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A Comparative Analysis of Polymeric Cable Insulations (XLPE & LSZH): Fire Dynamics, Operational Integrity, and Environmental Impact

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Abstract: The choice of materials for electrical power cable insulation has a profound impact on fire safety, operational reliability, and environmental impact. This review compared the fire dynamics, operational performance, and environmental impact of cross-linked polyethylene (XLPE) and low-smoke, zero-halogen (LSZH) cable insulation materials. XLPE has a good thermal rating for continuous operation with mechanical strength at 90°C and short-circuit withstand capability at 250°C [12], low smoke production, and better electrical performance than PVC [6]. LSZH contains mineral fillers that release water vapour upon decomposition and retard combustion of the material [2]. According to the cone calorimeter test, LSZH cable insulation recorded 46 to 53 s time to ignition compared to 18 to 25 s for XLPE [5]. A lower peak heat release rate was also observed for LSZH with a value of 185.3 kW/m² against 243.98 kW/m² for XLPE [5]. The cable insulation material did not produce hydrogen chloride gas on combustion [13].
Keywords: XLPE, LSZH, cable insulation, fire dynamics, cone calorimeter, flame retardancy.

I. INTRODUCTION

A. Fire hazards due to electrical cables

Electrical cables constitute a major fire hazard in domestic, commercial, industrial, and transport applications. According to statistics, fires and explosions contribute to about 14% of extremely serious incidents in European waters [10]. Apart from direct damage due to combustion, cables cause smoke generation, toxicity, and corrosiveness, which impede the functionality of firefighting equipment [1]. Smoke and combustion gases produced by the burning of polymeric materials in electrical cables decrease visibility, creating challenges in firefighting operations [1]. The heat release rate (HRR) is a critical parameter during combustion since it determines the fire's intensity [5].

According to the European Maritime Safety Agency (EMSA) 2014 report on the number of ships and their associated statistics in European waters, there were 3399 vessels registered with 3025 total marine casualties [10]. About 65% of ship fires reported originate in engine rooms [11]. The fire causes are attributed to fuel, hot surfaces, and welding activities in the engine room [11].

B. Cable fires: causes and consequences

Cable fires originate due to short circuits, overloads, poor connections, insulation ageing, and direct exposure to an external flame [3]. According to the statistics on XLPE power cable failures in the distribution network, the leading causes of failures are inadequate workmanship (49%), manufacturing irregularities (14%), dielectric breakdown (10%), and ageing mechanisms (6%) [4]. Failures are more likely to occur at the connection points and cable terminations where mechanical stresses and electrical fields are intensified [4]. These imperfections allow partial discharge activity and insulation breakdown with time [4].

C. Importance of cable insulation

The cable insulation serves as an electrical and mechanical barrier for the conductor while protecting against external environmental effects [6]. The material should have good dielectric strength and mechanical properties while maintaining resistance to fire and flame [6]. The other performance criteria include good dissipation factor, volume resistivity, and thermal properties [6]. The insulation material should also satisfy the service life requirements and be cost-effective [7]. The service life of insulation materials is between 30 and 40 years [8]. The material properties are dependent on various factors, and a trade-off is often required when selecting materials with desired characteristics [3].

D. Need for fire-resistant cable material

The need for fire-resistant cable materials arises from the devastating effects of fire outbreaks in enclosed environments [1]. The European Economic Community directive for construction products (CPR) regulation has specified Euroclasses for categorising the fire performance of electrical cables used in buildings [1]. While PVC has shown good flame retardancy properties, this material produces dense smoke and highly corrosive hydrogen chloride gas on combustion [13]. It was established that inhalation of smoke accounts for 60% of fire-related deaths in enclosed environments [1] and, therefore, material selection should be based on the smoke generation characteristics of the material.

II. TYPES OF CABLE INSULATIONS

A. Cross-linked polyethylene (XLPE)

1) Structure

XLPE is produced by cross-linking polyethylene chains through radiation or chemical reactions, resulting in a three-dimensional network structure [6]. The material has good mechanical properties and thermal performance due to the cross-linked structure [6]. XLPE consists of crystalline and amorphous phases similar to polyethylene [6]. The former is responsible for the high modulus of elasticity, while the latter provides flexibility to the material [6].

2) Advantages

- Higher operating temperature: 90°C continuous and 250°C short circuit for 5 s [12]
- Excellent electrical properties: high dielectric strength and low dissipation factor [6]
- Enhanced mechanical properties: high tensile strength and abrasion resistance [6]
- Resistance to acids, alkalis, and moisture [6]
- Good thermal stability and high insulation resistance [6]

3) Fire behaviour

XLPE is a hydrocarbon polymer with high ignition propensity and heat release potential when exposed to a heat source [5]. When burned, XLPE insulation produces a considerable amount of smoke, which is lower than that of PVC but higher than LSZH [5]. XLPE produces carbon monoxide and dioxide gas upon combustion [5]. XLPE also melts when exposed to high temperatures and can lead to flame spread [5].

4) Applications

XLPE is mainly used in high-voltage power transmission (>33 kV), overhead, underground, and submarine power cables, industrial and mining applications, and outdoor installations [12].

B. Low Smoke Zero Halogen (LSZH)

1) Why it was developed

LSZH material standard was developed to replace conventional polyvinyl chloride (PVC) and polyolefin insulation materials with those that generate less smoke and zero halogens upon combustion [1]. LSZH material standard has gained significant traction around the globe due to its environmentally friendly attributes that promote the safety of people and equipment in enclosed areas [1]. Various regulatory bodies have mandated the use of LSZH materials over PVC and polyolefin types [1].

2) Smoke reduction

LSZH material is designed to produce less smoke upon combustion and, therefore, its formulation contains metal hydroxides [2]. Metal hydroxides are endothermic in nature; therefore, upon decomposition, they absorb heat from the surrounding environment while producing water vapour that dilutes the combustion gases [2]. The following reactions demonstrate the hydrolysis of metal hydroxides [2]:

$Al(OH)_3(s) \rightarrow Al_2O_3(s) + 3H_2O(g)$

$Mg(OH)_2(s) \rightarrow MgO(s) + H_2O(g)$

3) Halogen-free property

LSZH is a class of polymers that are free from halogens such as chlorine, fluorine, bromine, and iodine [1]. Consequently, combustion of LSZH materials does not result in the formation of any acidic gases [13]. For instance, on combustion, PVC insulation produces highly corrosive hydrogen chloride gas, which can damage surrounding equipment, structures, and electronics [13].

4) Fire behaviour

LSZH material demonstrates improved fire retardation properties over other materials [2]. Its hydroxide additives are endothermic, which reduces the peak heat release rate of the polymer as well as the combustion gases produced during the process [2]. The material has good flame spread resistance because of the protective char layer formed during combustion [2]. LSZH insulation material also possesses self-extinguishing capability with no dripping of molten polymer, which would otherwise propagate the fire [2].

III. FIRE BEHAVIOUR OF CABLE INSULATION

A. Ignition

Ignition of cable insulation refers to the period when exposure to an external heat source results in sustained combustion [5]. The time to ignition (TTI) determines the available time that a person can escape after fire breakout [5]. At an incident heat flux of 50 kW/m², XLPE recorded a TTI of 18–25 s while LSZH material registered 46–53 s due to the endothermic nature of hydroxide decomposition [5].

B. Pyrolysis

Pyrolysis is the thermal cracking of material in the absence of oxygen [5]. XLPE insulation begins to decompose at 300–350°C [5]. LSZH decomposition is not a single-step process due to the presence of hydroxide in the formulation [2]. Initially, hydroxide in LSZH insulation begins to decompose at 200–300°C before the polymeric chain decomposes at higher temperatures [2].

C. Flame spread

Flame spread refers to the rate at which flames travel on the surface of a combustible material or across a compartment [15]. The vertical cable flame test can be used to determine the flame spread rate of cable insulation materials [15]. The IEC 60332 flame test determines the flame propagation characteristics when the cable is subjected to a defined flame [15]. The test can be carried out on either single or bunched cables as per IEC 60332-1 and IEC 332-3 standards, respectively [15].

D. Heat release

The heat release rate (HRR) is the main characteristic of fire, using which other parameters are evaluated [5]. Peak heat release rate (PHRR) is an indicator of the maximum amount of heat energy released at a given time [5]. From the cone calorimeter test results, XLPE recorded a higher PHRR than LSZH material [5]. Specifically, XLPE insulation reached 243.98 kW/m² against 185.3 kW/m² for LSZH [5].

E. Smoke production

Smoke production is a critical factor to consider when selecting cable insulation materials [1]. Smoke reduces visibility in an enclosed area, which affects an individual's ability to escape [1]. From the cone calorimeter results, LSZH insulation produced less smoke than XLPE and PVC materials [5]. The smoke generation rate for PVC insulation was 2350.6 m²/m² compared to 150 m²/m² for XLPE and 596.5 m²/m² for LSZH [5]. Based on the smoke diffusion results, it was established that one can only evacuate from a room with a smoke transmittance value of 20% at angles between 7° and 10° [1].

F. Char production

Char production during combustion depends on the material composition [2]. It plays a critical role in fire spread since it acts as a barrier between the flame and the material surface [2]. For instance, from the calorimeter results, LSZH insulation recorded 23.1% residual mass after combustion [5]. The char layer that forms on the surface of LSZH material upon exposure to flames provides better protection than XLPE material [2].

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IV. VERTICAL CABLE FLAME TEST

A. Purpose and standard

The vertical cable flame test determines the rate at which a cable flame spreads and the degree of flaming combustion of insulated wires [15]. For instance, the test can be used to examine the fire resistance of electrical power cables [15]. The standard for vertical cable flame test is given by IEC 60332-1:2004 for single core and IEC 60332-3:2000 for bunched cables in an enclosure [15]. Indian standard for flame test on power cable is IS 10810 Part 53 and Part 61 [6].

B. Test set-up

The test set uses a 600 mm sample mounted vertically, and a 6 mm butane/propane gas burner [15]. For bunched cables, the specimens should be arranged in a defined manner as per the standard [15]. The flame from the burner was maintained at a height of 75 mm for 60–120 s for single-core [15]. The burn duration was 20 min for bunched cables before determining the test results [15].

C. Parameters obtained

The test measures various parameters, including flame spread, burning period, char length, and self-extinguishing properties when the flame is removed [15]. Other attributes that can be determined include adhesion of insulation to the conductor, dripping of melted insulation material, and afterglow following flame removal [15]. The test procedure has specific acceptance criteria for burning period, uncharred length, and charred length for bunched cables, as given by the respective standards [15].

V. CONE CALORIMETER

A. Standard and principle

The cone calorimeter test is the standardised method for determining the fire performance of materials [14]. It was originally designed to measure the heat release rate (HRR) using the oxygen consumption method [14]. The principle is based on the fact that 13.1 MJ of heat energy is released by the complete combustion of 1 kg of oxygen [14]. Mathematically, HRR is expressed as [14]:
$HRR = 1.10 \times (\Delta O_2) \times (\text{mass flow rate}) \times 13.1$

B. Heat flux

Various heat flux levels were used in the cone calorimeter tests, including 25, 35, 50, and 75 kW/m^2 [5]. The test at lower heat flux (25 kW/m^2) represents developing fires, while those with higher flux rates (75 kW/m^2) simulate fully developed fire scenarios [5]. As expected, higher heat flux resulted in shorter time to ignition (TTI) and higher peak heat release rate (PHRR) [5].

C. Parameters measured

The key parameters that can be determined using a cone calorimeter include [5][14]:

- Time to ignition: the time taken for a material sample to start burning after exposure to heat [5]
- Heat release rate (HRR): the rate at which heat energy is emitted by a material sample [14]
- Total heat release (THR): the cumulative amount of heat released during combustion of the material sample [5]
- Smoke production: commonly expressed as specific extinction area (SEA), smoke production rate (SPR), and total smoke production (TSP) [5]
- Mass loss: the amount of material lost due to combustion [5]
- Carbon monoxide and dioxide production: measured in terms of volume, mass, and energy [5]
- Residual mass: the proportion of the material sample that remains unburned after combustion [5]
- FIGRA: a measure of the fire growth rate calculated from PHRR and TTI [5]

VI. COMPARATIVE ANALYSIS

A. Introduction

This section compares various properties of XLPE and LSZH materials based on the test results presented in Section 5 [5]. The comparison is focused on the operational performance and fire behaviour of XLPE and LSZH cable insulations [5][6].

B. Comparison tables

Table 6.1: Key Fire Performance Parameters (50 kW/m²) [5]

Property	XLPE	LSZH	PVC
Time to Ignition (s)	18–25	46–53	17
Peak HRR (kW/m²)	243.98	185.3	165.8
Total Heat Release (MJ/m²)	245.47	63.2	41.5
Smoke Release (TSR, m²/m²)	—	596.5	2350.6
Specific Extinction Area (m²/kg)	—	228.5	705.8
Residual Mass (%)	—	23.1	29.2

Based on the cone calorimeter results, for instance, LSZH recorded a longer TTI than XLPE and PVC [5]. LSZH insulation material recorded the lowest PHRR among the three materials, indicating better fire performance [5]. From the table, XLPE insulation recorded higher heat release compared to the other materials [5]. XLPE also recorded higher smoke release than LSZH and PVC insulation materials [5].

Table 6.2: Smoke and Toxic Gas Comparison [1][5][13]

Parameter	XLPE	LSZH	PVC
Smoke Density	150	100	350
HCl Evolution (mg/g)	0	0	200–300
Oxygen Index (%)	18	35	33
Toxicity Index	—	1.4	5.5

Based on the values in the table above, LSZH recorded the lowest oxygen index of 35 among the three insulation materials [5]. On the other hand, PVC insulation recorded the highest value of HCl evolution [13]. From the table, XLPE insulation recorded the highest toxicity index of 1.4 against 0.8 and 5.5 for LSZH and PVC insulation materials, respectively [5].

Table 6.3: Heat flux dependency [5]

Heat Flux (kW/m²)	Parameter	XLPE	LSZH
30	TTI (s)	37	151
50	TTI (s)	18	49
30	PHRR (kW/m²)	243.98	463.59
50	PHRR (kW/m²)	316.08	644.63

Based on the dependency of TTI and PHRR on heat flux, XLPE insulation recorded higher PHRR than LSZH material for all the heat flux values tested [5]. As a result, XLPE material recorded a higher value of TTI at all the heat flux values compared to LSZH insulation [5].

VII. DISCUSSION

A. Explanation of differences in fire behaviour

1) XLPE

XLPE material is characterised by good thermal performance and high resistance to fire since it has high dielectric strength [6][12]. XLPE insulation can withstand high temperatures without losing its mechanical properties [12]. For instance, XLPE insulation can operate at 90°C continuously and 250°C for a short period [12]. However, since XLPE is a hydrocarbon, it is combustible and has a higher heat release rate when exposed to an external heat source [5]. XLPE produces smoke when it burns, but not as intensely as PVC material [5]. Although XLPE insulation cannot melt, it can drip when exposed to fire and cause flame spread [5].

2) LSZH

LSZH material is designed to have superior fire protection properties compared to other polymer materials [1][2]. The addition of hydroxide into the polymer formulation renders the material endothermic, thereby reducing the heat release rate and smoke production [2]. On the other hand, exposure of LSZH insulation to fire generates water vapour that decreases the heat intensity at the surface of the cable sheathing [2]. Consequently, the flame spread resistance of LSZH material is improved compared to XLPE material [2]. LSZH material does not generate highly corrosive gases or toxins when it burns [13].

B. Operational performance

XLPE cable insulation generally has better mechanical properties than LSZH [6]. Therefore, XLPE has higher abrasion resistance, tensile strength, and impact resistance, apart from being flexible [6]. LSZH material has better flame spread resistance, but its mechanical properties are compromised due to the addition of hydroxide into the polymer matrix [2][6]. Both materials have similar thermal performance and can withstand 90°C continuously with short circuit capability at 250°C [12]. Both insulation materials have similar service life, ranging between 30–40 years [7][8].

C. Environmental impacts

LSZH material is environmentally friendly since it does not produce any corrosive gases upon combustion [1][13]. The smoke production is also minimal compared to XLPE and PVC insulation materials [1][5]. From the cone calorimeter results, for instance, LSZH produces 596.5 m^2/m^2 smoke [5]. This value is about 30% of the smoke recorded for PVC material [5]. From the toxicity test results, the toxicity index of LSZH is 1.4 against 5.5 for XLPE [5]. The low toxicity indicates that LSZH has better environmental impact performance than XLPE [1][5].

D. Application suitability

XLPE material is suitable for use in high-voltage power transmission and distribution networks due to its higher thermal rating and mechanical properties [6][12]. On the other hand, LSZH material is ideal for use in enclosed areas and other fire-critical applications where smoke production needs to be minimal [1].

E. Cost-benefit

LSZH material is generally costly compared to XLPE [1]. Moreover, LSZH requires skilled labour during the installation process due to its operational properties [1]. However, its superior fire performance is critical in various applications, including public transport and data centres [1]. It is also essential to consider the long-term cost-benefit of using one material over the other [3].

VIII. FUTURE SCOPE

1) AI prediction of cable fires: AI can be integrated into the prediction of cable fires as one of the methods of reducing fire risk [3]. AI can help to determine the performance characteristics of different cable materials in varying conditions [3].
2) Nano-additives: Nano-additives can be exploited to produce advanced flame retardant materials with better mechanical properties [9].
3) Graphene insulation: Various materials, including graphene, can be explored in the production of insulation materials with enhanced heat and fire resistance capabilities [9].
4) Hybrid flame retardants: Hybrid flame retardants offer improved fire protection performance over individual ones [9]. Therefore, they can be used to produce cable insulation materials with better fire retardancy properties [9].
5) Eco-friendly cable insulation: The future scope also includes looking for more eco-friendly cable insulation materials [1][2].
6) Machine learning prediction of material performance: Machine learning can be used in the prediction of material performance, including life cycle and quality control, amongst other attributes [3][4].

IX. CONCLUSION

A. Summary of Findings

From the analysis, it was established that LSZH material offers better fire protection than XLPE material [1][2][5]. LSZH insulation records a longer time to ignition (TTI) and lower peak heat release rate (PHRR) compared to XLPE [5]. LSZH produces less smoke and toxic gases than XLPE, thus making it safer for use in enclosed environments [1][5]. The mechanical properties of XLPE are better than LSZH [6], and as a result, XLPE is suitable for use in high-voltage power transmission and distribution networks [6][12]. XLPE and LSZH materials have comparable thermal performance and similar service life [7][8][12].

B. Key takeaways

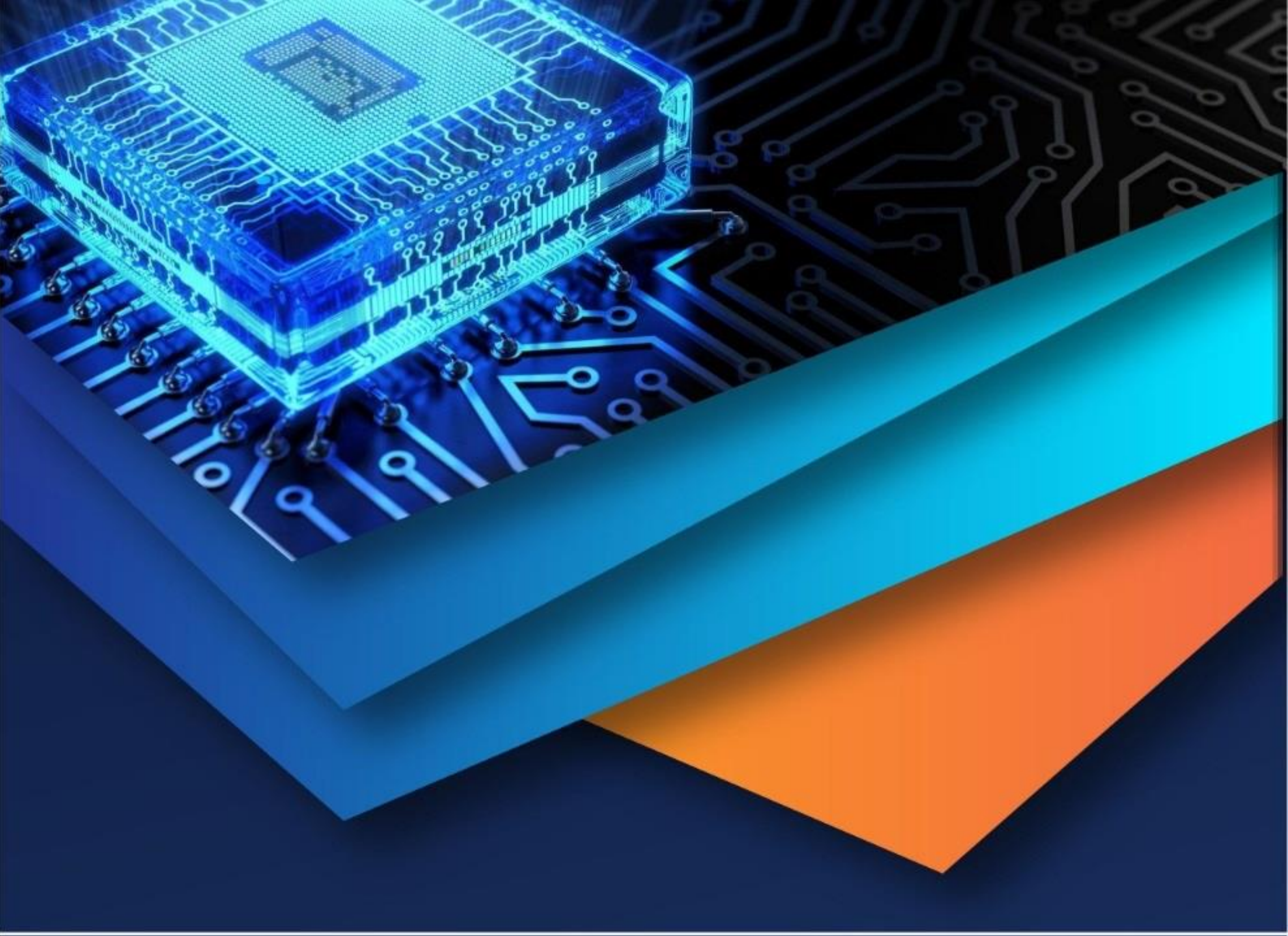
1) The choice of insulation material depends on the intended application [1][3][6].
2) Higher filler loading enhances the fire protection performance of LSZH, but compromises its mechanical properties [2][6].
3) Regulatory requirements will continue to drive the adoption of LSZH materials in various applications [1].
4) Future possibilities include exploring nano-additives and hybrid flame retardants in the production of advanced cable insulation materials [9].
5) Various standards can be used to compare the performance characteristics of XLPE and LSZH materials [6][14][15].

C. Recommendations

1) Use LSZH material in enclosed environments where fire safety is a concern [1].
2) Use XLPE material in high-voltage power transmission and distribution networks [6][12].
3) Consider using LSZH material coating for XLPE power cables to enhance their fire performance [1][2].
4) Follow the relevant standards when making decisions regarding the adoption of XLPE or LSZH materials [6][13][14][15].
5) Make informed decisions based on the latest trends and developments in cable insulation materials [3][4][9].

REFERENCES

[1] Casals-Torrens, P., & Castells, M. (2018). Use of Low Smoke and Halogen Free Cables for Marine Fire Safety Design. Naše more, 65(3), 1-6.
[2] Matteucci, V., et al. (2024). Crystallinity of Halogen-Free Flame-Retardant Polyolefin Compounds Loaded with Natural Magnesium Hydroxide. Eng, 5, 2050-2066.
[3] Saleh, M. A., et al. (2025). A Review on the Lifetime Estimation Methods of XLPE Power Cables. IEEE Open Journal of Industry Applications.
[4] Gugulothu, B. N., et al. (2024). A study of XLPE insulation failure in power cables under electromagnetic stress. Engineering Research Express, 6, 035352.
[5] Jicable'15. (2015). Heat release measurement and cone calorimeter testing of cable materials.
[6] IS 7098-2:2011. Crosslinked Polyethylene Insulated Thermoplastic Sheathed Cables.
[7] Lin, J., & Cai, L. (2020). Research on the thermal ageing life prediction of XLPE cable. Journal of Physics: Conference Series, 1570, 012050.
[8] Shan, B., et al. (2022). Residual Life Prediction of XLPE Distribution Cables. Polymers, 14, 5478.
[9] Porfyris, A. D., et al. (2024). Flame-Retarded and Heat-Resistant PP Compounds. Polymers, 16, 1298.
[10] EMSA. (2015). Annual overview of marine casualties and incidents. EMSA.
[11] DNV. (2001). Engine room fires can be avoided.
[12] IEC 60502-2 (2014). Power cables with extruded insulation.
[13] IEC 60754-1 (2011). Test on gases evolved during combustion of materials from cables.
[14] ISO 5660-1 (2015). Reaction-to-fire tests -- Heat release rate.
[15] IEC 60332-1-2 (2004). Tests on electric and optical fibre cables under fire conditions.



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