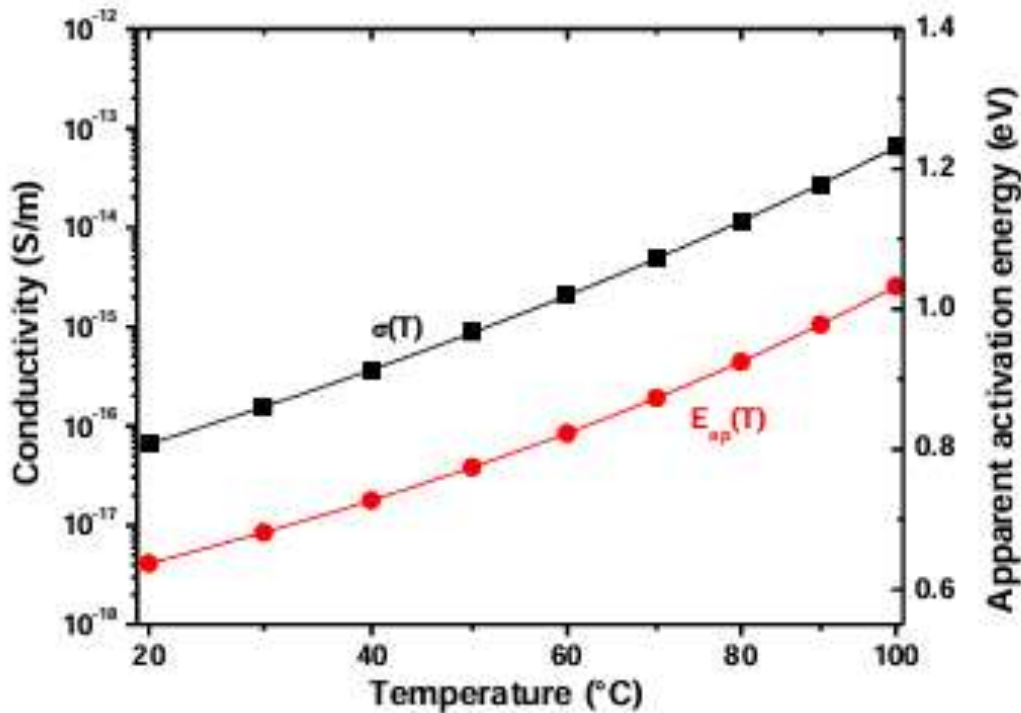


Figure 7. Arrhenius graph of the temperature dependence of the conductivity of EPDM[6]

4. Research gap:-

Across reviewed paper, the research related to individual factors such as external heating, arc fault, overcurrent but it fails to identify and research the combined effects of these factors on the flame spread and ignition. The research conducted is based on the laboratory testing however they have not investigated in parameters like electric overload, short circuit and combined effects of cable aging and cable bundle and ventilation and real fire scenario. The above reviewed papers study is conducted on single core cable having 3 layers and mainly focus on vertical arrangement the long exposure fire requires more study. But it fails to compare the both vertical and horizontal arrangement of same cable.

5. Discussion:-

The findings from the reviewed literature demonstrate that electrical cable fires are influenced by the interaction of cable construction, insulation material, conductor type, electrical loading, and surrounding environmental conditions. Rather than resulting from a single factor, cable ignition and flame propagation occur through combined thermal, electrical, and material degradation processes. The review indicates that polymeric insulation materials, particularly PVC and XLPE, significantly affect fire behaviour because their decomposition produces combustible gases that sustain flame spread. The performance of cables during fire is therefore strongly dependent on the thermal stability and combustion characteristics of the insulation system.

The analysis also highlights the important role of conductor materials. Copper conductors generally improve fire resistance by acting as heat sinks, reducing localized temperature rise and delaying ignition, whereas aluminium conductors provide comparatively lower thermal dissipation. Similarly, metallic armouring and protective sheaths improve cable survivability by limiting flame penetration and reducing heat release and smoke production. These

findings suggest that cable design should consider both electrical performance and fire safety requirements during material selection.

Another significant observation is that cable fire behaviour varies with installation configuration. Vertical cable arrangements tend to support greater flame spread than horizontal arrangements because of differences in heat transfer, insulation thickness, and combustion dynamics. Furthermore, external heat exposure, internal Joule heating, short circuits, and overload conditions can occur simultaneously in actual installations, making real fire scenarios more complex than standardized laboratory tests. Existing experimental studies often investigate these factors independently, which limits their applicability to practical industrial environments.

The review also emphasizes the importance of passive fire protection systems, including intumescent coatings, fire barriers, and fire-stop materials. These systems delay heat transfer, reduce flame spread, and improve cable circuit integrity during fire. However, their effectiveness depends on correct installation, material compatibility, and exposure conditions. Therefore, standard qualification tests should be supplemented with realistic large-scale fire experiments that account for cable ageing, cable bundles, ventilation, and combined electrical faults.

6. Conclusion

This review demonstrates that electrical cable fires remain a significant threat to modern residential, commercial, industrial, and critical infrastructure because cables act as both ignition sources and combustible fuel. Fire behaviour is controlled by the interaction of conductor material, insulation properties, cable geometry, installation arrangement, electrical loading, and environmental conditions. Understanding these interactions is essential for improving fire risk assessment and ensuring the reliability of electrical systems. Empirical analysis of electrical cable and passive fire protection of cable fire.

The literature confirms that copper conductors, metallic armouring, and suitable insulation materials can improve fire resistance, while passive fire protection systems such as intumescent coatings and fire barriers significantly reduce flame spread and delay cable failure. Nevertheless, current testing standards do not fully represent the complex conditions encountered during actual industrial fires, where multiple electrical and thermal hazards occur simultaneously.

The review also identifies important knowledge gaps related to combined fault conditions, long-duration fire exposure, cable ageing, ventilation effects, and bundled cable installations. Addressing these gaps through full-scale experimental studies will improve the prediction of cable fire behaviour and enhance the design of effective passive fire protection systems.

Overall, integrating optimized cable design, appropriate passive fire protection, realistic fire testing, and predictive fire modelling will strengthen electrical fire safety, improve system resilience, and reduce the risk of fire-related damage and service interruption in critical infrastructure.

7.Reference:-

- [1] Rao, S., & Rao, S. (2005). *Testing, Commissioning Operation and Maintenance of Electrical Equipments (Questions and Answers on Useful Practical Aspects.)*. Khanna Publishers.
- [2] Gong, T., Xie, Q., & Huang, X. (2018). Fire behaviors of flame-retardant cables part I: decomposition, swelling and spontaneous ignition. *Fire safety journal*, 95, 113-121.
- [3] Kaczorek-Chrobak, K., & Fangrat, J. (2019). Influence of constructional-material parameters on the fire properties of electric cables. *Energies*, 12(23), 4569.
- [4] Huang, X., & Nakamura, Y. (2020). A Review of Fundamental Combustion Phenomena in Wire Fires: A Review of Fundamental Combustion Phenomena in Wire Fires. *Fire Technology*, 56(1), 315-360.
- [5] Li, G., Guo, J., Kang, Y., Huang, Q., Zhao, J., & Liu, C. (2025). Classification and prevention of electrical fires: a comprehensive review. *Fire*, 8(4), 154.
- [6] Teyssedre, G., Vu, T. T. N., & Le Roy, S. (2022). Insulating materials for HVDC cable accessories: Effects on the electric field in nonstationary situations. *IEEE Electrical Insulation Magazine*, 38(5), 6-17.
- [7] Yu, F., Wang, S., Tang, K., Lin, Y., Wang, S., & Zhang, Y. (2024). Research progress on the fire characteristics of electric cables and wires. *Fire*, 7(6), 186.
- [8] Anghelescu, L., Handra, A. D., & Diaconu, B. M. (2025). Degradation pathways of electrical cable insulation: A review of aging mechanisms and fire hazards. *Fire*, 8(10), 397.