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Fire Safety Assessment of Polymeric Cables and Materials based on Heat Release Rate, Combustion Smoke and Toxicity

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This paper presents and discusses heat release measurement, smoke and toxicity data obtained on cables: power, communication, automobile, wires and other materials used for various applications in power plants, petroleum refineries, metro rail, automobile industries. Fire survival cables intended to maintain electrical integrity under flaming conditions and flame retardant low smoke cables have been evaluated and their performance discussed. Fire safety assessment methods of cables and materials are reviewed and heat release rate, smoke, toxicity data and flammability characteristics obtained on materials like polystyrene, cellulosic fibre materials, upholstery, FRP/GRP laminate and others are discussed. Cushioning materials like polyurethane foam (slab stack, rigid PU, Expandable Graphite foam), thermally densified polyester block have been evaluated for HRR, smoke properties and the results are discussed. The toxicity of these materials evaluated as per NES 713/NCD 1409 are summarised.

1.0 INTRODUCTION

Polymeric cables and materials are in use for various applications in nuclear, hydel and thermal power plants, oil refineries, locomotives, automobiles and high rise buildings. Cables are designed to carry power and communication signals for long distances. Polyvinyl chloride (PVC), butyl rubber, cross-linked polyethylene (XLPE) and other materials are extensively used as insulating and sheathing/jacketing materials in cable construction. For decades, PVC compounds due to their excellent mechanical and chemical properties were in use. But these materials produce highly corrosive gases during combustion which cause problems of corrosion to electrical apparatus and metallic structures even months after the fire. They are gradually being replaced by zero halogen materials. Further zero halogen flame retardant materials find a wider application. Cables rarely cause fire, and in the event of fire can act as a pathway along which fire can travel and spread. Fire survival cables designed to maintain electrical integrity under flaming conditions are also used in specific areas.

Polymeric materials are also extensively used for the construction of locomotives. Rail coaches are primarily constructed with stainless steel body and floors with plymetal panel (plywood/metal). FRP is used for the interiors: the floors, side walls, end walls and window frames. The floor covering materials (nylon carpets, styrene butadiene rubber mats), curtains, drapes, fabrics; seat cushioning/covering materials are abundantly used. Flexible polyurethane foam has become the choice of cushioning material and other miscellaneous materials like phenolic/wood laminate for dining/coffee tables and window/door gasketing materials are also used. However, the abundant usage of these materials

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poses a great threat in the event of fire. Fire involving these materials produces heat, spreads flame, smoke, toxic and corrosive gas fumes. These lethal combustion products can cause acute and delayed toxological effects. Statistics indicate most of the fire victims die or are affected by smoke rather than the asphyxia which is the principal mechanism of intoxication, mediated by oxygen depletion, carbon monoxide inhalation and sometimes even by hydrocyanic acid inhalation. In recent times, due to increase in fire accidents and with loss of lives and property, regulatory authorities have enforced strict laws and regulations to minimise the risk of fire by assessing the 'Fire hazard' of materials used in railways. Thus the classification of the fire hazard, associated with flame spread along runs of cables poses a challenge for building services installation and design. In this paper, fire safety assessment methods are reviewed and heat release measurements on power, data and communication cables and other materials are presented and discussed.

2.0 FIRE SAFETY EVALUATION TECHNIQUES

The fire and smoke characteristics of cable material are evaluated by several test methods and more are being published every year. Some of the important fire tests on cables are—HRR measurements using cone calorimeter: ASTM 1354[1]/ISO 5660[2], wire/cable bunch flame propagation: IEC 332-3[3]/IEEE 383[4]/IS 10810 Part 62[5], smoke density of wire/cable: IEC 1034 Part 1, 2[6]/IS 10810 Part 63[7], ASTM E 662[8] for specific optical smoke density, ASTM 2843[9] for smoke density from the burning or decomposition of plastics, Limiting Oxygen Index (LOI) test as per ASTM 2863[10]/IS 10810, Part 58, Evolved combustion gases of wire/cable: IEC 754 Part 1 and 2[11], Toxicity index test as per NES 713[12]/NCD 1409, UL 94[13] for flammability of plastics, Fire survival test: (IEC 331[14]/ BS 6387 category C, W and Z[15] etc.

The fire safety requirements in the international standards of locomotives are based on the exigencies of the fire behaviour of individual materials that the passenger train compartments are made up of. In the United States, the fire safety of passenger trains is addressed through small scale flammability and smoke emission tests and performance criteria based on guidelines by the Federal Railroad Administration[16] (FRA) and National Fire Protection Association[17] (NEPA). The FRA test methods include measures of material flammability and smoke in terms of downward flame spread (ASTM E 162, D 3675 and E 648). FAR 25.853 (a) and ASTM C-542 are small burner tests which measure the resistance of a material to ignition and burning for a small sample of the material. ASTM E 662 measures the smoke generation from small, solid specimens exposed in (i) a flaming mode to a radiant heat flux of 35 kW/m^2 and (ii) a non-flaming mode to only a radiant heat flux of 25 kW/m^2. The European National Standard (BS 6853),[18]German Standard[19]DIN 5510, French Standard NF F 16101/2 are generally adopted for evaluation of materials. However, these standards are likely to be withdrawn and replaced by one standard EN45545: Railway applications[20]—Fire protection of railway vehicles Part 2. This standard covers the requirements of fire behaviour of materials and components for cables; Vertical flame spread (EN 50266-2-4) IEC 332 Part 3, Specific optical density (EN -50268-2) IEC 1034. Smoke optical density and toxicity (ISO-5659-2), Ignitability of curtains, sunblinds and air filter materials, lateral flame spread (ISO 5658-2). Seat assemblies are tested using furniture calorimeter or cone calorimeter.

Heat Release Rate (HRR) test methods are used to predict the real-scale burning behaviour of materials and assemblies as they quantify fire size, rate of fire growth and consequently the release of associated smoke and toxic gases[21,22]. HRR is considered to be a key indicator of fire performance and is defined as the amount of energy that a material produces while burning. MARHE, the maximum average rate of heat emission is another parameter which is used to assess the fire behaviour of materials.

3.0 HEAT RELEASE MEASUREMENT

3.1 Cone calorimeter

The cone calorimeter is a test method which provides measurements of HRR, specimen mass loss, smoke production and combustion gases. The heat release measurements on cables and materials were made using the cone calorimeter shown in Fig. 1. The instrument is based on the principle of oxygen consumption calorimetry for measuring rate of heat release, where the net heat of combustion of any organic material is directly related to the amount of oxygen required for combustion. A laser diode is used for smoke obscuration studies: smoke production rate, effective heat of combustion, specific extinction area etc. The instrument is also fitted with CO_2, CO analysers for providing additional information like CO_2/CO ratios and their production rates. The test specimens can be irradiated at heat fluxes from 10–100 kW/m^2 using a truncated conical heater element to simulate a range of fire intensities. The tests were conducted as per ASTM E 1354-2003 standard[1]. The material specimen size of 100 x 100 mm in area and different thickness plaques were considered in the present study.

FIG. 1 A VIEW OF CONE CALORIMETER

3.2 Specimen preparation

Cone calorimeter tests were performed both on polymeric materials used in cable construction and on actual cables. The material specimen size of 100 x 100 mm in area and 3 mm thick plaques were considered in the present study. The specimens were wrapped in a single layer of aluminium foil of 0.1 mm thickness with the shiny side towards the specimen, covering the sides and bottom and the top surface exposed to thermal irradiance. In case of cables, specimen length each of 100 mm were cut and positioned side by side, in an aluminium foil tray of 0.1 mm thickness and the wrapped specimen was placed on top of a bed of low density refractory fibre blanket in the sample holder. The edged frame was placed over the wrapped cables and fibre blanket and the frame screwed to the pan to secure it in position as shown Fig. 2. The number of cables for each test was arrived by dividing 100 by the diameter of the cable. Cables having diameter upto 19 mm were included in the study. It is presumed that the non-planar surfaces upto 50 mm would not affect the test results as we would see only small variations in incident flux levels of 0.1%[23]. The cable samples were conditioned for 24 hours at 23°C and 50% relative humidity to ensure that the specimen has constant mass before test.

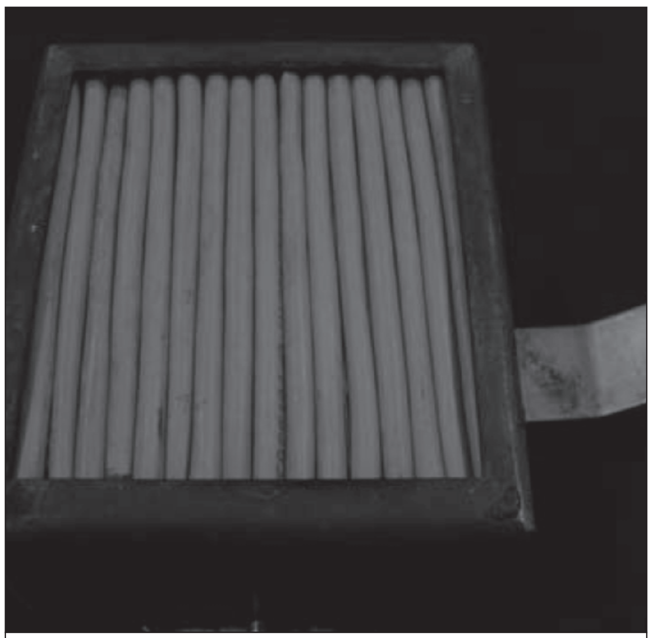


FIG. 2 CABLE TRAY WITH SAMPLES FOR TEST

4.0 CONE RESULTS AND DISCUSSION

4.1 Materials

In recent years, there is an increasing number of applications requiring halogen-free products. PVC materials are replaced with LSZH and ZHFR materials which are free of halogens are being extensively used in numerous types of safe and environmentally friendly products. ZHFR materials are widely employed for sheathing of power/energy, telecommunication, data and fibre optic applications. Different grade compounds are used to meet the requirements of electrical, mechanical, fire performance and water immersion properties.

The fire behaviour of materials like PVC, FR PVC, ZHFR and HDPE (High Density Polyethylene) was evaluated using cone calorimeter, which allowed quantification of the combustion behaviour of the polymers under well-ventilated, controlled radiant heat transfer conditions simulating real fire conditions. The description of polymers studied is presented in Table 1.

TABLE 1

DESCRIPTION OF POLYMERS STUDIED

Polymer sample	Description
PVC	Standard PVC compound, comprising plasticiser (DOP), chalk calcium/zinc stabilisers and titanium dioxide
FR PVC	Flame retardant PVC typically used for cable sheathing, comprising plasticiser, aluminium hydroxide, antimony trioxide, zinc borate, titanium dioxide, antimony trioxide zinc borate and lead stabiliser
ZHFR	General compound used to meet the requirements of electrical, mechanical, fire performance and water immersion properties
HDPE	Thermoplastic or cross-linked material used as main insulation in cable construction

Samples of 100 × 100 mm surface area and 3mm thick plaques were irradiated at heat fluxes of 25 and 50 kW/m^2. The results are presented in Table 2. HRR curve is single numbers via the initial peak Heat Release and the averages of the HRR over a set time (60, 180, 300 secs) after ignition of the specimen. The total heat release is the cumulative heat release (area under the heat release curve) over the duration of the test. From the Table, it is seen that the ignition time reduces with increasing heat flux while peak HRR increases and times to peak HRR decrease. Heats of combustion; the enthalpy of reaction when fuel and oxidant at standard conditions are reacted to form products of combustion at standard condition is higher for HDPE and ZHFR compared to PVC and FR PVC. The volume of smoke production was determined as specific extinction area (SEA, m^2/m).The specific extinction area values at 50 kW/m^2 are higher than the values at 25 kW/m^2. Figs. 3A and 3B show variation of rate of heat release, smoke production rate as a function of time at 25 kW/m^2 and Figs. 3C and 3D show the variation of HRR at 50 kW/m^2. The figures depict that the time to ignition is in the increasing order for the materials PVC, FR PVC, HDPE and ZHFR.

4.2 Cables

The study of cables is grouped into different categories: low voltage power cable, data, telephone cables and automobile cables.

4.2.1 Power cable

The FR PVC outer sheath of 3 × 300 sq.mm size power cable with XLPE as the main insulation was evaluated. The sheath was cut into 100 × 100 mm sizes and exposed to a thermal flux of 35, 50 and 75 kW/m^2. The variation of sample thickness was also studied at a heat flux of 75 kW/m^2. The cone results are presented in Table 3. From the Table, it is observed that with a single layer of the sheath material, the time to ignition is much shorter at 50 kW/m^2 and 75 kW/m^2 compared to 35 kW/m^2.

TABLE 2

CONE CALORIMETER RESULTS FOR THREE DIFFERENT POLYMERS

	PVC		FR PVC		ZHFR		HDPE	
Heat flux, kW/m^2	25	50	25	50	25	50	25	50
Time to ignition, s	129	49	171	47	369	60	298	59
Burning time, s	233	303	366	299	574	549	426	511
Heat release rate, kW/m^2	88.28	90.51	113.76	85.95	58.67	101.5	132.17	149.71
Heat release (peak), kW/m	321.41	230.32	126.67	222.39	109.98	248.28	595.63	849.55
Time to peak, s	145	85	205	105	405	105	365	125
Heat of combustion, kJ/m	12.16	10.51	12.31	12.45	27.80	25.59	40.33	31.90
Smoke (SEA), m^2/m	603.75	652.29	490.62	526.53	198.05	268.83	290.95	317.12
FIGRA, kW/sec	2.22	3.04	0.617	2.12	0.27	2.36	1.63	6.79

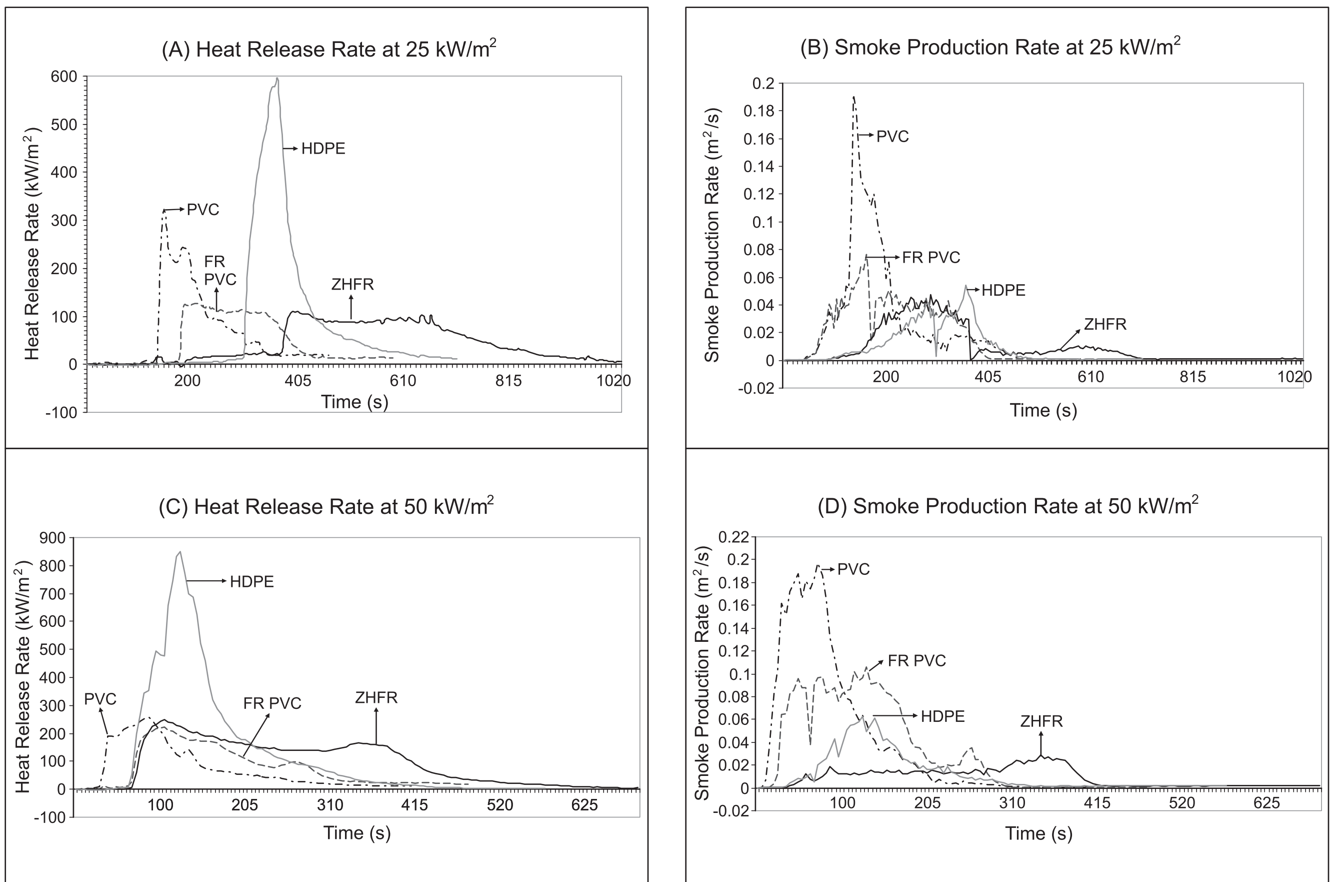


FIG. 3 VARIATION OF HRR AND SMOKE PRODUCTION RATE WITH TIME FOR PVC, FR PVC, ZHFR, AND HDPE AT 25 kW/m^2 AND 50 kW/m^2

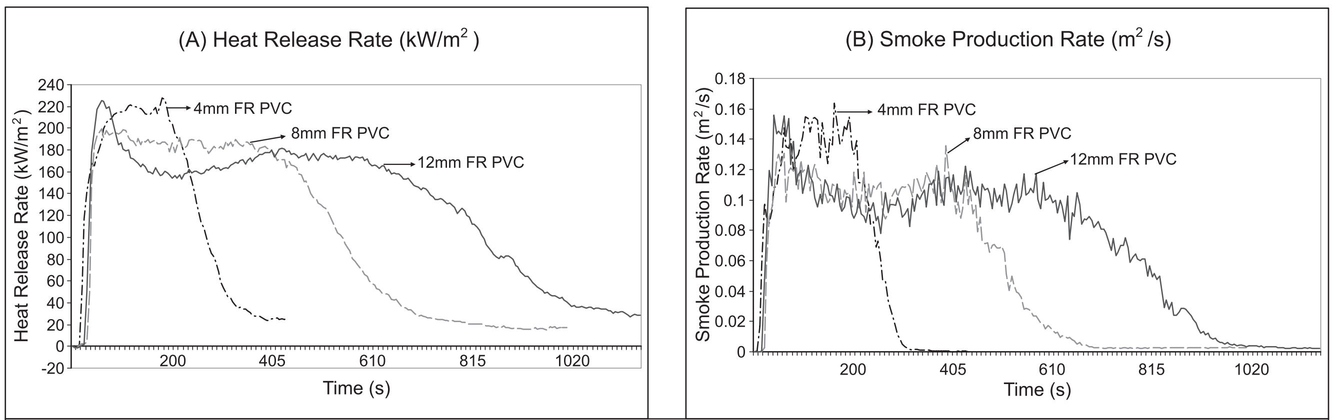


FIG. 4 VARIATION OF HRR AND SMOKE PRODUCTION RATE WITH TIME FOR FR PVC OUTER SHEATH OF POWER CABLE OF DIFFERENT THICKNESS AT 75 kW/m^2

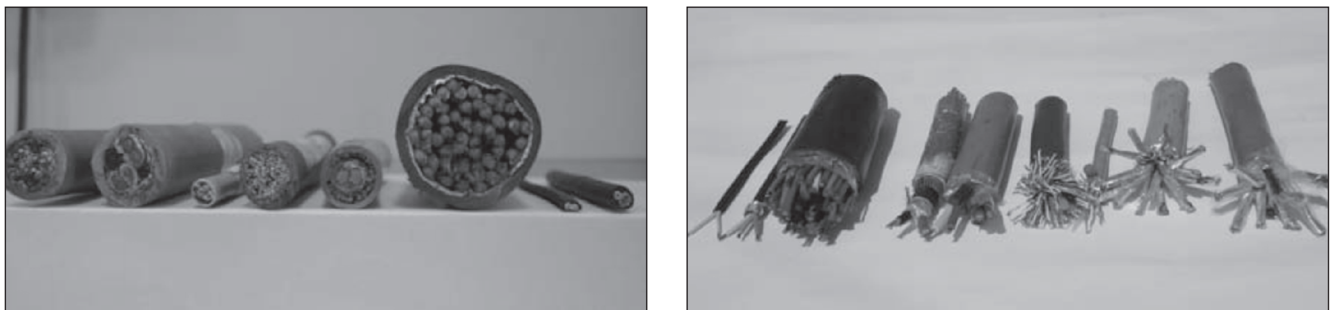


FIG. 5 THE VARIOUS DATA CABLES TESTED

All categories show that times to ignition reduce with increasing heat flux whilst peak HRR increases and the times to reach peak HRR decrease. The heat of combustion is approximately 13 kJ/m at all thermal irradiances and thickness. The smoke extinction area values ranged between 776 and 852 m^2/m for heat flux 25 to 75 kW/m^2.

4.2.1.1 Variation of HRR with thickness

The variation of HRR and other parameters with thickness of cable sheath at 75 kW/m^2 heat flux is studied. The burning time, total heat release, total smoke production increase with thickness are shown in Table 3. The average heat release rate is 122.2 kW/m^2 and the average specific extinction area is 846.67 m^2/m. Figs. 4A and 4B present pictorially the data of the rate of heat release, smoke production rate, and as a function of time. From these Figs., it is evident that the burning time and smoke production are nearly proportional to the thickness of the sample, as the quantity of combustible material has increased**.** The toxicity of the gases characterised by carbon monoxide production (not shown) sustains for a longer duration with increase in thickness of the sample.

4.2.2 Data cables

The data cables tested are shown in Fig. 5. Description of the cables is given in Table 4. Each cable varied in their construction and material. The sample preparation for the tests is as described earlier.

The data cables were evaluated at a heat flux of either 25, 35, 50 and 75 kW/m^2 or a combination. Table 5 shows the typical data on these cables tested at 35 kW/m^2 and 50 kW/m^2. The data cables tested showed a variety of behaviours at different heat fluxes depending upon the cable composition and construction. One category of cable reaches the peak heat release very quickly. A second category shows a slower development and fluctuations in cone parameters due to different components of the cable contributing to the fire development.

TABLE 3

CONE CALORIMETER RESULTS POWER CABLE OUTER SHEATH

	Power cable, 3 × 300 sq.mm XLPE insulated, FR PVC outer sheathed							
	One layer of outer sheath (4 mm)			Two layers of outer sheath (8 mm)		Variation with thickness of outer sheath		
						4 mm	8 mm	12 mm
Heat flux, kW/m^2	35	50	75	50	75	75	75	75
Time to ignition, s	56	8	5	38	27	5	27	18
Burning time, s	477	452	395	891	773	395	773	1105
Heat release rate, kW/m^2	89.66	99.4	128.33	106.23	107.33	128.33	107.33	130.95
Heat release (peak), kW/m	172.01	192.36	227.9	168.37	199.62	227.9	199.62	225.61
Heat of combustion, kJ/m	13.8	13.2	12.93	14.61	13.8	12.93	13.8	14.10
Total heat release, MJ/m^2	52.8	57.1	55.1	114.2	105.3	55.1	105.3	149.3
Smoke (SEA), m^2/m	776.68	825.3	852.33	–	807.29	852.33	807.29	880.4
Total smoke release, m^2/m^2	2973.8	3284.3	3633.8	–	6203.7	3633.8	6203.7	9358.8
Total smoke production, m^2	26.3	30.2	32.1	–	54.8	32.1	54.8	82.7

A third category of cables shows a steady growth for the duration of the test and the fourth shows very little heat release throughout the test. A similar trend has been reported by other researchers[3]. The CO_2/CO ratios are high for non-FRLS compared to FRLS materials.

4.2.2.1 Cable 1

The construction of the cable is such that the 0.5 sq. mm multi-stranded copper is insulated with polyolefin material and each pair shielded with aluminium and polypropylene film. Further, the eight pairs are wrapped with polypropylene film and overall sheathed with FRLS PVC. These cables were tested at 35 and 50 kW/m^2.

Figs. 6A to 6D show the behaviour of cable tested. At 35 kW/m^2, the ignition time is quite long 652 secs and a single HRR peak is observed at 745 secs, whereas at 50 kW/m^2 prior to the dominant peak at 430 secs, a peak at 90 secs, and later at 730 and 1000 secs with fluctuating HRR values is observed. A similar trend is also observed in smoke production, CO and CO_2 rates. This trend is probably due to the masking effect of the metallic aluminium foil in between the cable cores and the different materials used in cable construction.

4.2.2.2 Cable 2

The materials used in the construction of this cable are polyolefin material for core insulation and FRLS PVC for outer sheath. The core size is 1.5 sq.mm multi-stranded copper and 2 pairs, each pair shielded with aluminium and polypropylene film. Further the two pairs are wrapped with pp film and overall sheathed with FRLS PVC. Figs. 7A to 7C show the HRR, smoke production and CO data. It is interesting to note that the cable did not get ignited at 25 kW/m^2 throughout the test and hence it was discarded.

However, at 35 and 50 kW/m^2, two prominent HRR peaks and small variations in other peaks are also observed. The trend is similar in smoke production, CO and CO_2 rates.

TABLE 4

DESCRIPTION OF VARIOUS DATA CABLES

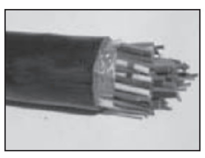
Cables		**Description**
Cable 1		Instrumentation cable intended for use in hydel, thermal plants. 8 pair, 0.5 sq.mm multi-stranded copper is insulated with polyolefin material and each pair shielded with aluminium and polypropylene film. Further the eight pairs are wrapped with polypropylene film and overall sheathed with FRLS PVC
Cable 2		Cable for use in oil refineries /petrochemical plants. 2 pair with core size of 1.5 sq.mm multi-stranded copper polyolefin insulated. Each pair shielded with aluminium and polypropylene film. Further the two pairs are wrapped with pp film and overall sheathed with FRLS PVC
Cable 3		Four pair cable with each copper core insulated with FTP category LSZH polyethylene material and all the 4 pairs shielded with aluminium foil and the overall FTP category LSZH sheathed
TC Cable 1 (Telecom)		1.5 sq.mm 25 pair FRLS cable. Each copper core insulated with polyolefin insulation and all the pairs wrapped with aluminium and polyester film and overall sheathed with FRLS PVC
TC Cable 2 (Telecom)		0.5 sq.mm, 48 pair, polyolefin insulation, non-FRLS PVC outer sheathed cable for telecom application
FS cable (Fire survival		Fire survival cable, 1.5 sq.mm 1 pair 600/1000 volts used in metro rail. Each copper core insulated with mica and polyolefin sheathed. The pair of cores is further shielded with aluminium foil and polyester film and sheathed with FRLS PVC. Further sheath is protected with steel armour and overall sheathed with FRLS PVC
AM Cable 1 (Automobile)		37/0.13 mm ATC Thermoplastic elastomer insulated, Thermoplastic rubber sheathed 2 core cable for automobile industry
AM Cable 2 (Automobile)		19/0.2 mm ATC special Thermoplastic rubber insulated 3 core screened and Thermoplastic rubber sheathed cable for automobile industry

TABLE 5

CONE RESULTS FOR THE DIFFERENT DATA CABLES AT HEAT FLUX 35 kW/m² AND 50 kW/m²

	Cable 1		Cable 2		Cable 3		TC Cable 1		FS Cable
Heat flux kW/m²	35	50	35	50	35	50	35	50	35
Time to ignition, s	652	82	124	70	74	37	169	49	120
Burning time, s	1005	1267	1564	1232	1049	698	1830	1336	1753
Heat release rate, kW/m²	95.86	105.54	114.77	155.68	58.63	89.2	85.65	113.55	106.39
Heat release (peak), kW/m	146.97	169.91	177.99	248.0	171.69	274.72	204.77	257.31	175.11
Heat of combustion, kJ/m	18	15.50	19.67	19.68	26.61	26.16	30.07	30.13	27
Smoke (SEA), m²/m	577.57	354.52	369.66	554.37	247.14	276.66	304.57	306.04	172.43
Carbon monoxide yield, kg/kg	0.144	0.1326	0.1591	0.1667	35	–	0.09992	0.0429	0.0433
Carbon dioxide yield, kg/kg	2.02	1.66	1.79	5.348	74	–	3.52	2.96	2.67
CO_2/CO ratio	14	12.5	11.25	32.08	2.11	–	35.2	68.99	61.66

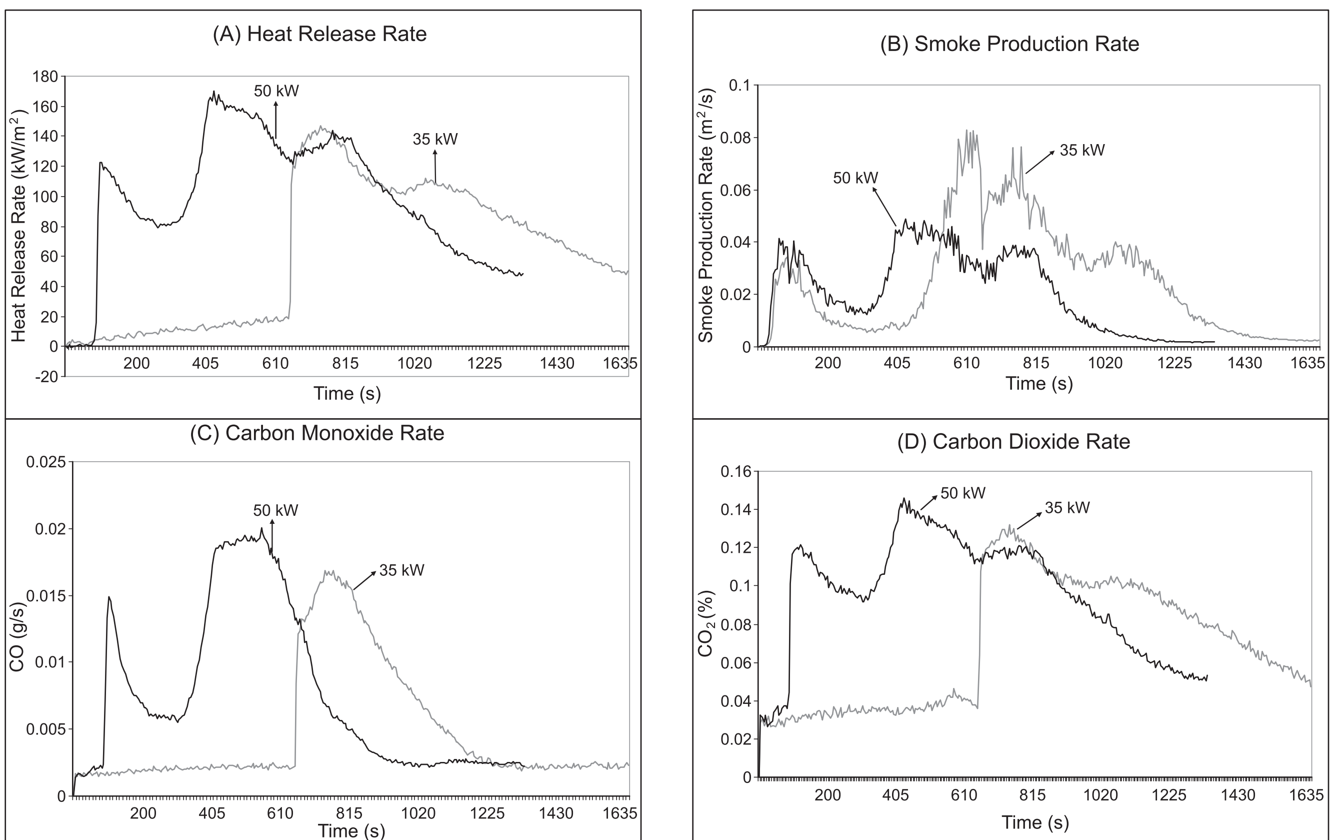


FIG. 6. VARIATION OF HRR, SMOKE PRODUCTION RATE, CO AND CO_2 WITH TIME FOR 0.5 sq. mm, 8 PAIR FRLS DATA CABLE AT 35 AND 50 kW/m²

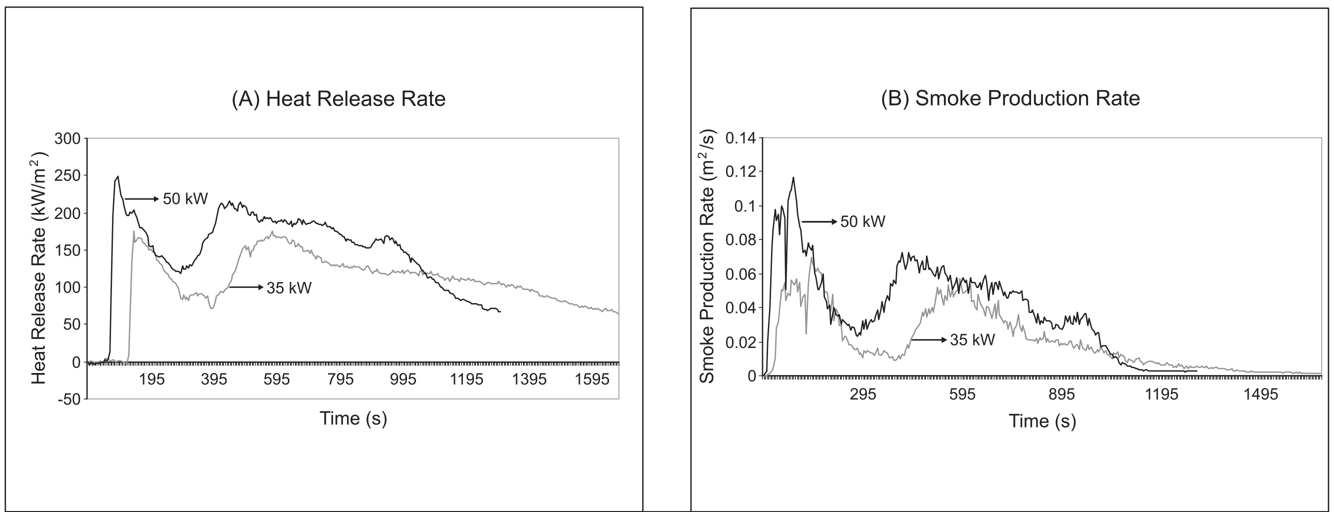


FIG. 7. VARIATION OF HRR AND SMOKE PRODUCTION RATE WITH TIME FOR 1.5 sq. mm, 2 PAIR FRLS DATA CABLE AT 25 AND 35 kW/m^2

4.2.2.3 Cable 3

This is a four pair cable with each copper core insulated with FTP category LSZH polyethylene material and all the 4 pairs shielded with aluminium foil and the overall FTP category LSZH sheathed. The cable has been tested at 25, 35 and 50 kW/m^2 and the results are shown in Figs. 8A to 8C. The time to peak HRR decreases while HRR increases with heat flux.

The CO peaks also vary according to the burning process. Since both core and outer sheath insulation are from the same material, very few HRR peaks were observed. The material during burning softens and runs into molten liquid flowing through the side walls of the container with dropping flamelet.

4.2.3 TC Cable

This is a non-FRLS cable for use in telecommunication applications. The materials used in construction of the TC cable 1 are 0.5 sq.mm multi-stranded copper, polyolefin material, and aluminium and polypropylene film for inner shield. Twenty-five pairs are wrapped with polypropylene film and overall sheathed with non-FRLS PVC. The test results are shown in Figs. 9A to 9D. Since the sheathing material used is non-FRLS, the ignition times are very short, 49 secs at 50 kW/m^2 and 169 secs at 35 kW/m^2. The burning times are quite long compared to FRLS cables. As observed in other cables, the HRR peaks are observed at varying times due to metallic shielding of the insulation used in the construction of the cable. The CO and CO_2 production are also high and sustain till the end of the test. A similar trend is observed for TC cable 2 (Data not shown).

4.2.4 FS cable

The fire survival cable is intended for use in maintaining electrical integrity even under fire condition. The cable is a single pair, 1.5 sq.mm copper core insulated with mica and polyolefin sheathed.

Further, the sheath is protected with steel armour and overall sheathed with FRLS PVC cable. The cable was tested at 35 and 50 kW/m^2. The HRR, smoke production rate, CO and CO_2 production rate curves are shown in Figs. 10A to 10D. From these figures, it is evident that the time to peak HRR between the first peak and second peak is pretty large and CO_2 to CO ratio is very high compared to other cables (Table 5).

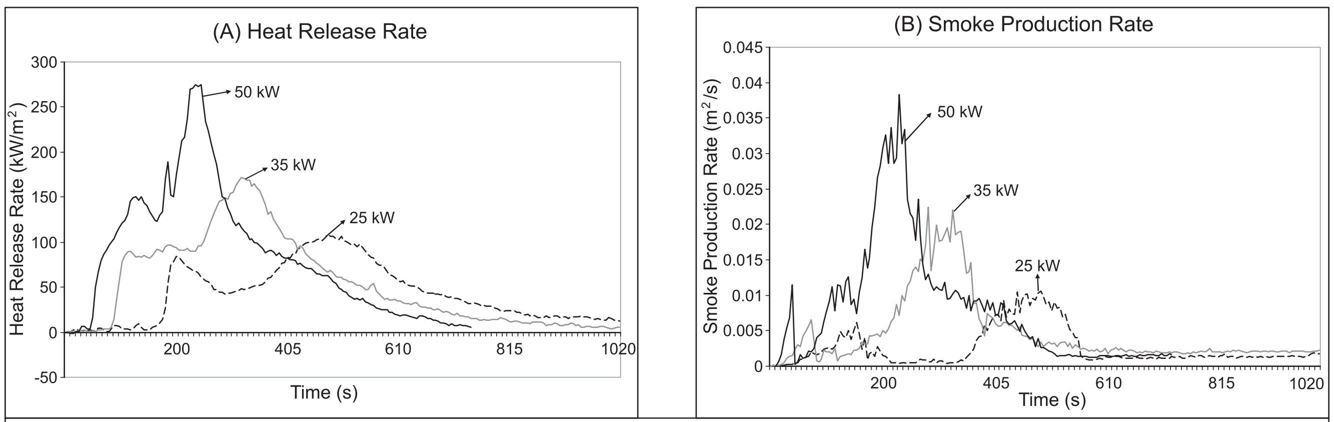


FIG. 8 VARIATION OF HRR AND SMOKE PRODUCTION RATE, WITH TIME FOR FTP CATEGORY FRLS DATA CABLE AT 25, 35 AND 50 kW/m²

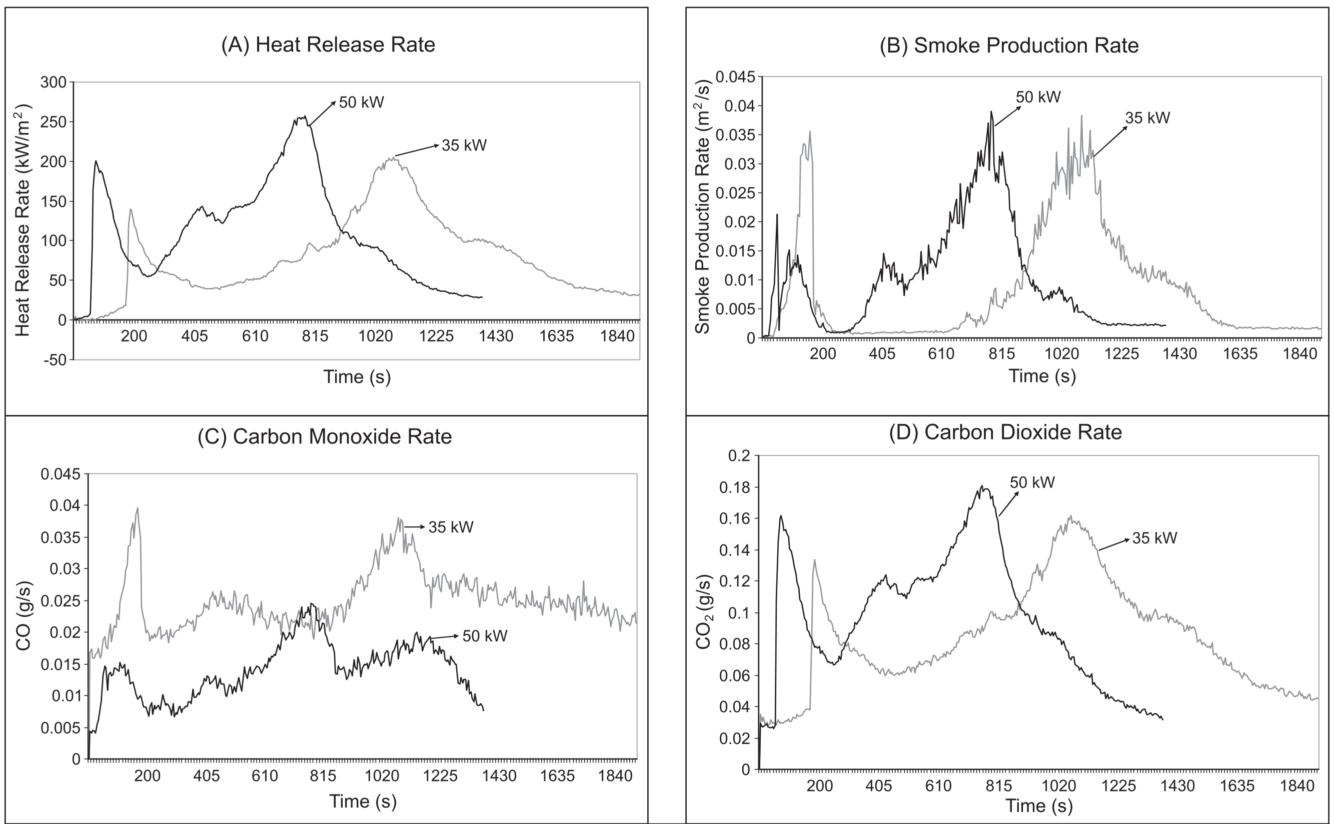


FIG. 9 VARIATION OF HRR, SMOKE PRODUCTION RATE, CO AND CO_2 WITH TIME FOR 25 PAIR NON-FRLS CABLE AT 35 AND 50 kW/m²

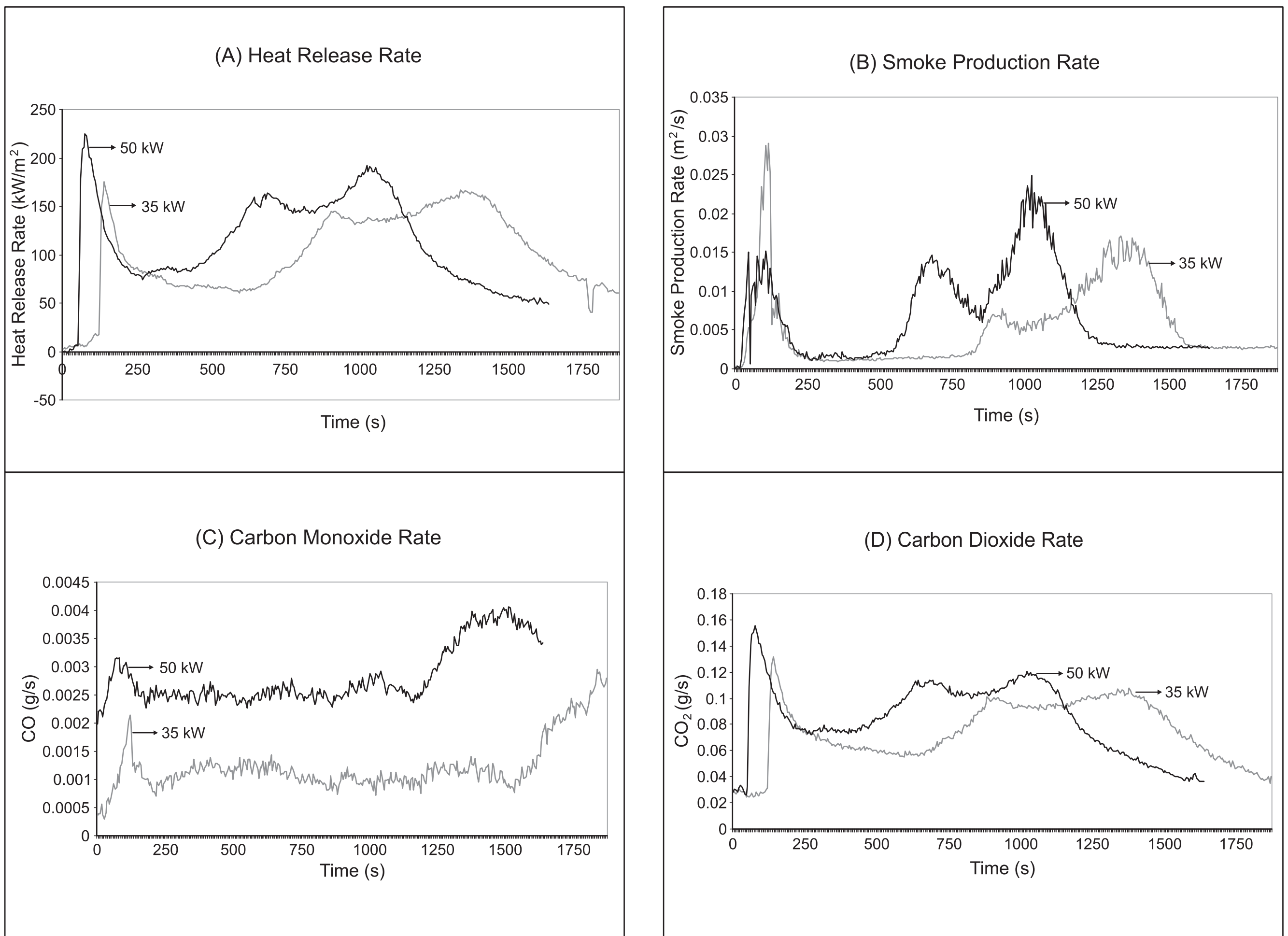


FIG. 10 VARIATION OF HRR, SP, CO AND CO_2 WITH TIME FOR FIRE SURVIVAL CABLE AT 35 AND 50 kW/m^2

4.2.5 AM Cables

These cables are intended for use in automobile industry. Automobile Cable 1 is 37/0.13 mm ATC Thermoplastic Elastomer insulated, Thermoplastic rubber sheathed 2 core cable. Automobile Cable 2 is 19/0.2 mm ATC special TPR insulated 3 core screened and TPR sheathed cable. The HRR data of these cables are shown in Table 6 and graphically presented in Figs. 11A and 11B. Unlike other cables, only single HRR peaks and the time to peak decrease with heat flux are observed. The heat release peaks increase with increase in heat fluxes. The heat of combustion is observed to vary between 27.18 to 33.04 kJ/m.

TABLE 6

CONE RESULTS FOR DIFFERENT HEAT FLUXES

	25 kW	**35 kW**	**50 kW**
Time to ignition, s	297	73	15
Burning time, s	301	427	164
Heat release rate, kW/m^2	119.35	107.10	105.37
Heat release(peak), kW/m	373.11	594.39	939.6
Heat of combustion, kJ/m	27.18	33.04	31.74

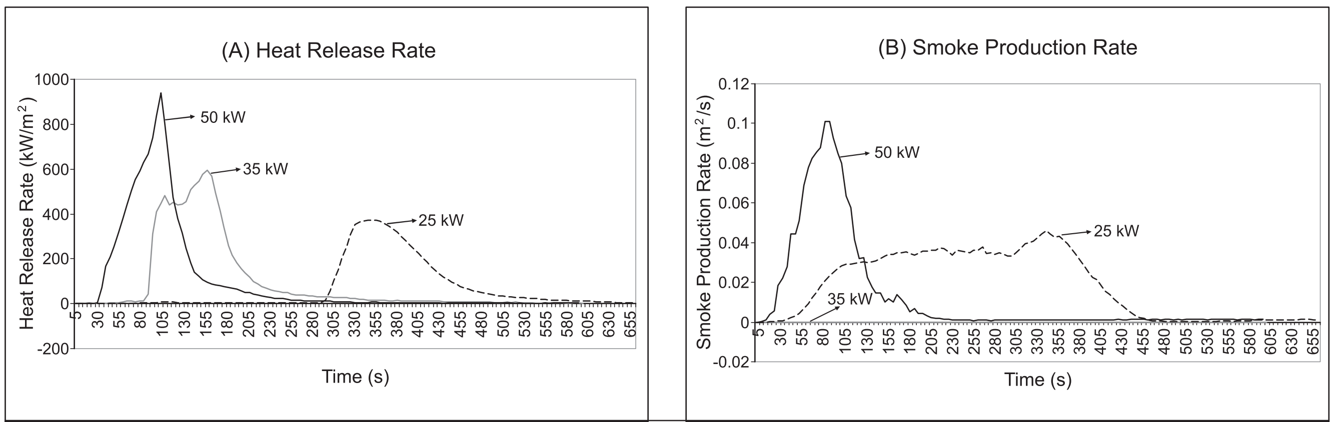


FIG. 11 VARIATION OF HRR, SMOKE PRODUCTION RATE WITH TIME FOR 37/0.13 mm ATC THERMOPLASTIC ELASTOMER INSULATED, THERMOPLASTIC RUBBER SHEATHED 2 CORE CABLE AT 35 AND 50 kW/m^2

4.3 Discussion

The fire behaviour of various materials showed that the time to peak (HRR) is in the increasing order for materials PVC, FR PVC, HDPE and ZHFR. The time to ignition of PVC and FR PVC (Table 2) shows that the fire retardation is very effective at both a heat flux of 35 and 50 kW/m^2. FIGRA values are higher for PVC compared to FR PVC.

The cables tested showed a variety of behaviours at different heat fluxes depending upon the cable composition and construction. One category of cable reaches peak heat release very quickly. A second shows a slower development and the fluctuations of the curve show different components of the cable contributing to the fire development. A third shows steady growth for the duration of the test and the fourth category shows very little heat release throughout the test.

Results of testing of the cables under the different heat fluxes summarised in Table 5 reveal that there is a marked difference in time to ignition (as shown in brackets) between cable 1 and all other cables at 35 kW/m^2 heat flux. Cable 1 (652 secs), cable 4 (169 secs), cable 2 (124 secs), FS cable (120 secs) and cable 3 (74 secs). Prominent difference is not observed at 50 kW/m^2 heat flux. The ignition times in case of non-FRLS cables (cable 4) are very short, 49 secs at 50 kW/m^2 and 169 secs at 35 kW/m^2 and the burning times are quite long compared to FRLS cables.

All cables show multiple peaks of HRR attributed to different materials used in the construction of cable and shielding effect of aluminium and mica in between the cable cores. The HRR peaks are observed at varying times due to metallic shielding of the insulation used in the construction of the cable. This trend is due to the masking effect of the metallic aluminium foil. CO_2/CO ratios are high for non-FRLS compared to FRLS materials. The CO and CO_2 productions are also high and sustain till the rest of the test.

5.0 MATERIALS USED IN LOCOMOTIVES

5.1 Interiors (floor, side walls, window frames), wood, FRP, polycarbonate materials, flooring mats, curtains

The materials that are used in construction of rail coaches have been evaluated and presented in Table 7. From Table 7, it is evident that HRR is maximum in the case of polycarbonate material (255.9) and in the decreasing order for silicone rubber (123.6), wood (123.3), FR seat covering material (81.3), FRP sheet (62.85), curtain fabric (51.98) and PVC flooring material (20.61). In case of polycarbonate material, the

TABLE 7

CONE RESULTS FOR THE MATERIALS AT HEAT FLUX 50 kW/m^2

Material	Polycarbonate sheet	Silicone rubber	Densified wood	FR seat covering material	Fibre reinforced plastic	PVC flooring material	Curtain fabric
Time to ignition, s	158	88	65	21	117	23	61
Burning time, s	427	434	745	448	548	84	201
Heat release rate (60), kW/m^2	225.9	123.6	123.3	81.3	62.85	20.61	51.98
Heat release (peak), kW/m^2	507.9	255.0	318.2	165.4	214.7	103.9	285.6
Heat of combustion, kJ/m	24.78	15.76	11.59	13.22	17.75	2.99	6.53
Smoke (SEA), m^2/kg	655.1	307.6	44.66	351.5	158.9	597.7	487.7
CO yield , kg/kg	0.075	0.006	0.019	0.099	0.041	0.035	0.118
CO_2 yield , kg/kg	1.9	0.94	1.19	1.05	1.70	0.34	1.91
CO_2/CO ratio	25.47	156.7	62.63	10.66	41.16	9.7	16.18
MARHE	230	86.8	141.0	129.1	141.0	24.9	78.4

time to ignition is much longer but produces high smoke, HRR and peak HRR compared to other materials. Based on MAHRE, the densified wood, seat material and FRP fall under one category, silicone rubber and curtain fabric the other category. Flooring and seat covering material are vulnerable to ignition but HRR are much lower compared to other materials.

5.2 Cushioning materials

Flexible polyurethane foam (rigid, slab stack, graphite) and thermal bonded polyester blocks have become the choice of cushioning material for seats and berths in rail coaches. Combustion being the surface phenomena, PU foams differ largely in their burning behaviour. Due to their low bulk density, ranging from 15 to 80 kg/m^3, they have a very high surface to mass ratio and are vulnerable to combustion, easily ignitable and swift in developing fire. One way to prevent fire propagation is through the use of flame retardants. The commonly used flame retardants are based on halogens, phosphorous, metal hydroxides, melamine and antimony trioxide, etc. New approaches to the provision of flame retardancy such as nanocomposites and expandable graphite are being developed.

Alternatively, densified thermal bonded polyester blocks are also used as cushioning material which is made using a mixture of hollow polyester fibre with low melt polyester fibre. The PU foam and thermal bonded polyester material complies with the following requirements. *Bracketed values are for thermal bonded polyester. Density 49-50 (*50±3) kg/m^3, Tensile strength 1 kg/cm^2 min (*2.5), Elongation at break 100%(min)(*110), Load quotient 1.9:1 (*3:1), Indentation hardness index 15-22 @25% (*15-24), 21-24 @ 40% (*29-35), Resistance to spread flame minimum class B as per appendix 8 of UIC 564—2, deterioration of visibility due to smoke class B (*A) as per appendix 15 of UIC 564—2, limiting oxygen index minimum; 28, IS 13501 and toxicity index as per NCD 1409, < 1 (*< 0.7), flammability test as per IS 7888, Cl.11.

Several cushioning materials have been evaluated for heat release, combustion smoke, flammability and toxicity. Table 8 presents the cone results of different types of cushioning materials evaluated at 35 kW/m^2 and 50 kW/m^2 heat flux.

From Table 8, it is seen that PU foams are easily ignitable compared to densified thermally bonded polyester. The HRR and peak (HRR) values are much higher for PU than thermally bonded polyester or expandable graphite PU. In terms of HRR, peak (HRR), MAHRE expandable graphite PU is better rated than others. During testing, it was observed that at 35 kW/m^2 heat flux, the thermally bonded polyester block did not get ignited at all. However, at 50 kW/m^2 the material shrinks in size, changes to molten state and gets ignited with release of heat and smoke whereas in case of graphite PU, the ignition times are more or less the same for different heat fluxes and release less heat compared to others. Also during burning, the sample does not foam too much but forms a bristle type residue with a shiny glow continuing for some time even after the flame is out. Rigid and flexible PU foams once ignited, burst into a fully developed flame without leaving any residue.

6.0 TOXICITY[8] (NES 713/NCD 1409)

This test explores the toxicity of the products of combustion in terms of small molecular species arising when a small sample of material is completely burnt in excess air under specified conditions. The evaluation of the toxicity is made through the determination of the following gases: carbon oxides (CO, CO_2), halogen acids (HCl, HBr, HF), prussic acid (HCN), nitric oxides (NO_x), acrylonitrile (CH_2CHCN). The Toxicity Index (TI) is defined as the numerical summation of the toxicity factors of selected gases produced by complete combustion of the material in air.

TABLE 8

CONE RESULTS FOR CUSHIONING MATERIALS AT 35 kW/m^2 AND 50 kW/m^2 HEAT FLUX

	Moulded rigid polyurethane		**Flexible polyurethane (Slab stack)**		**Expandable graphite polyurethane**		**Densified thermally bonded polyester**	
Heat flux, kW/m^2	35	50	35	50	35	50	35	50
Time to ignition, s	6	6	6	38	6	26	-	163
Burning time, s	340	193	317	242	583	361	-	379
Heat release rate (60), kW/m^2	178.6	272.95	170.1	192.31	26.26	47.22	5	130.23
Heat release (peak), kW/m^2	306.8	417.97	292.3	389.47	74.44	94.84	9.56	213.96
Heat of combustion, kJ/m	25.98	24.52	23.3	24.21	17.64	19.10	3.2	15.51
Smoke (SEA), m^2/kg	390.3	431.49	296.9	318.90	3.34	-	575.2	291.31
CO yield , kg/kg	0.052	0.0372	0.046	0.043	0.076	0.036	0.054	0.0286
CO_2 yield , kg/kg	2.02	1.91	1.86	1.86	2.53	1.95	1.73	1.69
CO_2/CO ratio	38.85	51.34	40.43	43.25	33.29	54.16	32.04	59.09
MARHE	236.2	318.0	221.2	228.1	56.7	59.1	4.2	83.3

Fig. 12 illustrates the test chamber used for determining the toxicity of a material. The chamber consists of an airtight enclosure of at least 0.7 m^3 volume, lined with opaque plastic sheeting material having a sliding door fitted with a transparent plastic panel. Gas reaction tubes are used for detection of gases and their concentration. Table 9 presents the toxicity index values of different polymeric materials that were evaluated. The requirement by the railway board is that toxicity should be less than 1. From Table 9, it is seen that only certain materials like densified wood, FR boards, fire retardant curtain fabrics, thermal bonded polyester cushioning materials meet the requirement. The cushioning materials, polyurethane foams: rigid, slab stack have Toxicity Index values ranging from 3 to 6.

FIG. 12 TOXICITY INDEX APPARATUS

TABLE 9

TYPICAL VALUES OF TOXICITY INDEX OF MATERIALS

Description of the material	**Sample numbers**	**Gases detected**	**Total Toxicity Index**
Laminated densified wood	A, B, C	CO_2, CO, acrylonitrile	0.9987, 0.9481, 0.9551
FRP Board	MF, MMF, PP	CO_2, CO, NO_x, HCHO, acrylonitrile	1.7891, 1.8257, 0.3378
FRP/GRP phenolic material	A, B	CO_2, CO, acrylonitrile	0.7923, 0.7843
Polycarbonate material	A	CO_2	1.0521
Fire retardant curtain cloth	A	CO_2, CO, HCHO, phenol	0.8875
	B	CO_2, NO_x	0.8849
PVC coated nylon fabric	A	CO_2, CO, NO_x	2.8871
Solid layered PVC coated upholstery cloth	A	CO_2, CO, HCl	0.719
	B, C	CO_2, CO, NO_x, HCl	2.5366, 3.8739
Rubber sample	A	CO_2, acrylonitrile, HCHO	0.7482
Densified thermal bonded polyester blocks	A, B, C, D, E	CO_2, CO	0.4939, 0.6364, 0.4377, 0.4728, 0.4174
Flexible PVC vinyl flooring	A, B, C	CO_2, HCl	2.6297, 3.2200, 1.3319
Graphite polyurethane foam	A, B	CO_2, CO, NO_x, HCHO, acrylonitrile	1.9082, 2.7038
Polyurethane foam (Slab stack)	A, B, C, D, F, G, F	CO_2, CO, NO_x, HCl, HCHO, acrylonitrile	3.2846, 5.299, 3.850, 5.2427, 3.7998, 6.3002, 4.6306
High density moulded polyurethane form	A, B	CO_2, CO, NO_x, acrylonitrile	6.1599, 6.2064
	C, D, E, F, G	CO_2, CO, NO_x, HCHO, acrylonitrile	3.6968, 2.7742, 4.7426, 3.022, 3.6475
	H, I	CO_2, NO_x, HCHO, acrylonitrile	2.6909, 4.4305
PVC insulated and PVC sheathed cable	Sheath, filler, insulation	CO_2, CO, NO_x, HCHO, HCl, sulphur dioxide, H_2S, ammonia, acrylonitrile	13.25, 1.35, 14.0
EPR insulated and thermo polyolefin sheathed cable	Sheath, filler, insulation		1.35, 0.87, 1.2

7.0 CONCLUSIONS

Cone calorimeter measurements provide key parameters which help to ascertain the fire behaviour of material under different thermal fluxes. The behaviour of cables in a fire depends on a number of factors, including their constituent materials and construction. The component material and the construction of the cable are very important, as is the nature of the given fire.

Ignition times are much longer for FRLS cables compared to non-FRLS cables. FRLS cables have shown better results in terms of HRR, MAHRE and smoke. CO_2/CO ratios are also high for non-FRLS compared to FRLS cables. The burning cables and materials can propagate flames from one area to another or they can add to the amount of fuel available for combustion and liberate smoke containing toxic and corrosive gases.

Based on MAHRE, the densified wood, seat material and FRP can be classified under one category, silicone rubber and curtain fabric in the other category. Flooring and seat covering materials are vulnerable to ignition but HRR are much lower compared to other materials.

PU foams are easily ignitable compared to densified thermally bonded polyester. The HRR and peak (HRR) values are much higher for PU than thermally bonded polyester or expandable graphite PU. In terms of HRR, peak (HRR) and MAHRE expandable graphite PU is better rated than others. Toxicity index is less than 1 only for few materials.

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