

# Failure analysis and risk mitigations of cables under fire exposed conditions -Case studies

Sheetal Panchal, Shailesh Patel  
Electrical Research & Development Association, Vadodara  
[sheetal@erda.org](mailto:sheetal@erda.org)

## ABSTRACT

*In the era of increasing demand and dynamic need of electricity, cables are at the heart of each phase from electricity generation to transmission and distribution. In electrical utilities, many a time's fire accidents caused due to electricity, the cables have played crucial role for fire occurrence. Cable failures pose significant risks to electrical infrastructure, safety, and operational continuity. Failure of cables might be attributed to manufacturing flaws, operational loads, installation strategies, external environmental conditions or ageing. Understanding the different types of cable failures and their cause is crucial for effective identification and resolution of these problems. Here this paper presents a comprehensive investigation into the root causes and mechanisms behind fire-induced failures in cables by laboratory simulation and testing, those exhibit probable causes including inferior material properties, unsuitable cable structure and assembly, insulation breakdown, inappropriate installation practices, and external fire exposure.*

*This paper depict few case studies of failed cables under fire condition. At ERDA, extensive testing of cables are conducted according to national and international standards. There are specialized test methodologies to check compatibility of cable to survive under fire condition like fire retardant test, oxygen index test, temperature index test, and smoke density test. Cables which are failed, have been analysed to identify the causes of failures. Further remedial measures are proposed to mitigate the risk associated with cable failures.*

Key words: failure of cables, fire induced failures, fire testing, root cause, mitigations for cables

## 1. INTRODUCTION

In a world increasingly reliant on automation, electrification, and smart infrastructure, cables are the invisible threads holding everything together. Whether in high-speed data centers, underground metro systems, offshore platforms, or nuclear power plants, cables silently deliver power and signals. When a fire occurs, these same cables can turn from enablers into liabilities, becoming ignition sources, paths for flame spread, or points of catastrophic system failure. The components designed to keep systems running can, under fire exposure, bring them down in seconds. Damage occurs not only due to the flame but also due to toxic fumes. In many of the fire incidents, loss of human lives has been found not only due to fire but due to suffocation, due to inhaling of poisonous gases and not finding way of exit due to highly dense dark smoke.

The failure mechanisms of cables under fire conditions are complex and often involve a combination of thermal degradation, electrical breakdown, and chemical transformation of insulation materials. In many documented fire incidents, investigations have revealed that inadequate fire protection, poor maintenance

practices, improper jointing, or substandard cable materials contributed to the accelerated failure of cable systems.

This paper presents a focused analysis of cable performance in fire-exposed conditions. Drawing from laboratory experiments, and regulatory data, it explores common failure modes and evaluates effective risk mitigation strategies. Emphasis is placed on the role of material selection, Choice of fire retardant cable, installation methods, and predictive assessment tools in enhancing the fire resilience of cable systems. The objective is to provide a practical yet technically sound understanding of how cable failures occur during fires and how these risks can be systematically reduced through choice and design of right cable for intended application. This paper looks at how and why cables fail when exposed to fire, based on both lab experiments .It also explores what we can do to reduce the risk—using better materials, improving design, construction and following stricter safety standards. The goal is to explain these issues in simple way.

## 2.0 To ensure Flame retardant property of Cables

To evaluate the flammability characteristic of cables and the insulating materials, various tests are

specified. The Bureau of Indian Standard (BIS) has also included various flammability tests in cable specifications. The various tests for the insulating materials and finished product listed in Table 1.

Table-1 : Tests for Materials and Cables		
A. Tests Covered in BIS		
No.	Test	Standard
1	Oxygen Index Test	As per IS:10810-Pt.58, ASTM D 2863
2	Flame Retardant Test on Single Cable	As per IS:10810-Pt.53, IEC 60332-Pt.1
3	Flame Retardant Test on Bunched Cable	As per IS:10810-Pt.62, IEC 60332-Pt.3
4	Temperature Index Test	As per IS:10810-Pt.64, ISO 4589
5	Flame Retardant Test (Swedish Chimney)	As per IS:10810-Pt.61, SS:4241475
6	Smoke Density Test (3M <sup>3</sup> Chamber)	As per IS:10810-Pt.63, IEC 61034
7	Smoke Density Test	As per ASTM D 2843
8	Acid Gas Generation Test	As per IS:10810-Pt.59, IEC 754-Pt.1
B. Other Flammability Test		
9	Flammability Test	As per IEEE 383
10	pH & Conductivity Test	As per IEC 754-Pt.2
11	Fire Survival Tests (For Category C,W,Z)	As per IEC 60331-Pt.11, BS:6387, BS 8491, BS EN 50200, IS 17505
12	Toxicity Index Test	As per NES 713

## 3. CASE STUDIES

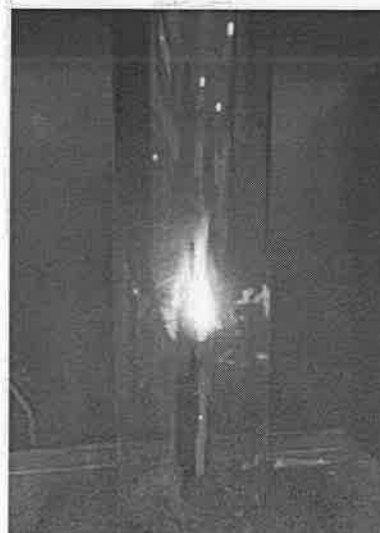
Based on our wide experience on testing of cables as per national and international standards, the following case-studies on failure of LV and HV cables are presented.

Table 2: Case study details

Case Study	Type of cable	Type of failure observed
1	2 Core x 6 sq.mm FRLSH cable	Oxygen index failure
2	1 Core x 120 sq. mm Stranded compacted aluminium conductor, cross linked polyethylene (XLPE) insulated & black coloured FRLSH PVC ST2 outer sheathed 1100V LT XLPE cable	Cable burnt during Flame retardance test on bunched cable
3	1 X 2 X 1.5 mm <sup>2</sup> /7 EI2 insulated & LSZH black colour sheathed armoured cable. Type of insulation: EI2, Type of Sheath : LSZH	Tests for electric cables under fire conditions: circuit integrity under fire

### Case Study # 1: 2C x 6 Sq.mm LT XLPE insulated & Black coloured Extruded PVC FRLSH outer sheathed armoured cable as per IS 7098 Part-1

To check the flame retardant property of cable "Oxygen Index Test" is conducted as per the method laid down in ASTM D 2863. The test is also described in IS: 10810-Pt.58. By definition, "Oxygen Index" is the minimum concentration of Oxygen (% volume) required just to support burning of a material. For a good flame resistant material, the minimum index value should be 29%. The test helps evaluate the fire resistance of materials, critical for applications where fire is a risk.



If the material is inherently highly flammable means it requires low oxygen to burn, have a low heat of combustion, poor thermal stability, or other properties that make it less flame-retardant, poor flame retardant characteristics. In this study Oxygen index value has been determined for cable FRLSH PVC outer sheath material.

Sr. No.	Sample description	Oxygen index value, %	Remark
1	2C x 6 Sq.mm PVC FRLSH Cable	24.5	fail
2	4C x 16 Sq.mm PVC FRLSH Cable	33.0	pass

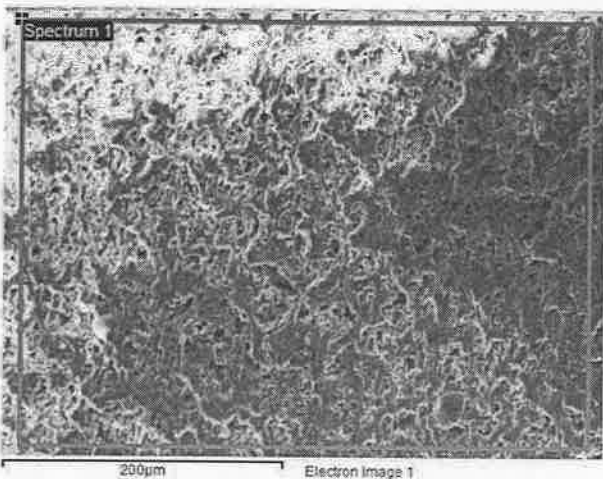
For finding out the root cause of low value of oxygen index we have carried out SEMEDS analysis.

**SEM-EDS study on cable outer sheath:**

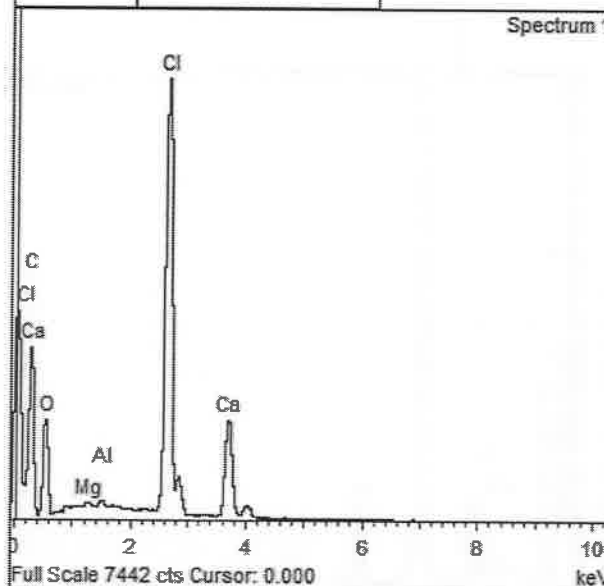
This is very informative scientific technique that combines Scanning Electron Microscopy (SEM) to produce high-resolution images of a sample's surface and Energy-Dispersive X-ray Spectroscopy (EDS) to determine the elemental analysis of materials. For analysis of failure of oxygen index test further SEM-EDS dual technique is used to study the structure and composition of materials at the micro and nano levels.

**SEM and EDS results of 2C x 6 sq.mm FRLSH cable**

Sample: 2 C x 6 sq.mm FRLSH Cable  
 Type: PVC FRLSH outer sheath  
 ID: Failed in OI test

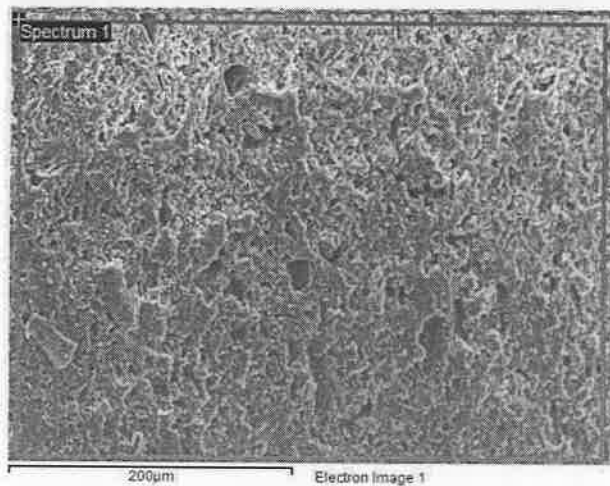


Element	Weight%	Atomic%
C K	50.66	66.73
O K	21.29	21.05
Mg K	0.15	0.1
Al K	0.19	0.11
Cl K	20.76	9.27
Ca K	6.95	2.74
Totals	100	

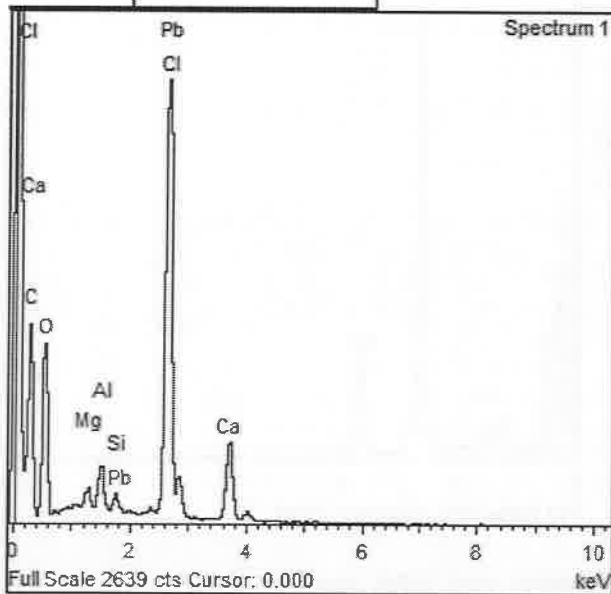


**SEM and EDS results of 4C x 16 sq.mm FRLSH cable**

Sample: 4 C x 16 sq.mm FRLSH Cable  
 Type: PVC FRLSH outer sheath  
 ID: Pass in OI test



Element	Weight%	Atomic%
C K	44.88	59.77
O K	28.54	28.53
Mg K	0.56	0.37
Al K	1.11	0.66
Si K	0.47	0.27
Cl K	18.82	8.49
Ca K	4.59	1.83
Pb M	1.02	0.08
Totals	100	



From above case study Root cause for low oxygen index value is lack of flame retardant additives and use of flammable base polymers.

In failed cable it is observed that flame retardant additives Si and PVC stabilizers lead Pb is missing in element analysis. While in passed cable these elements are present.

PVC insulation is self-extinguishing, but it can still let fire spread. OI value can be increased with flame-retardant additives. If the additives in the insulation material are not proper then there may be chances of OI failure. Flame-retardant additives increase OI but may reduce thermal stability (since they can decompose at lower temperatures).

Stabilizers (like lead, Ca-Zn, or tin stabilizers in PVC) improve thermal stability but don't directly affect OI. So, high OI does not automatically mean high thermal stability. That's why PVC cables always need thermal stabilizers.

### Case Study # 2: Flame retardance test on bunched cable

This test is required to evaluate the fire resisting property of cable, when numbers of cables are running in parallel in cable duct or cable tray. The test procedure is laid down in IEC: 60332-Pt.3 and IS: 10810-Pt.62. This test is divided into three test categories namely A, B and C. This category decides the number of test specimens each of 3.5 meter length, required for testing.

The test specimens are then mounted on a ladder in test chamber and specific flame through ribbon burner is applied for a specific time. After removal of flame and all burning has ceased, the test sample wiped clean and measured the charred portion. The maximum extent of charred portion shall not exceed 2.5 meter length from the bottom edge of the burner. We have tested different cables to check its flame retardant property when no of cables are bunched together and results are mentioned in table 4.

Sr. No.	Sample description of Cable	Requirement	Obtained value	Remarks
1	Fiber optic Armoured cable, LSZH material	Maximum extent of charred portion measured to the sample shall not have reached height exceeding 2.5 meter height above the bottom edge of burner	Reached height 0.93 meter Armour Coverage : 94 %	Meeting the standard requirement
2	Armoured cable, LSZH material	Max charred portion : 2.5 meter	Reached height 3.0 meter Armour coverage : 84 %	Not meeting the standard requirement
3	Unarmoured cable , LSZH material	Max charred portion : 2.5 meter	Reached height 3.0 meter	Not meeting the standard requirement

4	1C x 1.5 sq.mm Copper conductor mica Tape XLPE insulated LSOH outer sheathed cable	Max charred portion : 2.5 meter	Reached height 0.85 meter	Meeting the standard requirement
5	1Cx 300 sq.mm ,cu/semicon /XLPE/semicon/cu tape/ fiber glass tape/ unarmoured FR PVC ST2 MV cable	Max charred portion : 2.5 meter	Reached height 3.0 meter	Not meeting the standard requirement
6	1 Core x 120 sq. mm Stranded compacted aluminium conductor, cross linked polyethylene (XLPE) insulated & black coloured FRLSH PVC ST2 outer sheathed 1100V LT XLPE cable	Max charred portion : 2.5 meter	Whole sample burnt	Not meeting the standard requirement
7	1C X 1000 sq.mm, stranded copper conductor, extruded semi conducting conductor screen, XLPE insulated, extruded semiconducting insulation screen/ semiconducting tape/ hard drawn aluminium round wire armour/ non semi conductive tape and overall PVC type FR ST-2 outer jacketed 33/33 kV grade cable	Max charred portion : 2.5 meter	Reached height 3.0 meter	Not meeting the standard requirement
8	1CX400 sq mm plain copper conductor (Class 2), Semiconducting tape, semi conducting conductor screen /XLPE insulation/Extruded semiconducting insulation screen Semiconducting water swellable tape, Helically applied plain copper wires followed by open helix plain copper tape binder, Plain water swellable tape, Polypropylene tape(S) bedding, Double layer of aluminium tape armour, FRLS PVC Type ST-2 outer sheath (Black colour) cable	Max charred portion : 2.5 meter	Reached height 3.0 meter	Not meeting the standard requirement
9	CAT-6 U/UTP ECCS Armoured Double Jacket LSZH- LSZH cable	Max charred portion : 2.5 meter	Reached height 0.80 meter	Meeting the standard requirement

From the above case study Table 4 it is observed that a flame retardant test on bunched cables fails if the insufficient fire resistance in the cable's sheathing material or premature degradation of the insulation system. Second reason for failure is when cable is unarmoured where there's no metallic barrier to restrict heat in those cases cable catch fire easily and propagate the fire. Armouring (i.e steel tape or wire) provides a physical barrier to flame spread.

Unarmoured cables lack this protection, so fire travels easily along the plastic layers and cable gaps.

Also it is observed that even if armoured cable is used but if armour coverage is less than 90 % in this case there may be a chance of failure of cable because flame enters from the gap of armour and it propagate the fire and fire reached a height of more than 2.5 meter. So Armour coverage should be greater than 90 %.

The root cause is Inadequate Fire Resistance of Materials:

The outer sheathing or insulation material may not be sufficiently fire-resistant, leading to early ignition and rapid fire propagation.

Material Degradation:

The materials used may not effectively resist the high temperatures and flame impingement for the required duration, causing them to degrade, release flammable gases, and allow the fire to spread further.

Poor Insulation/Sheath Design:

If the insulation or sheath doesn't have appropriate fire-resistant properties like glass mica tapes or intumescent layers, it can fail to protect the inner components from the heat.

Remedial measures to Improve Flame retardance in unarmoured cables

- Properly formulated flame-retardant or LSZH compounds should be used.
- Uniform sheath thickness and coverage
- Mica tapes, fire-resistant fillers, or fire barrier layers should be used in design of cable.

**Case Study # 3:** Circuit integrity for electric cables under fire conditions

As the name reflects, in this test, the cable has to maintain circuit integrity under the fire condition. The different cables are tested as per IEC 60331-Pt.11 and BS: 6387. It evaluates a cable's ability to maintain electrical continuity under fire conditions (typically 750 to 950°C for 90 or 180 minutes).

The test is basically categories into three categories- C, W and Z. The category C evaluates cable resistance to fire alone, category W evaluates the resistance to fire with water and category Z evaluates resistance to fire with mechanical shock.

**Sample 1:** 1 X 2 X 1.5 mm<sup>2</sup> /7 EI2 insulated & LSZH black colour sheathed armoured cable.

Checked circuit integrity at 830 °C for 90\* minutes with mechanical shock applied at interval of 5 Min ± 10 s

No 2A fuse was ruptured nor any lamp was extinguished during the test period

**Sample 2:** 2 core X 1.5 mm<sup>2</sup> copper conductor glass mica tape XLPE insulated LSOH outer sheathed 0.6/1.0 kV cable.

-Circuit integrity at 950 °C for 3 hours  
Withstood for 3 hours

**Sample 3:** 1 X 2 X 1.5 mm<sup>2</sup> /7 EI2 insulated & LSZH black colour sheathed unarmoured cable.

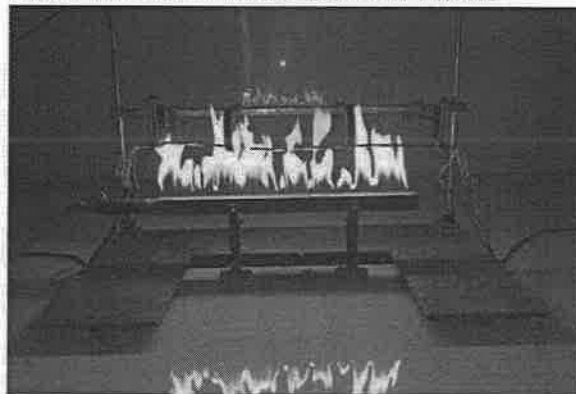
Circuit integrity at 830 °C for 90\* minutes with mechanical shock applied at interval of 5 Min ± 10 s

Not withstood, and lamp was extinguished during the test period

**Sample 4 :** 1 X 2 X 1.5 mm<sup>2</sup> /7 EI2 insulated & LSZH black colour sheathed unarmoured cable

Resistance to fire of cables required to maintain circuit integrity under fire conditions

Protocol C for resistance to fire alone  
As per Cl. No. 6 of BS : 6387:2013  
(At 950 ± 40 °C for 03 hrs)  
Withstood for 28 minutes instead of 3 hours



**Protocol W for resistance to fire with Water**

As per Cl. No. 7 of BS : 6387:2013  
At 650 ± 40 °C for 15 minutes and then continued for next 15 minutes with water spray  
During the water spray lamps were extinguished

#### **Protocol Z for resistance to fire with mechanical shock**

As per Cl. No. 8 of BS : 6387:2013

At  $950\pm 40^{\circ}\text{C}$  with mechanical shock applied for 15 minutes

Withstood for 8 minutes only

From the above tests on various samples, it is observed that when the flame is applied alone or flame with water spray is applied simultaneously or the flame and mechanical impact are applied simultaneously the ash formed under the fire condition, it may penetrate into conductor or leaves the conductor surface, due to which conductor will open and make a shorting. So when in cable construction flame barrier mica tape, LSZH outer sheath and armoured is used then this cable withstood circuit integrity in fire condition. On the other side it is observed that when the outer sheath material is good but no any flame barrier is used it does not withstood circuit integrity under fire condition.

#### **4. Acknowledgements**

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#### **5. CONCLUSION**

To prevent cable failure in fire conditions properly formulated flame-retardant or LSZH outer sheathed cables shall be used. When numbers of cables are running in parallel in cable duct or cable tray or installed in bunched condition armoured cables with full armour coverage shall be used. In fire-survival cables for fire barriers special fire barrier tape (like mica tape) shall be used in construction of cable. Mica tape or fire-resistant barrier must fully wrap the conductor with overlap. LSZH sheathed and armoured cables are meeting the requirement of Circuit integrity for electric cables under fire conditions, However, if they are not armoured, they are fail to maintain circuit integrity under fire condition.

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# Underground cable sheath grounding System

Naitik Patel  
*R&D Manager at*  
*ETP Earthing & LPS Solution Pvt.Ltd*  
technical@etpearthing.com

**Abstract.** The modeling of single core cable has an important influence on the calculation of cable sheath cross-connected grounding current and voltage. A suitable equivalent circuit can greatly reduce the complexity of the model. In this paper, the theoretical calculation of  $\pi$  type equivalent circuit of cable is analyzed, and the equivalent circuit of cable sheath grounding system is analyzed. Then the calculation equation of sheath circulation and induced voltage is obtained. Finally, by simulating two kinds of sheath grounding faults, two kinds of sheath grounding fault location are summarized.

## 1 Introduction

In recent years, underground cable has been widely used in urban high voltage transmission and distribution system because of its advantages of not occupying the ground and not affecting urban traffic. However, which has created new problems, such as cable shaft water caused by short circuit sheath, road construction cable and other faults. Therefore, it is necessary to analyze the circuit model of underground cable to lay a foundation for further analysis of cable sheath grounding system.

The cable is modelled as a four-phase distributed parameter line, and the self-impedance and mutual impedance of the three cable sheaths and the ground wire are taken into account. An analysis of a simple distribution system shows that the voltage of a grounded system can be easily calculated using  $\pi$  equivalent circuits[1]. The reference[2] describes the single-core cable as an extensible numerical model to calculate real-time cable ratings for underground medium voltage cables. The reference[3] analyzes the circuit model of in-phase multiple parallel lines, proposes the calculation method of line sequence impedance, and verifies the current distribution coefficient of the cable with the actual line.

High voltage single core XLPE (cross-linked polyethylene) cable is often used in urban power transmission and distribution system to meet the demand of long-distance and large capacity electric energy. The cable structure is shown in Figure 1. When the core transmits electrical energy, the metal sheath of the cable generates an induced voltage. When the metal sheath is grounded, an induced current is generated on the sheath. As a result, the induced voltage generated by the cable metal sheath will increase with the increase of cable length, and too high induced voltage will breakdown PE outer sheath, serious will destroy XLPE