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Flammability Characteristics of Electrical Cables Using the Cone Calorimeter

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U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
National Engineering Laboratory
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Flammability Characteristics of Electrical Cables Using the Cone Calorimeter

by

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Abstracts

Cone calorimeter tests were performed on eight multi-conductor electrical cables. Measurements of ignition delay time, heat release rate, mass loss rate, and gas and smoke generation rates were made in the vertical (2 irradiance levels) and horizontal (3 irradiance levels) orientations. It was found that comparable ignition delay times were observed for all of the cross-linked polyolefin jacketed cables. The PVC jacketed cable had a substantially lower ignition delay time. All of the cables exhibited an ignition delay time dependence on external irradiance approximately proportional to $1/\dot{q}_e''^2$. Sample orientation did not significantly effect the ignition delay time. Heat release rate measurements showed that the cables burned in multiple stages. Each stage of burning was associated with the decomposition of a layer of the cable assembly. For some cables at low external irradiances (25 kW/m^2), only the outer jacket of the cable burned. At higher irradiances (above 50 kW/m^2), the outer jacket burst open exposing the interior cable materials and secondary heat release rate peaks resulted. Changes in the cable components actually burning were reflected in variations in mass loss, gas and smoke generation rates as well as small changes in the effective heat of combustion. HBr and $HC\ell$ were detected during the burning of some of the cables. The production of HCN was detected at some point during the combustion of most of these cables.

Keywords: Cables; combustion; cone calorimeter; flammability; ignition delay time; heat release rate; gas yield; smoke yield.

1.0 INTRODUCTION

A 1978 study conducted by the National Research Council [1] found that the flammability hazards associated with the burning of electrical cables in enclosures included ignition, flame spread, smoke and toxic gas production. One of the major conclusions of this report was the need to develop additional test methods that could accurately assess end-use fire performance from a battery of small-scale tests. The test methods should be able to predict large-scale performance of single cables, which may burn only with difficulty as well as bundled cables, which can burn vigourously [2].

Fire hazard is a multi-dimensional phenomenon requiring the integration of several material and environmental fire properties. Therefore, in attempting to set flammability standards for cables, it must be understood that small-scale test data must be in some way related to "real" fire situations. This may be relatively simple, such as correlating ignition delay times to an externally imposed irradiance, or very complex, such as correlating fire growth and spread to thermal energy feedback and enclosure conditions. The development of new polymeric materials for use in high performance applications, such as naval shipboard power and communications cables, has increased the interest in characterizing cable flammability so that large-scale fire performance can be predicted from small-scale test results.

This report is a first step in the development of small-scale to large-scale correlation parameters. It begins with a short literature review of small-scale fire tests of cables to determine basic fire properties relevant to cable flammability. This study characterizes the flammability properties of eight electric cables intended for naval shipboard power and communication transmission. Flammability characteristics were determined under different external irradiances and orientations using the small-scale cone calorimeter.

2.0 LITERATURE REVIEW

Spade [3] has rightly pointed out that cables are a composite of a number of layers of materials. With the exception of fiber-optic cables, cables are composed of metallic conductors and non-metallic polymers. Therefore, any test that evaluates a material's performance independent of the construction does not adequately assess the fire performance of assemblied cables. The presence of a metallic conductor (i.e., size of conductor and relationship to insulation thickness) can have a considerable effect on the overall fire performance of a cable composite. For cables at room temperature, the conductor can act as a heat sink, while elevating the conductor temperature can reverse this effect. Under simulated power load conditions, Lupton et al [4] found that increasing conductor temperature increased the size of the char area and the extent of upward flame spread.

Beyreis et al [5] developed a procedure for using the results from ASTM E-84 to classify cables according to flame spread and smoke generation characteristics. They used a cable rack placed in the upper part of the ASTM E-84 tunnel with multiple cable runs. Przybyla et al [6] used this procedure to evaluate four cables for use in air handling spaces.

Gouldson [7] reviewed numerous fire tests for wire and cable, including ASTM E-84, and concluded that, while most of the standard tests evaluated material or cable performance, they did not provide appropriate information for classification and hazard assessment. He found that a modified Ohio State University Release Rate Apparatus could be used to evaluate flame spread, heat release, smoke and toxic gas generation of wire and cables. Pocock and Geremia [8] used a similar heat release apparatus to evaluate the fire performance of a set of cables with a range of physical characteristics. They found the effect of external irradiance on heat and smoke release rates to be dependent on cable diameter and the ratio of copper conductor cross-sectional area to total cable cross-sectional area. Spacing between cables had no significant effect on the rate of heat release or smoke generation. Alvares et al [9] also measured the heat release rate, in addition to ignition delay time and smoke generation rate, using a large-scale calorimeter. They found that common insulating materials could not be easily ignited, and burned with relatively little heat output and slow rate of flame spread unless the surface-to-volume ratio of insulation to conductor was great. Tewarson et al [10,11] used a rate of heat release apparatus to categorize similar flammability parameters of electric cables. They found that the fire hazard of cables could be evaluated based on the functional relationship of the external irradiance and the rate of heat release, which measures fire intensity and sensitivity to external irradiances. Tewarson et al [11] also investigated the relationship between cable ignition properties and electrical integrity. He found that, for cables that did not melt or soften, electrical integrity followed ignition delay time. For cables that melted or softened, electrical integrity was independent of ignition delay time.

This review, while not exhaustive, has demonstrated the research trend towards evaluating a material's basic fire characteristics under controlled thermal conditions. The basic measurements are ignition delay time, rate of heat release, gas and smoke generation rate, and flame spread. The NBS Cone Calorimeter was used in this study to evaluate eight electric cables exposed to different external irradiances in terms of; ignition delay time, rate of heat release, yields of several gaseous products, and production of particulates (visible smoke). Currently, these variables represent the information necessary for hazard evaluation.

3.0 MATERIALS

Table 1 lists the military specifications and the physical characteristics of the electrical cables used in this study. The identifying nomenclature follows the relevant military standards for wire and cable. All cables were composed of multiple conductors with several layers of insulating polymeric materials. Their overall diameters varied from 14.0 mm (12 conductors) to 28.3 mm (44 conductors). The outer jackets of seven of the cables were made from compounds of cross-linked polyolefin. Cable MNW-44 had an outer jacket of poly(vinyl chloride). Conductor insulation was either polyproplene, cross-linked polyethylene, or silicon rubber with polyester binder and fillers. No information was provided concerning the potential presence of other additives. Four cables had no metallic shielding. Two cables, TTXSO-6 and 2XSAW-14, had metallic shielding on wire pairs and the entire bundle. One cable, LS2SWAU-10, had a metallic shield on the entire bundle, and one cable, LSTTRS-6, had shielding only on wire pairs.

Test specimens were cut into 100 mm lengths. A sample holder with an exposed surface area of 94 mm by 94 mm was used to test all of the cable assemblies. A single layer of cable segments was placed in the sample holder. The number of cable segments depended on the overall diameter of each cable. Because cable diameters were not even multiples of the sample holder size, cables did not completely fill the exposed sample holder surface. However, during a fire test each of the cables swelled above the initial sample surface and expanded to fill all void spaces in the sample holder. Cable MNW-44 melted and formed a pool of liquid polymer during the combustion process. The effective surface area became the exposed area of the sample holder.

4.0 TEST METHOD

The NBS Cone Calorimeter, figure 1, has been previously described by Babrauskas [12] and Babrauskas and Parker [13] and is currently pending as an ASTM standard test method [14]. Briefly, this is a bench-scale instrument, from which heat release rate is determined by measurement of oxygen depletion in the gas flow stream of combustion products and air. An external radiant flux of up to 100 kW/m^2 may be imposed by a temperature-controlled heater. Since the heater behaves very nearly as an ideal black body, the effective spectral distribution is likely to be very close to that expected from room fires [13]. An electric spark ignitor mounted above the specimen is used to ignite the pyrolysis products from the specimen exposed to a preset irradiance. Changes in sample mass during an experiment are measured continuously by a load cell. Smoke obscuration and decomposition products are also measured continuously. Smoke obscuration is determined by measuring the extinction of light from a helium-neon laser located in the exhaust duct downstream of the burning sample. A gas sampling arrangement in the exhaust duct provides appropriate gas samples to: a flame ionization analyzer for total hydrocarbon measurements, a paramagnetic oxygen analyzer for oxygen consumption, and a pair of non-dispersive infrared analyzers for the determination of CO and CO_2. For one sample per irradiance level, a portion of the gaseous products and soot in the main exhaust duct was collected by replacing the soot collection filter with a batch sampling apparatus. These batch samples were analyzed for acid gas concentration.

Figure 2 shows a diagram of the gas sampling apparatus. The gaseous products were collected in 250 mℓ glass impinger bottles containing approximately 125 mℓ of 5 mM KOH. Because of the nature of the rate of heat release data, two impingers were used during each test. One during the initial peak heat release rate and the second during a later peak heat release rate. The flow of gases through the impinger(s) was controlled by a mass flow controller. The ratio of gases collected to gases exhausted was nominally 1:1000; however, the exact value for each test was recorded and used in all computations.

After the collection period (i.e., collection time was determined by each peak heat release rate), the impingers were weighed and the contents transferred to plastic containers. Prior to analysis, the filter containing the soot was placed into the impinger solution. The samples were analyzed for $HC\ell$, HBr, and HCN on a commercially available ion chromatograph (Waters Model ILC-1 Ion/Liquid Chromatograph[1]) equipped with a Waters 430 Total Conductivity Detector and a Waters 460 Electrochemical Detector is used to analyze for Br^-, Cl^-, and CN^-. The electrochemical detector (specifically used for CN^- and small concentrations of Br^- in the absence of CN^-) was used with a Ag working electrode and a saturated $KC\ell$ reference electrode. An anion column (ICPAK-A) preceded by an Anion Guard-Pak Precolumn Module, both commercially available from Waters, were used. Chromatograms were recorded on a Spectra-Physics Model SP 4270 Integrator.

Samples were tested in both the horizontal and vertical positions, figure 3. In the horizontal position, samples were exposed to a preset external flux with the spark ignitor mounted above the center of the sample. In the vertical position, the spark ignitor was mounted on the vertical centerline above the top edge of the sample. For vertically mounted cable tests, cable

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[1]The identification of specific products or equipment does not imply recommendation or endorsement by the National Institute of Standards and Technology.

segments were oriented either parallel or perpendicular to the vertical centerline of the sample holder. Sparking was initiated at the beginning of the exposure and continued until sustained burning developed across the sample surface. Tests were terminated when flaming on the sample extinguished.

Three replicates of each cable were tested in the horizontal orientation at each of three external irradiances, 25 kW/m^2, 75 kW/m^2, and 100 kW/m^2. These are the values currently under consideration by the Navy for qualifying electrical cables for shipboard use. Because of problems encountered with the vertical tests of electric cables (these will be discussed below), three replicates of each cable were tested at only two external irradiances of 25 kW/m^2 and 50 kW/m^2.

Preliminary vertical tests on several cables showed that after ignition the cables ejected solid particulates, probably either $Mg(OH)_2$ or $A\ell(OH)_3$ [15]. These particulates fell on the lower portion of the coils of the Cone Calorimeter heater. As the tests proceeded, hot spots were developed that ultimately led to burnout of the heater. In order to prevent this from happening, a 52 mesh stainless steel wire screen was placed over the heater. This reduced the effective radiation reaching the sample surface. With the Cone heater set a 100 kW/m^2, the effective irradiance was only 50 kW/m^2. Cable MNW-44 was not tested in the vertical orientation because a preliminary test at 25 kW/m^2 resulted in liquified polymer flowing out of the heating zone to the base of the load cell.

5.0 TEST RESULTS

5.1 Ignition

Table 2 is a listing of the average ignition delay time and its standard deviation for each cable. Ignition delay times were determined for both the horizontal and vertical orientations. As expected, the data show that as the external irradiance increases the ignition delay time decreases. At 100 kW/m^2, the ignition delay time was about the same for all of the cables in both vertical and horizontal orientations, varying from 13 to 17 s, except for cable MNW-44 which had an ignition delay time of 4 s. The variation in ignition delay time increased with decreasing external irradiance. At 25 kW/m^2, the horizontally mounted cables exhibited ignition delay times for six cables varying from 225 s to 312 s. Cable MNW-14 had an ignition delay time of 95 s and cable 2XSAW-14 had a 536 s ignition delay time. Vertically mounted samples had an ignition delay time range of 184 s to 278 s except for cables MNW-44 and 2XSAW-14 with ignition delay times of 342 s and 63 s, respectively.

During vertical exposures, cable samples were oriented with the major axis of the cable segments either parallel or perpendicular to the vertical center line of the sample holder, figure 3. Figure 4 compares the individual ignition delay time results for the seven cables tested in the vertical orientation at 25 kW/m^2 external irradiance. Since two samples of each cable were tested parallel to the vertical and one perpendicular to the vertical, there are 14 data points shown in figure 4. The small number of samples tested did not allow for a meaningful comparison of average values. The solid line in figure 4 represents the null hypothesis, i.e., orientation of the major axis does not effect ignition delay time. Points on or near the line indicate that cable direction has no effect on ignition delay time. A linear regression using the general form:

$$Y = mX \tag{1}$$

was applied to the data, where m represents the regression coefficient. The regression analysis resulted in a equation:

$$Y = 0.93\ X \tag{2}$$

with a standard error of 0.19 and a correlation coefficient of 0.73. At the 0.95 level of confidence, the error range about the ideal regression coefficient, m_{th}, was found to be

$$m_{th} = 1 \pm 0.34 = 0.66 \text{ to } 1.34.$$

The actual regression coefficient lies within the range of the ideal regression coefficient. Therefore, without additional test data, the orientation of the major axis of the cable samples in the vertical plane did not appear to affect ignition delay time.

Because no directional effects were observed for vertically mounted specimens, the mean of all three specimens was computed to characterize the vertical ignition delay time. These data were compared to the ignition delay time data from horizontally mounted samples exposed to 25 kW/m^2. Figure 5 shows the ideal curve (solid line) and the actual data points. All the data lie below the ideal curve. This indicates that at 25 kW/m^2 the horizontal orientation produces longer ignition delay times than the vertical orientation. Repeating the linear regression analysis using the form of equation (1) yields:

$$Y = 0.74\ X \qquad (3)$$

with a correlation coefficient of 0.93 and a standard error of 0.12. At the 0.95 level of confidence, the error range about the regression coefficient, m_{th}, was

$$m_{th} = 1 \pm 0.21 = 0.79 \text{ to } 1.21.$$

The actual regression coefficient lies outside of the range of the regression coefficient of the ideal curve. While the differences observed between the two mounting orientations are significant, they are fairly small. At higher external irradiances, no significant differences could be measured between vertical and horizontal orientations. The preferential selection of one orientation would, therefore, not introduce a large error in the assessment of ignition delay time.

Brown et al [16] reviewed some of the literature on the ignition delay time of various materials. In general, they found that the ignition delay time, t_{ig}, is proportional to $1/\dot{q}''^{n}$, where $\dot{q}''$ is the external irradiance and n is either 1 or 2. If the material is thermally thin (i.e., the thermal wave reaches the back surface before ignition occurs), n will equal 1. If, however, the material is thermally thick, n will equal 2. Table 3 summarizes the results of a linear regression analysis of each of the cables for both vertical and horizontal sample orientations. The data, which vary from 1.99 to 2.53 for horizontal and from 1.77 to 2.46 for vertical samples, indicate that the cables behave like thermally thick materials.

5.2 Heat Release Rate

In general, the rate of heat release data for common materials and assemblies obtained on the cone calorimeter display a curve with a single peak heat release rate [17]. Composite materials have been shown to produce multiple heat release rate peaks [16]. Electric cables are multi-component systems (jacket, insulation, and wire) similar to multi-layer composite materials. Therefore, one would expect to see multiple heat release rate peaks for electric cables as the various layers crack and split exposing lower layer combustibles to the energy from the flame and external irradiance. Figures 6 and 7 show two types of heat release rate curves that were typical of the eight electric cables studied in this report. LSMDU-6, figure 6, shows two peaks, one narrow and the other broad, at 75 kW/m^2 and 100 kW/m^2 external irradiance. At 25 kW/m^2, no second peak was produced because the outer jacket did not split and crack exposing the inner structure of the cable. Most of the cables tested produced comparable results. Figure 7 shows the heat release rate data for cable MNW-44. This cable produced three peaks at 75 kW/m^2 and 100 kW/m^2. Each peak was narrow and appeared to have a higher value than the preceding peak. This cable also did not produce multiple peaks at 25 kW/m^2. No cables tested at 25 kW/m^2 produced a secondary peak heat release rate.

Large-scale fire test data for these cables were not available to develop correlation models and determine the appropriate averaging interval. However, Babrauskas and Krasny [18] developed a correlation model between the cone calorimeter and the furniture calorimeter for furniture assemblies that used the average rate of heat release from ignition to 180 s in the cone calorimeter to predict the peak rate of heat release in the furniture calorimeter. Characterizing cable flammability by fire performance during the first 180 s was inappropriate because substantial amounts of heat were released after this period. However, Kanury and Martin [17] used average heat release rate data to deduce physicochemical properties of essentially homogeneous materials exposed to different external irradiances. In order to smooth the heat release rate data for use in determining material thermal response characteristics and provide data for future correlation efforts, an incremental 60 s averaging method was used to characterize the cone calorimeter data. Averaging began with the onset of ignition. Unlike the procedure of Babrauskas and Krasny [18], this procedure retained the essential form of the original data.

The heat release rate characteristic of a product controls several important hazard parameters associated with fire growth in an enclosure. It affects:

- the compartment smoke filling rate;
- the mass flow rate between compartments;

- the time to ventilation controlled burning for vented compartments;
- the time to ignition of secondary items;
- the time to flashover, etc.

Because these cables produced multiple peak heat release rates, the selection of a hazard assessment parameter for the rate of heat release becomes somewhat problematic. In the absence of large-scale test data to determine which of the heat release rate measurement constructs best replicates end-use cable flammability, maximum and 60 s average peak heat release rates for the horizontal and vertical orientations are presented separately.

Table 4 summarizes the results of horizontal testing of all eight cables. This tabulation includes the maximum peak rate of heat release, RHR, the 60 s average RHR for each peak, and the effective heat of combustion, ΔH_{eff}, for each peak. In each case, the peak and 60 s average rate of heat release increased with increasing external irradiance. In general, the 60 s average for the first peak was greater than the 60 s average for any other peak at the same external irradiance. Cable MNW-44 displayed a third peak that had a higher rate of heat release than the other two peaks, at the same external irradiance.

Since the average ΔH_{eff} is the ratio of the average rate of heat release and the average rate of mass loss, fluctuations in either parameter would be reflected in changes in ΔH_{eff}. For the first peak heat release rate of these materials, the ΔH_{eff} varied from 12 MJ/kg for cable MNW-44 to 21 kJ/kg for cable LSMNW-44 with a coefficient of variation (CV) less than or equal to 0.1. In general, where there were secondary peak heat release rates, the ΔH_{eff} was larger for secondary peak heat release rates than for the first peak heat release rate. Greater variations in ΔH_{eff} were observed during a test as different layers of a cable became involved in the combustion process than were caused by changes in imposed external irradiance.

Figure 8 shows typical rate of heat release data for the vertical orientation at three external irradiances. The data show that two maxima were observed at 50 and 100 kW/m^2 but not at 25 kW/m^2 for cable LS2SWAU-10. This behavior was observed with four of the seven cables tested vertically. Two cables exhibited multiple maxima at 25 kW/m^2 as well as 50 kW/m^2 and one cable, LSMSCU-44 showed no secondary maxima at either tested irradiance, figure 9. As previously noted, one of three specimens of each cable tested at each irradiance level was mounted perpendicular to the vertical centerline of the sample holder. To determine if cable direction affected either the peak or 60 s average heat release rate, a comparison was made between individual test results for peak heat release rates, figure 10, and 60 s average of the first peak heat release rates, figure 11, for the seven cables tested in the vertical orientation at both external irradiances. Since two samples of each cable were tested parallel to the vertical and one perpendicular to the vertical, there are 28 data points shown in figures 10 and 11. Following a similar analysis as described in section 4.1, a linear regression analysis of the form Y = mX was performed and the error in the regression coefficient assigned to the ideal (i.e., null hypothesis that cable direction in the vertical orientation has no effect on rate of heat release) curve (solid line). The results of this analysis, summarized on the next page, show that, while a bias appears in the distribution of the data points, the scatter in the data, at the 95% level of confidence for the range of the range of the ideal curve, indicates that primary cable direction does not have a strong effect on the rate of heat release.

	Regression Coefficient	Range of Ideal Curve	Correlation Coefficient
Peak	0.88	0.88 - 1.12	0.92
60 s Avg.	0.90	0.90 - 1.10	0.90

Table 5 is a summary of the test results, combining parallel and perpendicularly oriented cables, of all eight cables in the vertical orientation. Similar to the horizontally mounted cable tests, these tests showed an increasing rate of heat release with increasing external irradiance. Five samples produced two maximum heat release rates. Two of these cable samples exhibited two maxima at 25 kW/m^2, which differed from the horizontal test results. One sample, LSMSCU-44, had produced only one peak heat release rate at 50 kW/m^2 in the vertical mounting orientation but two peaks at 75 kW/m^2 in the horizontal mounting orientation. Cable sample LSMDU-6 produced three maximums at 50 kW/m^2 and 100 kW/m^2 in the vertical mounting orientation. However, in the horizontal orientation, the same cable produced only two peaks at 75 kW/m^2 and 100 kW/m^2.

The effective heat of combustion, ΔH_{eff}, varied in the same way as was previously observed for the horizontal samples with CV less than or equal to 0.1. The range for the first peak ΔH_{eff} was 15 MJ/kg to 19 MJ/kg and the range for the secondary average 60 s peaks varied from 17 MJ/kg to 28 MJ/kg. Here also, the ΔH_{eff} was, in general, greater for the secondary peaks than for the first peak.

Brown et al [16] suggested that the dependence of the rate of heat release on the externally imposed irradiance of a given material could be described by a simple equation.

$$\dot{q}'' = T \cdot \dot{q}_e'' + \xi \qquad (4)$$

where $\dot{q}''$ = rate of heat release (kW/m^2)

$\dot{q}_e''$ = external irradiance (kW/m^2)

T = thermal sensitivity index [17]

ξ = extinction sensitivity index [17].

Based on work by Kanury and Martin [17], T represents a measure of the burning intensity of a material, while ξ, in principle, indicates whether the flame is self-sustaining in the absence of an external irradiance. Brown et al used the 60 s average rate of heat release during the initial peak and the external irradiance to characterize the thermal sensitivity index, T, and the extinction sensitivity index, ξ, of composite materials. They found that T ranged from 0.6, for composite materials least sensitive to changes in external irradiance, to 1.8, for composite materials most sensitive to changes in external irradiance. Negative values for ξ were indicative of a material's propensity to self-extinguish upon the removal of an external heat source.

Table 6 summarizes the results of the application (i.e., regression analysis) of equation (4) on the combined vertical and horizontal data for each cable material based on either the 60 s average heat release rate during the period of the first maximum $\dot{q}''$ or the maximum heat release rate. Based on the 60 s average heat release rate confidence intervals reported in table 6, cable sensitivity to fluctuations in external irradiance were approximately the same for all cables except for cable LSMSCU-44, which was the most sensitive cable with a T value of 3.4. Except for cable MNW-44, all of the other cables had cross-linked polyolefin jacketing material. Analyzing the peak heat release rate data shows that all of the cables had comparable T values except for cables MNW-44 and LSMSCU-44. Since researchers [8] have found that heat release rates depend on external irradiance and cable diameter, one would therefore expect to find that T also depended on the cable diameter. Figure 12 shows a modest correlation of 0.76 between T and cable diameter for the seven cross-linked polyolefin jacketed cables.

Based on the 60 s average rate of heat release, no negative values for ξ were calculated. The ξ values ranged from 47 to 95. This suggests that once these cables are ignited they will continue to burn even if the external source is removed.

Also included in table 6 are similar calculations using equation (4) based on the maximum rate of heat release. While T values are a little larger than the previous average based T's, they do not significantly alter the thermal sensitivity index, except for cable MNW-44. This is a PVC jacketed cable that has a T nearly seven times larger than most of the other cables. The maximum heat release rate of this cable is very sensitive to changes in the externally imposed irradiance. Also, its ξ value is negative, (all other cables have positive ξ values) which is an indicator of the cables propensity to self-extinguish.

If early fire development is of primary concern then one should use the 60 s average heat release rate of the primary jacket material (i.e., first peak). However, if long term fire exposure and growth are of primary concern, then the analysis must take into account the complete burning behavior of a cable. Under these latter circumstances the correct parameter of measure may be the maximum heat release rate, which represents a conservative estimate of the fire threat of a burning cable assembly.

5.3 Mass Loss Rates and Yields of Selected Gases

Tables 7 and 8 summarize the mass loss rate data and the yields of CO, CO_2, HCN, $HC\ell$, and HBr for cable samples tested in the horizontal and vertical orientations. No prior information was provided concerning the possible presence of CN^-, $C\ell^-$, or Br^- in the tested cables. For mass loss rate, CO and CO_2, the values reported are 60 s averages during each peak heat release rate. The HCN, $HC\ell$, and HBr values are determined over longer periods of time. However, the averaging periods include each peak heat release period.

As expected, the mass loss rate for a given cable assembly was found to be a function of the external irradiance, while the gas yields appeared to be relatively independent of external irradiance, at least within a factor of two. It can be seen from tables 7 and 8 that the mass loss rate is lower during the secondary heat release rate peak as compared to the first peak. However, in general, the CO yield increases by about a factor from two to five in both orientations. This may be due to the formation and presence of a char layer during the period of the second peak heat release rate. Cable MNW-44 is a PVC jacket cable that does not form a char layer during the early period of decomposition. In the horizontal orientation, the CO yield for this cable was relatively unchanged. Because of the high degree of ventilation in the cone calorimeter, CO_2 and H_2O were virtually unchanged from cable to cable fluctuating by about 10% to 15%. Again, in comparing the CO_2 and H_2O yields for each peak heat release rate, cable MNW-44 showed the largest change (CO_2 and H_2O for the first peak were 0.6 kg/kg and 0.3 kg/kg, respectively, and 1.2 kg/kg and 0.7 kg/kg, respectively, for the second peak heat release rate).

HCN was detected at some time during the combustion of every cable. Its production is indicative of the presence of nitrogen-containing compounds in the composition of every cable. The yields of HCN varied from 0.7 x 10^{-5} kg/kg for cable LSMDU-6 to 2.3 x 10^{-4} kg/kg for cable LSMSCU-44. These values are one to two orders of magnitude less than was produced from blocks of polyurethane foam [19].

$HC\ell$ was also produced by many cables. However, cable MNW-44 produced one to two orders of magnitude more $HC\ell$ than any other cable. For other PVC jacketed cables, Babrauskas et al [20] observed approximately the same order of magnitude concentrations.

The presence of HBr was detected in cables LSMDU-6 and LS2SWAU-10 in both the horizontal and vertical orientations. HBr was primarily seen during the development of the second heat release rate peak. Cable MNW-44 also showed quantities of HBr comparable to the other cables and cable LSMSCU-44 showed trace amounts of HBR in only the horizontal orientation. These concentrations are low in comparison to previously tested circuit boards (22.0×10^{-3} kg/kg) and television cabinets (69.0×10^{-3} kg/kg) [19].

The presence of HBR and HCℓ in the effluent gases are normally taken to be indicative of the addition of flame retardant compounds to the cable formulation. Information regarding the existence of such additives was not provided when the cables were submitted for testing. Therefore, it was not possible to predict the presence of HBR and HCℓ from the information presented in table 1.

5.4 Smoke and Soot Production

Smoke yield was measured by the extent of smoke obscuration of a monochromatic beam of light traversing a cross section of the exhaust stack. Instantaneous readings were averaged in the same manner as the rate of heat release. The soot yield was determined by measuring the amount of particulates collected on a filter during the entire testing period.

Table 9 summarizes the average smoke yield, σ, during each peak heat release rate period and the average overall soot yield, χ_s. The coefficient of variation for σ varied from 0.03 to 0.20. Vertical or horizontal sample exposures did not appear to alter smoke or soot yield. Both parameters generally increased with increasing external irradiance. Based on the coefficient of variation, the average smoke yield during the second peak heat release rate period was generally higher than during the first peak. This may be caused by the presence of a char layer resulting from the initial phase of decomposition. The smoke yield for cable MNW-44 was relatively constant during the horizontal tests. This cable formed a pool of molten polymer. Char formation was substantially delayed.

These results represent flow-through measurements that do not directly correspond to other small-scale tests, such as ASTM E-662 [18], whose measurements are cumulative. ASTM E-662 is a closed chamber test method which generally results in a reduced oxygen concentration at the site of combustion. It employs a polychromatic light source to measure smoke obscuration. These differences make any true correlation difficult. However, Lawson and Quintiere [19] have suggested that the maximum D_s value from ASTM E-662 can be related to flow-through measurements by:

$$\alpha \chi_s = \frac{D_{s,max}}{m''} \tag{8}$$

where

$D_{s,max}$ = the maximum specific optical density measured in ASTM E-662

m'' = the mass of sample consumed per unit exposed surface area

α = $\sigma/2.303$

σ = the average smoke yield.

6.0 DISCUSSION

For a given cable application, one is primarily concerned with either the ignition and subsequent fire growth of a cable assembly or the contribution a cable assembly will make to an existing fire in a duct or compartment. Within the context of this study, the emphasis will be directed towards the latter concern. In a broad sense, one would like to know how the selection of cable material will affect the development of hazardous fire conditions in a compartment. While it is beyond the scope of this work to conduct a full hazard analysis of compartment cable fires, it is possible to estimate the contribution of electrical cables to compartment flashover by applying relatively simple steady-state models. These calculations will answer the following questions:

- for a given ignition source in a compartment, will the cable ignite?
- if it ignites, what minimum area of ignited cable is required to augment the existing fire to produce flashover conditions?

Although these calculations address whether flashover occurs, they do not provide information on when it occurs.

Compartment flashover will be defined as occurring at an upper layer gas temperature of approximately 600°C [24]. The following analysis will be based on the experimental data used to characterize electrical cable fire performance in the cone calorimeter. There are four steps to this analysis:

- determine the minimum ignition energy;

- estimate the size of the fire source based on minimum ignition energy considerations;
- calculate the heat release rate necessary to reach flashover in a given compartment.
- using heat release rate data, determine the contribution of the electrical cables to flashover.

Before electrical cables can contribute to fire growth in a compartment, they must ignite. From the previous data, it is possible to calculate the minimum external radiant flux necessary to ignite these cables. Because it is believed by Navy fire control officers that within 300 s the fire will either be extinguished or out of control, Brown et al [16] used an exposure time of 300 s and called this parameter $MERF_{300}$. This information only defines the energy incident on the surface of the cable. How large a source fire would be necessary to result in this incident irradiance? A technique described by Modak [25] can be used to estimate the size of the fire source, Q_o, necessary to produce a $MERF_{300}$ irradiance on the surface of an cable.

$$Q_o = 4\pi\dot{q}''R^2/\chi_R \qquad (5)$$

where

$\dot{q}_e''$ = external irradiance at the $MERF_{300}$ (kW/m^2).

R = The radial distance between the center of the fire and the target material (m).

χ_R = The fraction of the total heat released by the source that is radiation. This value can range from 0.2 for non-luminous clean burning fuels to 0.45 for soot producing fuels.

This ignores any contribution of the hot gas layer in the upper part of a compartment to the total incident irradiance. In order to use equation (5), one must specify the distance, R, between the target and the fire source being considered.

Thomas [26] provides a method for calculating the heat release rate necessary to cause compartment flashover.

$$Q_{fo} = (378(A\sqrt{h}) + 7.8A_w) \qquad (6)$$

where A_w = area of the interior surfaces, m^2

A = area of outside opening, m^2

h = height of outside opening, m.

Equation (6) depends on the ventilation factor, $A\sqrt{h}$, the thermal properties of the compartment walls (contained within the constants), and the interior surface area of the compartment. With the constants shown, equation (5) assumes thermal properties comparable to typical gypsum wallboard construction. Thermal properties of ship enclosures can vary from exposed steel plates to composite joiner bulkhead materials and thermal insulation.

The difference between Q_{fo} and Q_o, is the amount of additional heat release rate necessary to cause flashover.

$$\Delta Q = Q_{fo} - Q_o \tag{7}$$

If ΔQ is positive, this must be contributed by the electric cable for the compartment to achieve flashover. If ΔQ is less than zero, the presence of the cable is immaterial; the compartment already has a fire source large enough to cause flashover.

Assuming that we have a compartment made of gysum wallboard with a single opening, table 10 summarizes the results of the preceding calculations with the following configuration values:

Room size:	Height	2.4 m
	Width	2.4 m
	Length	3.0 m
Opening:	Width	1.0 m
	Height	2.0 m
Distance:	R	1.0 m

According to equation (6), a compartment of this size would require a heat source of approximately 1300 kW in size in order to achieve flashover. If the source is assumed to burn with a non-luminous flame, χ_R is taken as 0.2. It can be seen that, with the exception of cable MNW-44, the compartment would have to contain a fire source large enough to cause compartment flashover. As the flame becomes sooty, χ_R approaches 0.45. In this case, the minimum fire size for ignition is not sufficient to cause compartment flashover. The excess energy needed for flashover must come from the burning cables. It ranged from 450 kW for cable 2XSAW-14 to 900 kW for cable MNW-44.

How much cable needs to become involved depends on several factors, which are beyond the scope of the study. These would include the rate of fire growth within the compartment, geometric arrangment, density (i.e., number of cables per unit volume), ambient temperature, cable temperature, proximity to other surfaces, flame spread along cable bundles, etc. However, assuming that cable fire performance can realisticly be derived from cone calorimeter tests, the ratio of the excess energy, ΔQ, needed to cause flashover to the average rate of heat release, $\dot{q}''$, per unit surface area at the $MERF_{300}$ irradiance yields an estimate of the amount of cable area necessary to cause compartment flashover. Again, for a non-luminous flame, only cable MNW-44 need be considered because the other cables require an ignition source large enough to cause compartment flashover before cable ignition would occur. The energy from approximately a surface area of 4.5 m^2 of cable MNW-44 would be necessary to augment the source fire to cause compartment flashover. For luminous flames (i.e., sooty flames), the cable areas for cables with crosslinked polyolefin jackets varied from 4.2 m^2 to 6.7 m^2. The PVC jacketed cable required about 11.5 m^2.

These estimates demonstrate one possible use of the data obtained from the cone calorimeter. It is important to point out that a full hazard assessment, as described in the work of Bukowski et al [23], requires more information than is currently available regarding the selection of scenarios, compartment geometry, enclosure materials, and compartment interconnections. In addition, a complete description of cable flammability in a compartment can not be accomplished without relating flame spread along the cable surface to fire growth.

7.0 CONCLUSIONS

Cone calorimeter tests were performed on eight multi-conductor electrical cables. Measurements of ignition delay time, heat release rate, mass loss rate, and gas and smoke generation rates were made in the vertical (2 irradiance levels) and horizontal (3 irradiance levels) orientations. These led to the following:

- Sample orientation had a small or no effect on the measured fire properties.

- All of the cables exhibited an ignition delay time data dependence on external irradiance approximately proportional to $1/\dot{q}_e''^2$ (exponent varied from 2.0 to 2.5). The PVC jacketed cable had a substantially lower ignition delay time at the same external irradiance than the cross-linked polyolefin jacketed cables.

- Cables burned in stages with the peak heat release rate a function of the layer of the cable assembly actually burning. Multiple peak heat release rates were observed above an external irradiance of 50 kW/m^2. Above this exposure, the outer jacket burst open exposing the interior cable materials.

- Sample calculations on the occurrance of flashover demonstrated the need to consider the end-use fire scenario prior to the selection of a cable rather than making cable selection based solely on cable performance in a single fire test.

8.0 RECOMMENDATIONS

Since cable flammability involves the propagation of a flame along the cable surface, it is also important to characterize cable flammability in terms of flame spread rate and relate these measurements to some measure of the rate of heat release. It is recommended that small-scale flame spread measurements be made on these cables. Large-scale tests can be used to verify these measurements and relate them to the rate of heat release.

While this report discusses a simple application of the cone calorimeter data to conduct a rudementry hazard analysis, it falls far short of a complete cable hazard assessment methodology. It is recommended that a full hazard analysis be performed on a select number of cables. The accuracy of this analysis could then be verified with large-scale tests of cable assemblies in relevant end-use configurations. The results would improve our ability to perform future hazard assessments based on the results of small-scale test methods.

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Table 1

Description of Electrical Cables

Cable Number	Military Specification	Number of Conductors	Material: Jacket	Material: Insulation	Material: Binder	Diameter (mm)	Cable Shielding: Pairs	Cable Shielding: Overall	Cable Content: Met'l[j] %	Cable Content: nMet'[k] %
MNW-44	C-915/71D	44	PVC[a]	PVC	PT[d]	21.4	NO	NO	60	40
TTXSO-6	C-0024640/5A(SH)	12(2x6)	XLPO[b]	XLPO & PVF[c]	PT	14.0	YES	YES	55	45
2XSAW-14	C-0024640/15A(SH)	14(2x7)	XLPO	XLPO & PVF	PT	17.3	YES	YES	40	60
LSMDU-6	C-0024643/5C(SH)	19	XLPO	XLPE[e] or EPR[f]	PT	25.4	NO	NO	50	50
LSTTRS-6	C-24643/13B	12(2x6)	XLPO	XLPE	PT[g]	22.4	YES	NO	30	70
LSMSCU-44	C-24643/18B	44	XLPO	SiR[h,i]	PT	28.3	NO	NO	30	70
LS2SWAU-10	C-24643/32B	20(2x10)	XLPO	XLPE	PT	21.1	NO	YES	30	70
LSMNW-44	C-24643/51B	44	XLPO	XLPE	PT	22.6	NO	NO	50	50

a) Poly(vinyl chloride)
b) Cross-Linked PolyOlefin
c) Poly(vinylidene fluoride)
d) Polyester
e) Cross-Linked Polyethylene
f) Ethylene Propylene Rubber
g) Polyamide secondary binder on each wire pair
h) Silicone Rubber
i) Glass Braid on each wire
j) Metallic Components of cable assembly
k) Non-metallic/Combustible components of cable assembly

Table 2

Average Ignition Delay Time, in seconds, and Standard Deviation for Vertically and Horizontally Tested Electrical Cables

		External Irradiance							
		25 kW/m^2		50 kW/m^2		75 kW/m^2		100 kW/m^2	
Cable Number	Orientation	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.
MNW-44	Horizontal	95	4	-		8	2	4	2
	Vertical	63[a]	-	-		-		-	
TTXSO-6	Horizontal	312	12	-		29	2	17	2
	Vertical	278	59	66	4	-		-	
2XSAW-14	Horizontal	536	121	-		30	4	17	1
	Vertical	342	73	62	3	-		-	
LSMDU-6	Horizontal	270	21	-		31	2	17	4
	Vertical	187	14	54	2	-		16[b]	<1
LSTTRS-6	Horizontal	284	37	-		26	4	13	2
	Vertical	209	12	58	3	-		-	
LSMSCU-44	Horizontal	278	28	-		24	1	13	1
	Vertical	209	15	52	3	-		-	
LS2SWAU-10	Horizontal	278	41	-		31	2	15	2
	Vertical	256	64	61	2	-		15[a]	-
LSMNW-44	Horizontal	225	18	-		24	2	13	1
	Vertical	184	12	47	4	-		13[a]	-

a) one test
b) mean of two tests

Table 3

Determination of the Regression Slope of Ignition Delay Time and External Irradiance for Vertical and Horizontal Exposure Conditions

Cable Number	Horizontal Regression Slope	Vertical Regression Slope
MNW-44	-2.28	--
TTXSO-6	-2.12	-2.08
2XSAW-14	-2.53	-2.46
LSMDU-6	-1.99	-1.77
LSTTRS-6	-2.21	-1.85
LSMSCU-44	-2.21	-2.01
LS2SWAU-10	-2.08	-2.05
LSMNW-44	-2.05	-1.91

Table 4

Peak Rate of Heat Release, Average Rate of Heat Release, and Effective Heat of Combustion for Horizontally Tested Electric Cables at Three External Irradiances

Cable Number	External Irradiance (kW/m^2)	Peak RHR[a] (kW/m^2)	Peak 60 s Average First (kW/m^2)	Second (kW/m^2)	Third (kW/m^2)	Effective Heat of Combustion (MJ/kg)
MNW-44	25	130	100	--[b]	--	12
	75	930	210	420	--	14(18,24)[c]
	100	1200	260	560	--	16(19,22)
TTXSO-6	25	100	90	--	--	17
	75	170	130	120	--	15(18)
	100	250	200	160	--	15(17)
2XSAW-14	25	160	100	--	--	19
	75	250	170	130	--	16(19)
	100	330	220	170	--	18(20)
LSMDU-6	25	140	100	--	--	19
	75	240	190	80	--	18(20)
	100	280	220	110	--	18(21)
LSTTRS-6	25	190	140	--	--	20
	75	270	220	130	--	18(22)
	100	350	280	170	--	19(22)
LSMSCU-44	25	160	130	--	--	20
	75	370	280	100	--	19
	100	540	400	130	--	20
LS2SWAU-10	25	110	90	--	--	18
	75	220	180	100	--	18
	100	280	220	140	--	17
LSMNW-44	25	180	140	--	--	21
	75	310	250	180	--	20(28)
	100	400	310	230	--	19(27)

a) Rate of Heat Release.
b) No Peak Observed.
c) Numbers in () values for second and third peaks.

Table 5

Peak Rate of Heat Release, Average Rate of Heat Release, and Effective Heat of Combustion for Vertically Tested Electric Cables at Several External Irradiances

Cable Number	External Irradiance (kW/m^2)	Peak RHR[a] (kW/m^2)	Peak 60 s Average First (kW/m^2)	Second (kW/m^2)	Third (kW/m^2)	Effective Heat of Combustion (MJ/kg)
TTXSO-6	25	140	110	--[b]	--	17
	50	200	140	150	--	16
2XSAW-14	25	130	100	80	--	18(18)[c]
	50	220	150	160	--	15(17)
LSMDU-6	25	110	110	--	--	15
	50	210	180	130	120[d]	15(20,20)
	100[e]	340	260	180	200[d]	17(17,19)
LSTTRS-6	25	180	140	--	--	18
	50	230	190	130	--	18(21)
LSMSCU-44	25	160	140	--	--	20
	50	270	230	--	--	18
LS2SWAU-10	25	140	110	40[e]	--	16(18)
	50	180	150	120	--	17(19)
	100[f]	270	160	180	--	15(18,-)
LSMNW-44	25	200	150	120	--	19(28)
	50	310	200	210	--	17(27)
	100[f]	400	330	310	--	18(25)

a) Rate of Heat Release.
b) No Peak Observed.
c) Numbers in () values for second and third peaks.
d) Observed in only one test.
e) Mean of two tests.
f) Only one test conducted.

Table 6

Tabulation of the Thermal Sensitivity Index, T, and Extinction Sensitivity Index, ξ, for all Eight Cables in Both the Vertical and Horizontal Mounting Orientations During the Period of the 60 s Average of the First Peak

Cable Number	First Peak 60s Avg Heat Release Rate		Maximum Heat Release Rate	
	T	ξ	T	ξ
MNW-44	2.1 ± 0.1[a]	47	14.5 ± 2.3	-214
TTXSO-6	1.2 ± 0.6	71	1.5 ± 0.9	89
2XSAW-14	1.5 ± 0.2	63	2.4 ± 0.5	88
LSMDU-6	1.7 ± 0.5	69	2.4 ± 0.6	70
LSTTRS-6	1.8 ± 0.2	95	2.1 ± 0.4	129
LSMSCU-44	3.4 ± 0.5	50	4.9 ± 0.6	32
LS2SWAU-10	1.2 ± 0.6	77	2.0 ± 0.3	76
LSMNW-44	2.3 ± 0.2	85	2.7 ± 0.6	134

a) 95% confidence interval about the regression coefficient.

Table 7

Tabulation of the Mass Loss Rate and Species Yields for CO, CO_2, HCN, HCℓ, HBr, and H_2O from Horizontal Mounted Samples during each Peak 60 s Average Heat Release Rate

		First Peak Heat Release Rate							Second Peak Heat Release Rate						
	External Irradiance	Mass Loss	Gas Species Yields (kg/kg)						Mass Loss	Gas Species Yields (kg/kg)					
Cable Number	(kW/m^2)	($g/s\text{-}m^2$)	CO ($\times 10^{-3}$)	CO_2	HCN[c] ($\times 10^{-5}$)	HCℓ[c] ($\times 10^{-3}$)	HBr[c] ($\times 10^{-3}$)	H_2O	($g/s\text{-}m^2$)	CO ($\times 10^{-3}$)	CO_2	HCN[c] ($\times 10^{-5}$)	HCℓ[c] ($\times 10^{-3}$)	HBr[c] ($\times 10^{-3}$)	H_2O
MNW-44	25	9	71.0	0.6	ND[a]	170.0	ND	0.3							
	75	23	60.0	0.6	ND	410.0	4.2	0.4	16.0	66.0	1.1	3.1	99.0	1.7	0.7
	100	27	58.0	0.6	3.0	120.0	Trace[b]	0.3	19.9	63.0	1.2	4.1	43.0	Trace	0.6
TTXSO-6	25	5	4.1	1.2	ND	ND	ND	0.9							
	75	9	4.0	1.1	ND	3.7	ND	0.9	6.9	11.0	1.3	2.9	3.0	ND	0.8
	100	12	7.5	1.2	ND	16.0	ND	0.8	9.2	14.0	1.3	4.5	4.8	ND	0.8
2XSAW-14	25	5	6.5	1.4	ND	ND	ND	0.9							
	75	11	5.4	1.2	Trace	3.4	ND	0.8	7.0	11.0	1.3	3.7	2.8	ND	0.8
	100	13	8.2	1.2	ND	5.9	ND	0.8	8.3	11.0	1.2	3.9	4.5	ND	0.8
LSMDU-6	25	6	4.7	1.3	0.7	ND	ND	0.9							
	75	11	5.6	1.3	ND	6.0	ND	0.9	4.1	54.0	1.1	ND	67.0	21.0	0.8
	100	13	6.9	1.2	ND	6.2	ND	0.8	5.2	53.0	1.2	ND	39.0	12.0	0.9
LSTTRS-6	25	7	5.6	1.5	Trace	ND	ND	0.8							
	75	12	5.8	1.5	1.1	9.6	ND	0.8	5.8	11.0	1.4	1.1	5.2	ND	0.9
	100	15	7.7	1.4	1.9	ND	ND	0.9	7.7	17.0	1.4	ND	1.1	ND	0.9
LSMSCU-44	25	7	4.9	1.5	3.7	ND	ND	0.9							
	75	16	6.1	1.5	1.3	6.4	Trace	0.8							
	100	21	7.1	1.5	3.1	3.9	ND	0.7	5.5	9.1	1.4	20.0	1.6	ND	0.8
LS2SWAU-10	25	6	4.7	1.2	ND	ND	ND	0.8							
	75	10	4.8	1.3	1.4	20.0	ND	0.9	5.0	13.0	1.3	0.6	9.3	2.1	0.9
	100	13	5.7	1.3	ND	4.0	ND	0.9	7.0	14.0	1.3	ND	6.0	Trace	0.8
LSMNW-44	25	7	5.4	1.5	1.1	ND	ND	0.8							
	75	14	7.0	1.4	2.1	ND	ND	0.7	6.5	25.0	1.7	6.6	2.2	ND	1.0
	100	17	8.4	1.4	ND	ND	ND	0.8	8.5	28.0	1.7	8.5	2.5	ND	1.1

a) Not Detected
b) Detected but at the lower resolution of the analytical technique.
c) average value for about 3 minutes.

Table 8

Tabulation of the Mass Loss Rate and Species Yields for CO, CO_2, HCN, HCℓ, HBr, and H_2O from Vertical Mounted Samples during each Peak 60 s Average Heat Release Rate

Cable Number	External Irradiance (kW/m^2)	First Peak Heat Release Rate: Mass Loss ($g/s\text{-}m^2$)	First Peak: Gas Species Yields (kg/kg) CO ($\times 10^{-3}$)	CO_2	HCN[c] ($\times 10^{-5}$)	HCℓ[c] ($\times 10^{-3}$)	HBr[c] ($\times 10^{-3}$)	H_2O	Second Peak Heat Release Rate: Mass Loss ($g/s\text{-}m^2$)	Second Peak: Gas Species Yields (kg/kg) CO ($\times 10^{-3}$)	CO_2	HCN[c] ($\times 10^{-5}$)	HCℓ[c] ($\times 10^{-3}$)	HBr[c] ($\times 10^{-3}$)	H_2O
TTXSO-6	25	6	3.6	1.4	5.6	ND[a]	ND	0.8	4.7	14.0	1.4	2.8	4.7	ND	0.6
	50	9	3.8	1.3	ND	2.6	ND	0.8	8.6	11.0	1.3	4.4	2.6	ND	0.7
2XSAW-14	25	5	4.2	1.4	ND	2.4	ND	0.8	4.2	17.0	1.2	2.1	1.2	ND	0.6
	50	10	4.1	1.2	ND	ND	ND	0.7	9.1	8.8	1.2	3.3	4.1	ND	0.7
LSMDU-6	25	7	3.8	1.4	1.5	6.1	ND	0.8							
	50	11	6.2	1.3	ND	4.5	2.5	0.8	6.1	47.0	1.3	ND	38.0	15.0	0.7
	100[d]	16	6.2	1.2				0.8	10.6	56.0	1.1				0.8
LSTTRS-6	25	7	5.8	1.6	2.5	ND	ND	0.8							
	50	12	6.8	1.4	1.5	3.5	ND	0.8	6.5	8.9	1.6	400.0	3.2	ND	0.8
LSMSCU-44	25	7	6.1	1.5	23.0	2.7	ND	0.7							
	50	13	7.5	1.5	2.0	ND	ND	0.7							
LS2SWAU-10	25	7	5.0	1.3	3.8	ND	ND	0.7	3.7	26.0	1.2	1.8	7.6	3.1	0.6
	50	10	4.7	1.4	Trace[b]	8.9	0.7	0.8	6.1	10.0	1.3	ND	10.0	1.8	0.7
	100[e]	11	3.3	1.2				0.9	10.1	14.0	1.1				0.7
LSMNW-44	25	8	6.0	1.6	ND	ND	ND	0.8	4.3	9.8	2.0	2.2	ND	ND	0.8
	50	12	6.7	1.5	ND	3.7	ND	0.8	7.9	24.0	1.8	4.5	1.8	ND	0.9
	100[e]	19	6.6	1.4				0.8	12.3	22.0	1.6				0.9

a) Not Detected.
b) Detected but at the lower resolution of the analytical technique.
c) Average value for about 3 minutes.
d) Based on 2 replicates.
e) Based on a single determination.

Table 9

Tabulation of the Average Overall Soot Yield and Smoke Concentration During Peak Heat Release Rates for Electrical Cables Mounted Horizontally and Vertically in the Cone Calorimeter

Cable Number	External Irradiance (kW/m^2)	Horizontal χ_s (kg/kg)	Horizontal σ_1[a] (m^2/kg)	Horizontal σ_2 (m^2/kg)	Horizontal σ_3 (m^2/kg)	Vertical χ_s (kg/kg)	Vertical σ_1 (m^2/kg)	Vertical σ_2 (m^2/kg)
MNW-44	25	5.8×10^{-2}	860	-	-	-	-	-
	50	-	-	-	-	-	-	-
	75	4.9×10^{-2}	1040	1040	1020	-	-	-
	100	5.1×10^{-2}	1060	1050	1010	-	-	-
TTXSO-6	25	6.0×10^{-3}	100	-	-	1.2×10^{-2}	60	-
	50	-	-	-	-	3.7×10^{-2}	150	280
	75	2.1×10^{-2}	230	320	-	-	-	-
	100	3.0×10^{-2}	350	360	-	-	-	-
2XSAW-14	25	4.5×10^{-2}	130	-	-	1.1×10^{-1}	60	-
	50	-	-	-	-	1.2×10^{-1}	180	400
	75	5.4×10^{-2}	270	340	-	-	-	-
	100	5.0×10^{-2}	340	430	-	-	-	-
LSMDU-6	25	7.5×10^{-3}	100	-	-	3.3×10^{-2}	70	-
	50	-	-	-	-	2.7×10^{-1}	230	575
	75	2.6×10^{-2}	270	-	-	-	-	-
	100	4.0×10^{-2}	350	750	-	3.8×10^{-2}	320	840[a]
LSTTRS-6	25	4.0×10^{-3}	150	-	-	6.5×10^{-3}	160	-
	50	-	-	-	-	5.5×10^{-2}	220	280
	75	3.6×10^{-2}	270	450	-	-	-	-
	100	2.9×10^{-2}	390	550	-	-	-	-
LSMSCU-44	25	4.1×10^{-2}	210	-	-	1.2×10^{-1}	130	-
	50	-	-	-	-	2.0×10^{-1}	260	-
	75	6.1×10^{-2}	280	500	-	-	-	-
	100	6.3×10^{-2}	310	420	-	-	-	-
LS2SWAU-10	25	4.5×10^{-2}	70	-	-	1.1×10^{-1}	60	-
	50	-	-	-	-	1.1×10^{-1}	170	330
	75	4.3×10^{-2}	230	320	-	-	-	-
	100	3.7×10^{-2}	310	390	-	6.5×10^{-2}	280	520[a]
LSMNW-44	25	1.0×10^{-2}	180	-	-	2.4×10^{-2}	180	-
	50	-	-	-	-	6.9×10^{-2}	290	650
	75	7.0×10^{-2}	320	700	-	-	-	-
	100	4.3×10^{-2}	380	830	-	4.3×10^{-2}	340	680[b]

a) σ_i represents the average smoke yield during the i^{th} peak heat release rate, where i=1,2,3.

b) single determination.

Table 10

Tabulation of the $MERF_{300}$ Irradiance, Fire Source Size, and Contribution of each Cable to Compartment Flashover At the Irradiance Level of $MERF_{300}$ for a Compartment as Described in the Report

Cable Number	$MERF_{300}$ (kW/m^2)	Average HRR[a] $\dot{q}''(MERF_{300})$ (kW/m^2)	Ignition Fire Source Size		Flashover Energy	Cable Energy Required		Cable Area for Flashover	
			$Q_0(0.20)$ (kW)	$Q_0(0.45)$ (kW)	Q_{fo} (kW)	$\Delta Q(0.20)$ (kW)	$\Delta Q(0.45)$ (kW)	$A(0.20)$ (m^2)	$A(0.45)$ (m^2)
MNW-44	15	80	950	400	1300	350	900	4.4	5.0
TTXSO-6	26	100	1650	750	1300	-350	550	---[b]	7.5
2XSAW-14	30	110	1900	850	1300	-600	450	---	7.7
LSMDU-6	21	105	1300	600	1300	0	700	---	6.7
LSTTRS-6	22	135	1400	600	1300	-100	700	---	5.7
LSMSCU-44	21	120	1300	600	1300	0	700	---	5.8
LS2SWAU-10	23	105	1400	650	1300	-100	650	---	5.0
LSMNW-44	21	130	1300	600	1300	0	700	---	6.2

a) Heat Release Rate
b) Cable not necessary for flashover

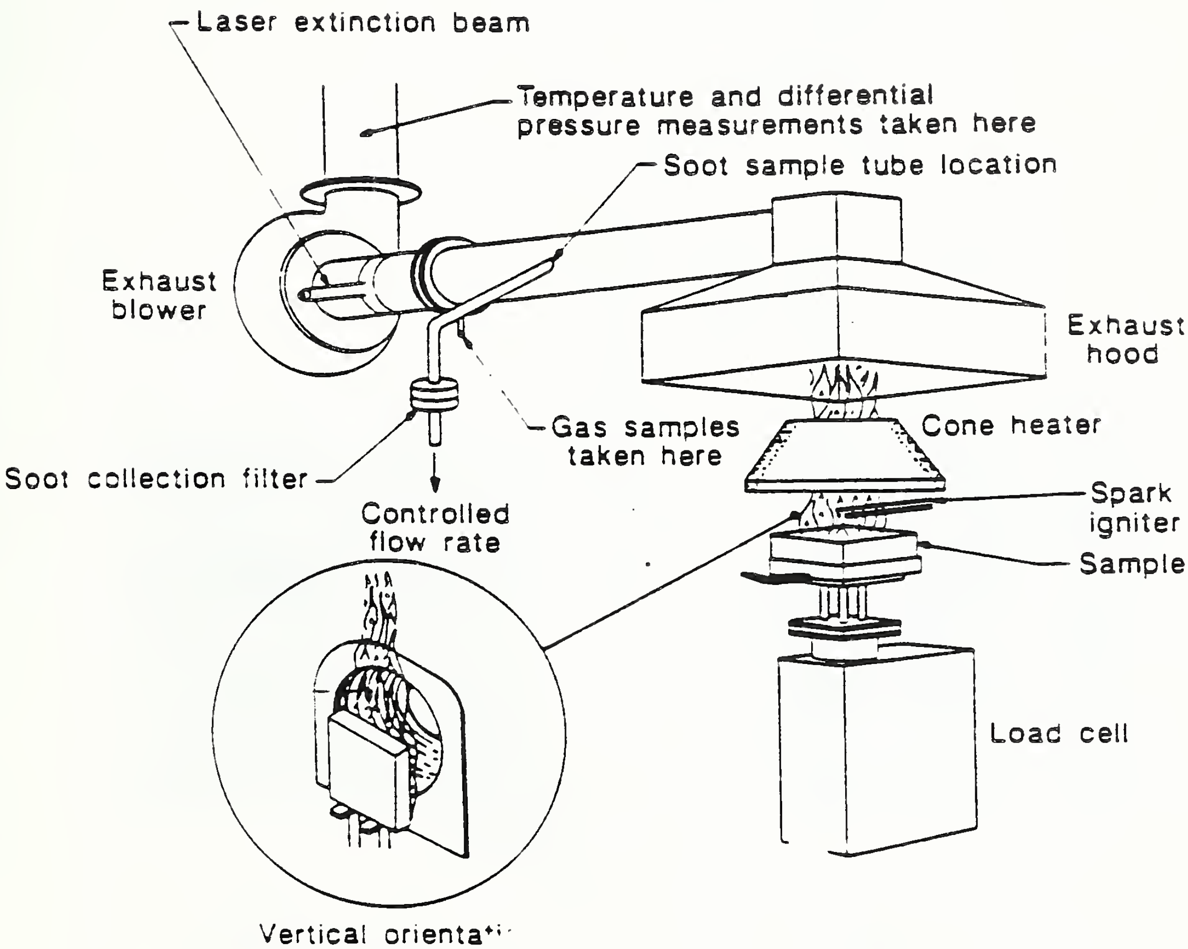

Figure 1. Schematic Representation of Cone Calorimeter

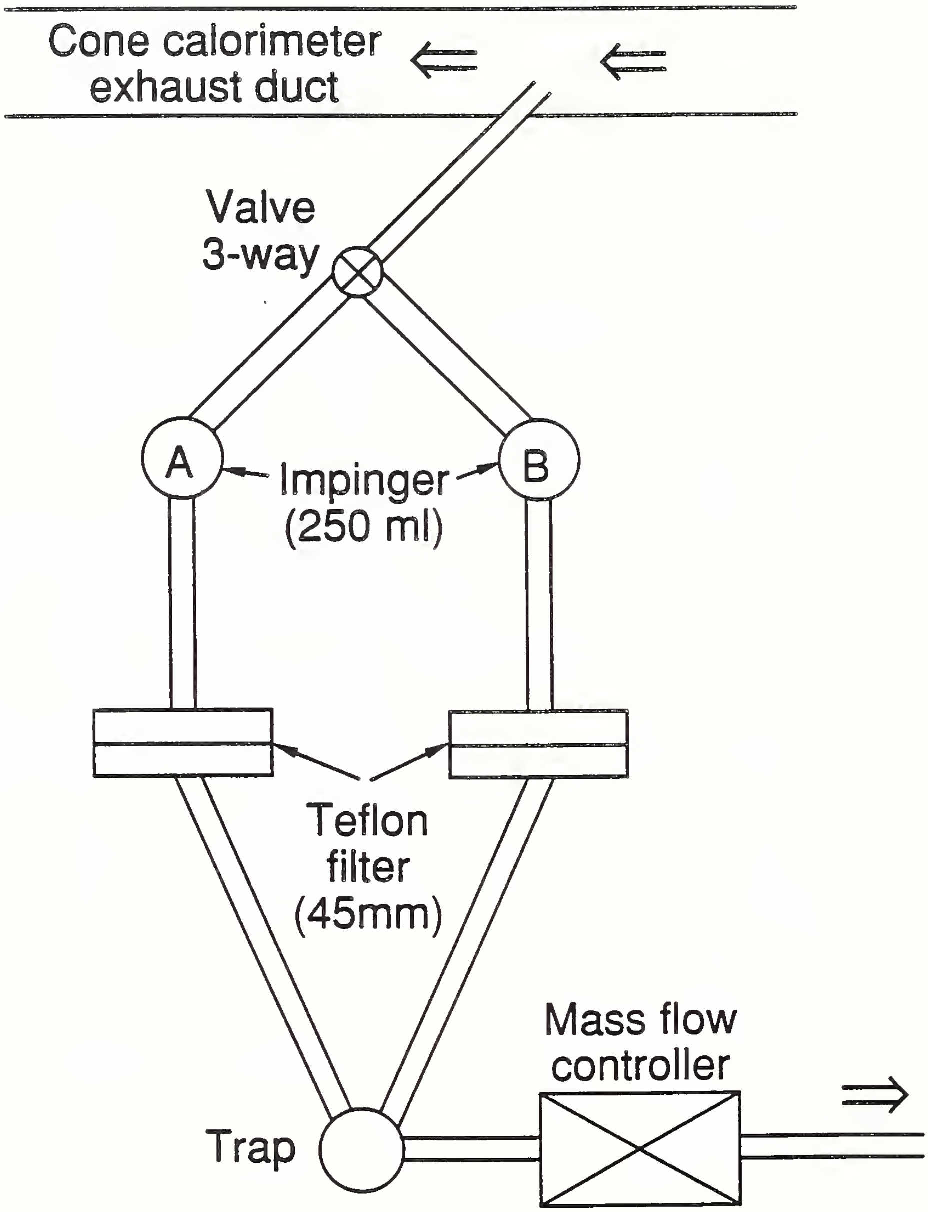

Figure 2. Schematic representation of gas sampling apparatus for HCN, HCℓ, and HBr determinations.

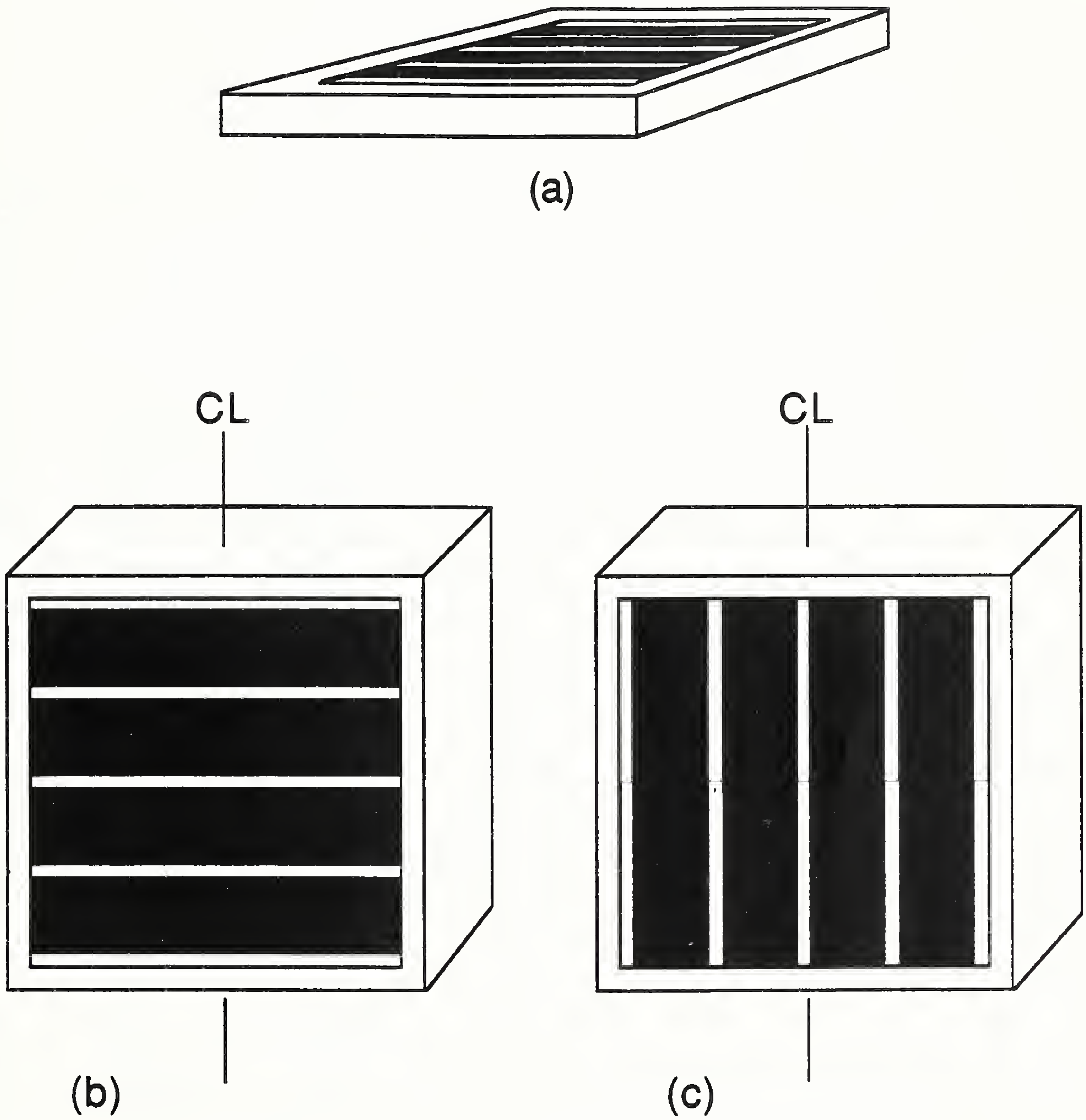

Figure 3. Cable arrangement in cone calorimeter sample holder: (a) horizontal holder; (b) vertical holder with cable lengths perpendicular to vertical centerline; (c) vertical holder with cable lengths parallel to vertical centerline.

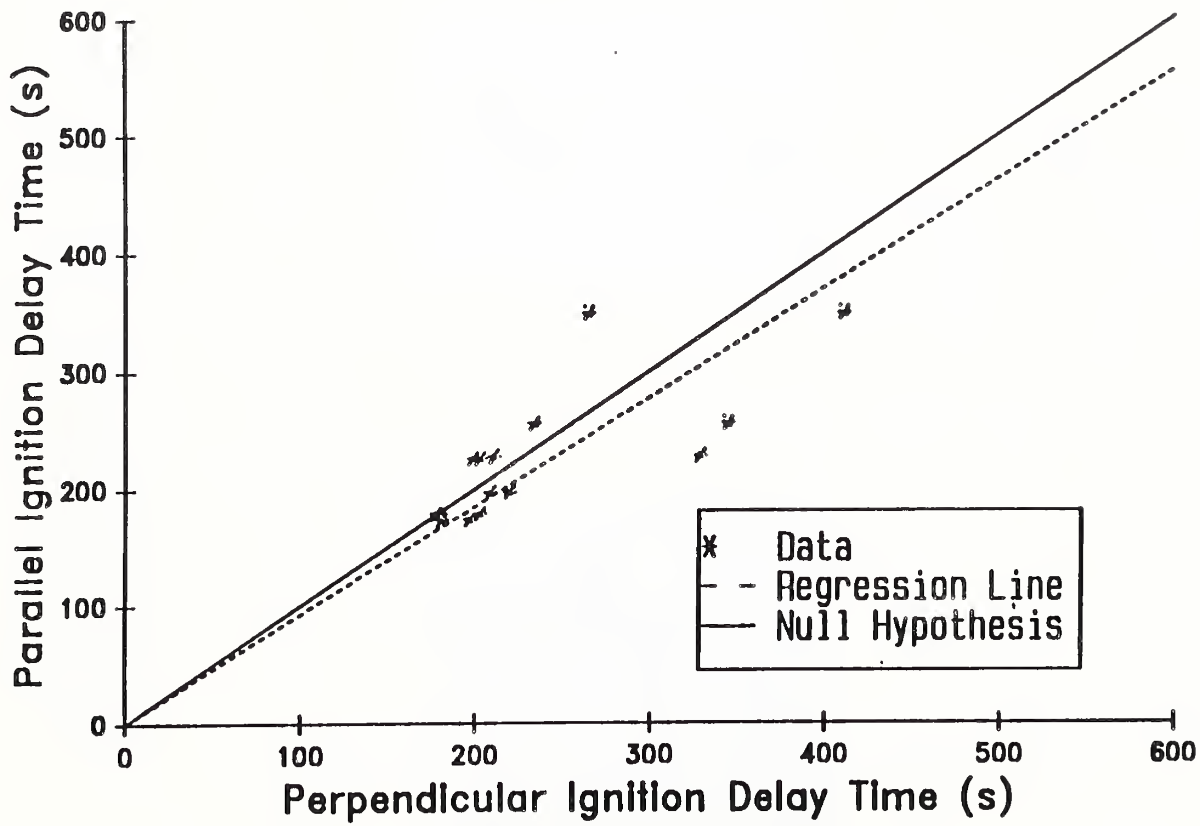

Figure 4. Ignition delay time comparison for parallel and perpendicular mounted samples in the vertical orientation.

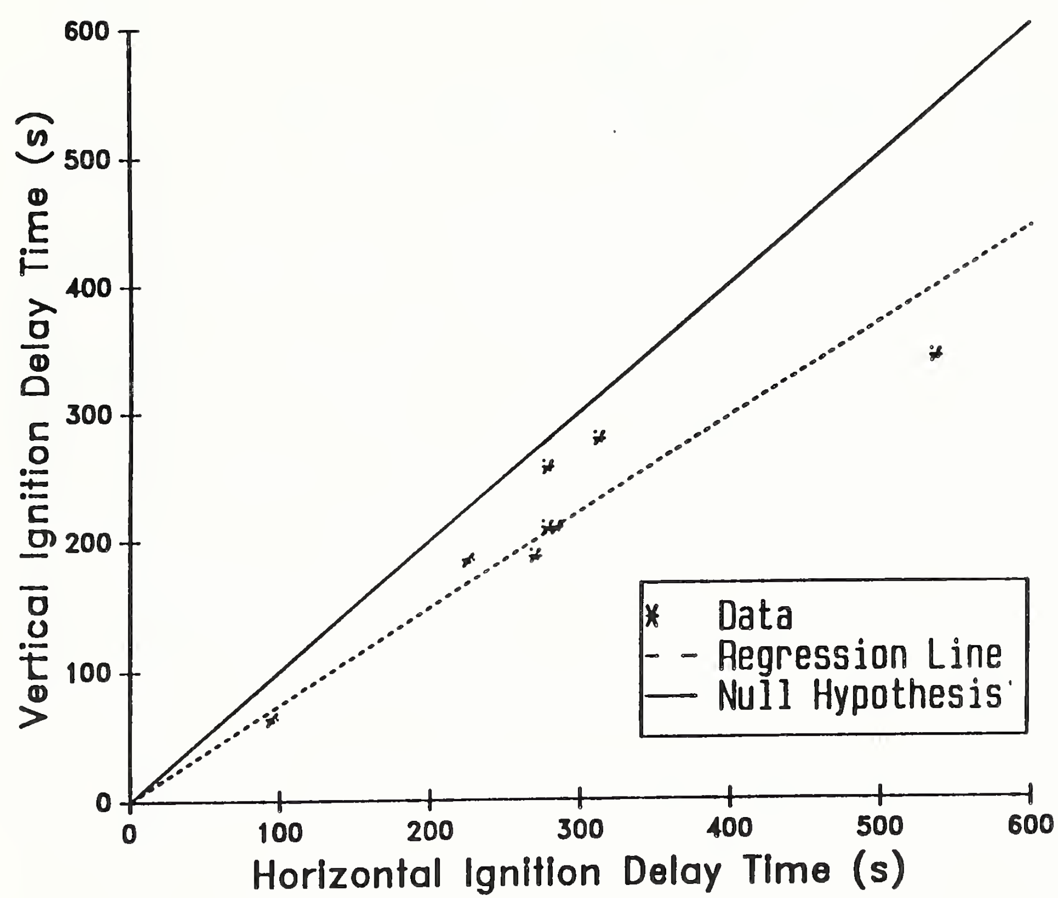

Figure 5. Comparison of ignition delay time for samples mounted in the horizontal and vertical orientations at an external irradiance of 25 kW/m^2.

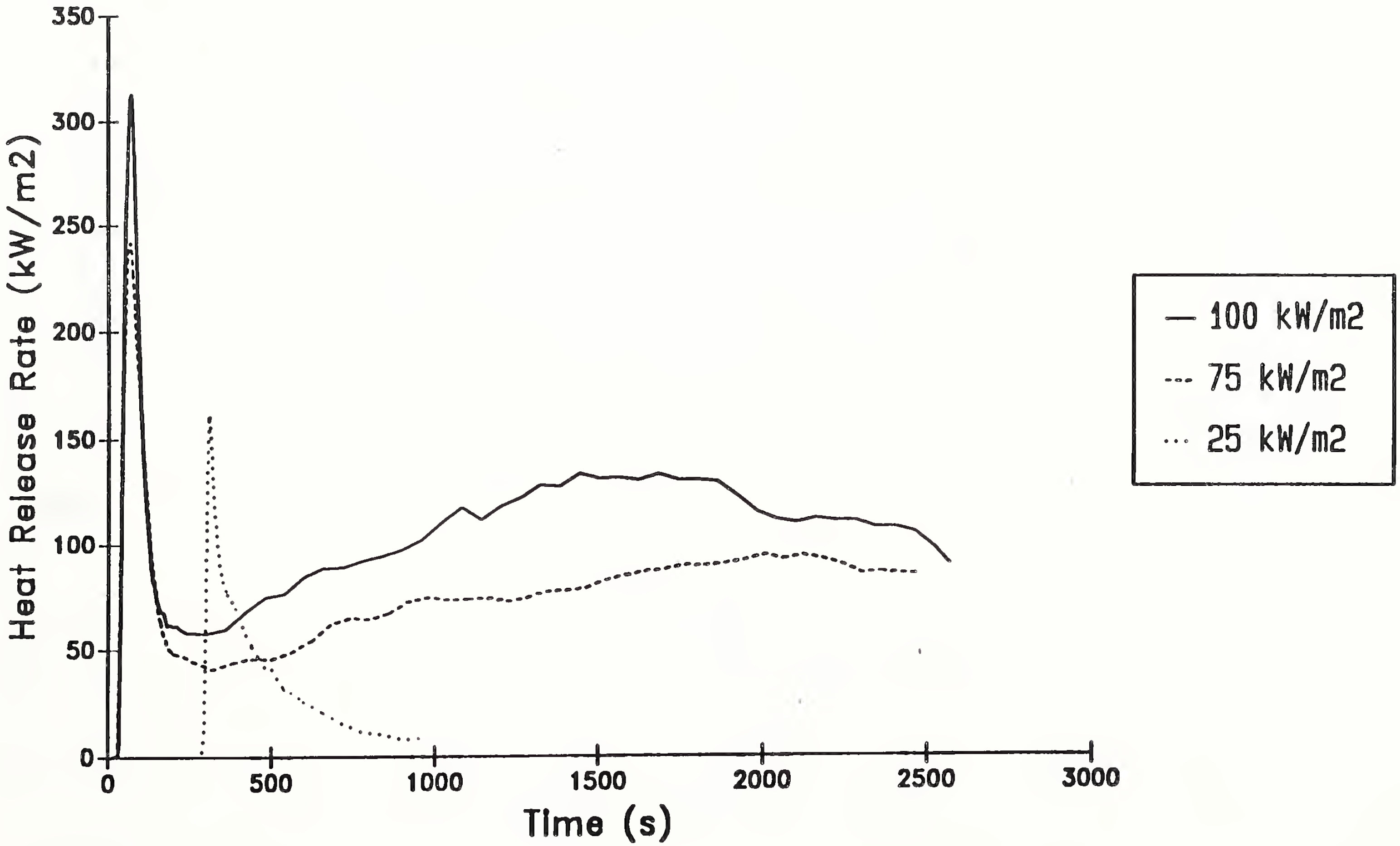

Figure 6. The rate of heat release for cable LSMDU-6 in the horizontal orientation at 25, 75, and 100 kW/m^2.

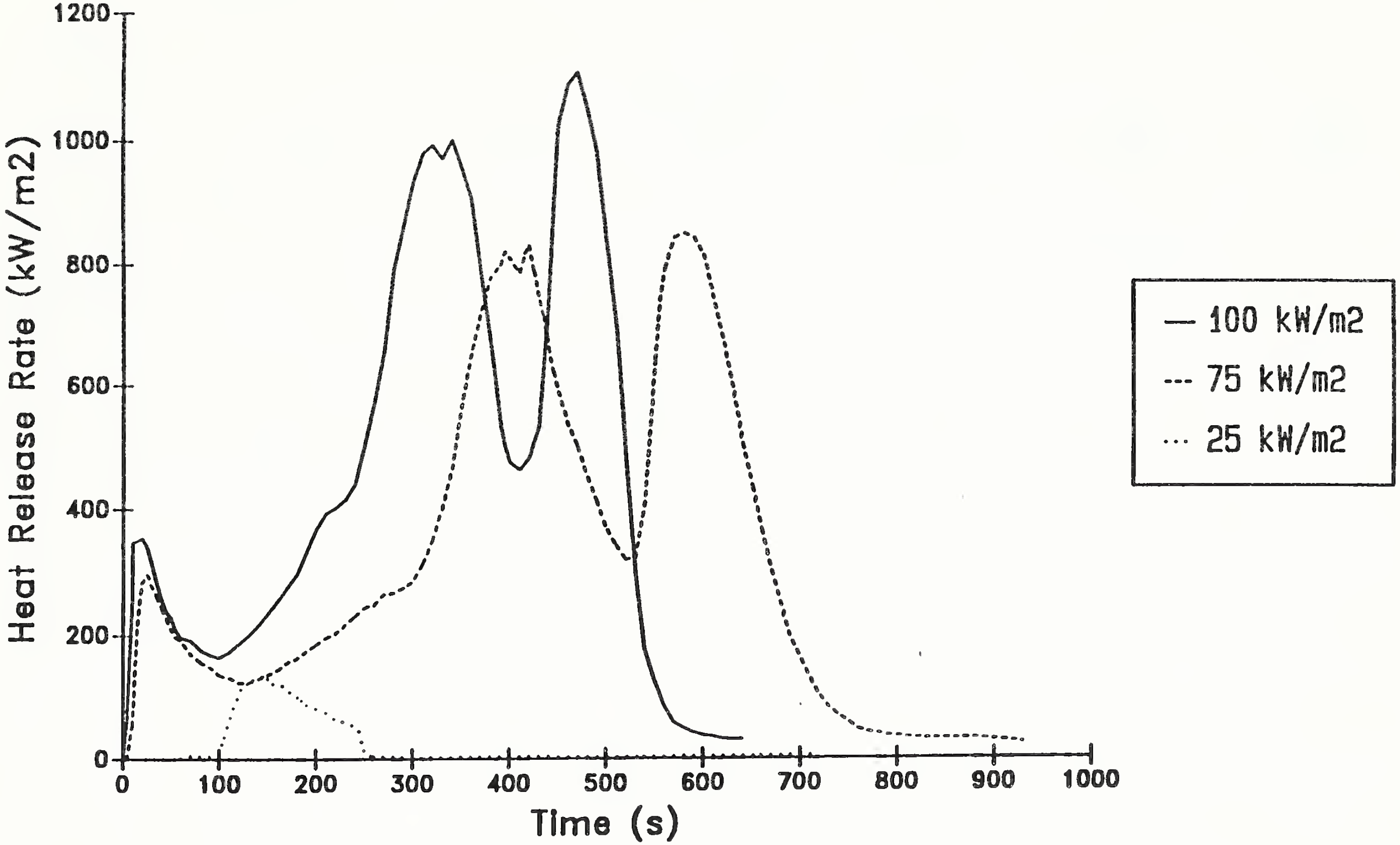

Figure 7. The rate of heat release for cable MNW-44 in the horizontal orientation at 25, 75, and 100 kW/m^2.

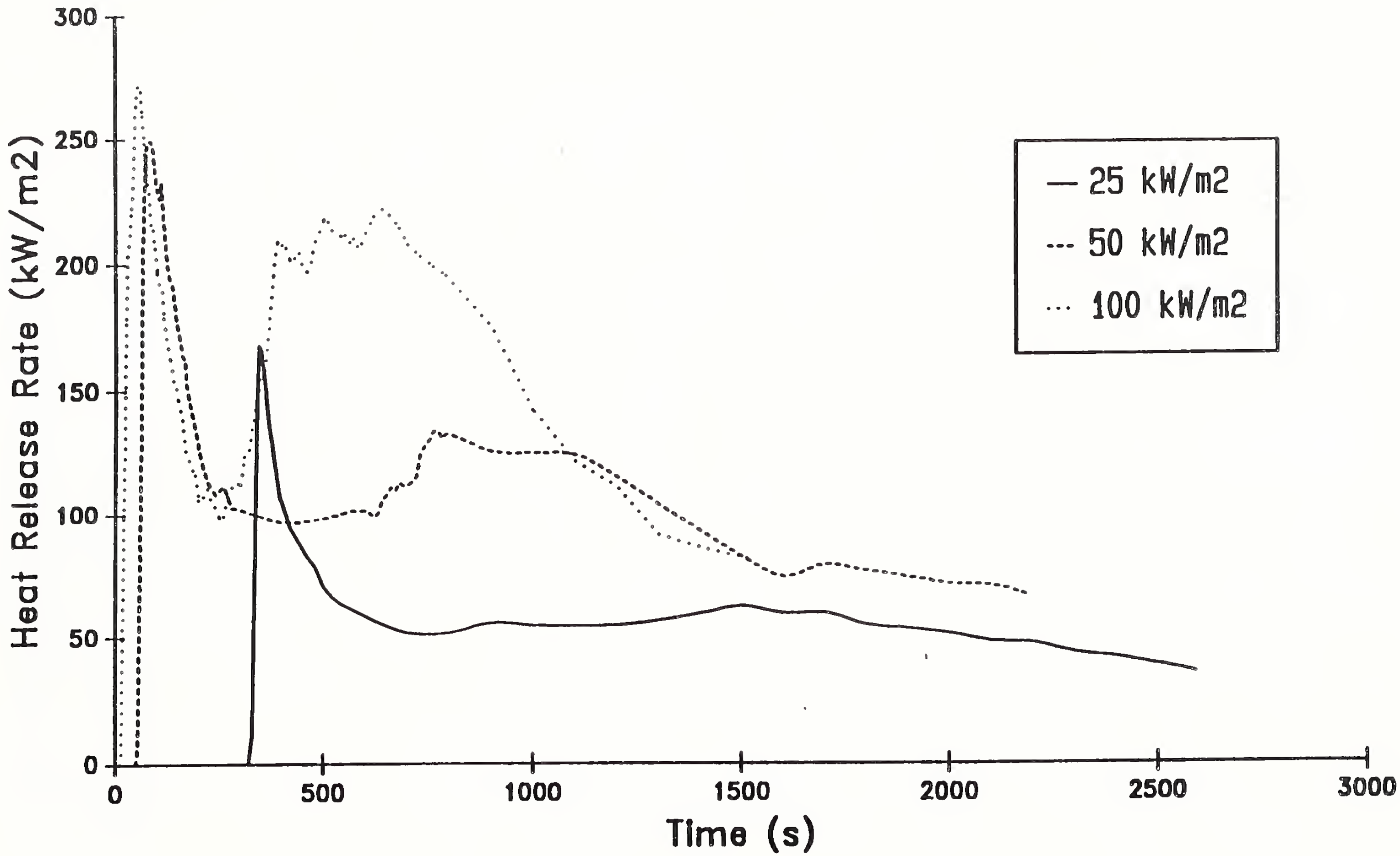

Figure 8. The rate of heat release for LS2SWAU-10 in the vertical orientation at external irradiances of 25 and 50 kW/m^2.

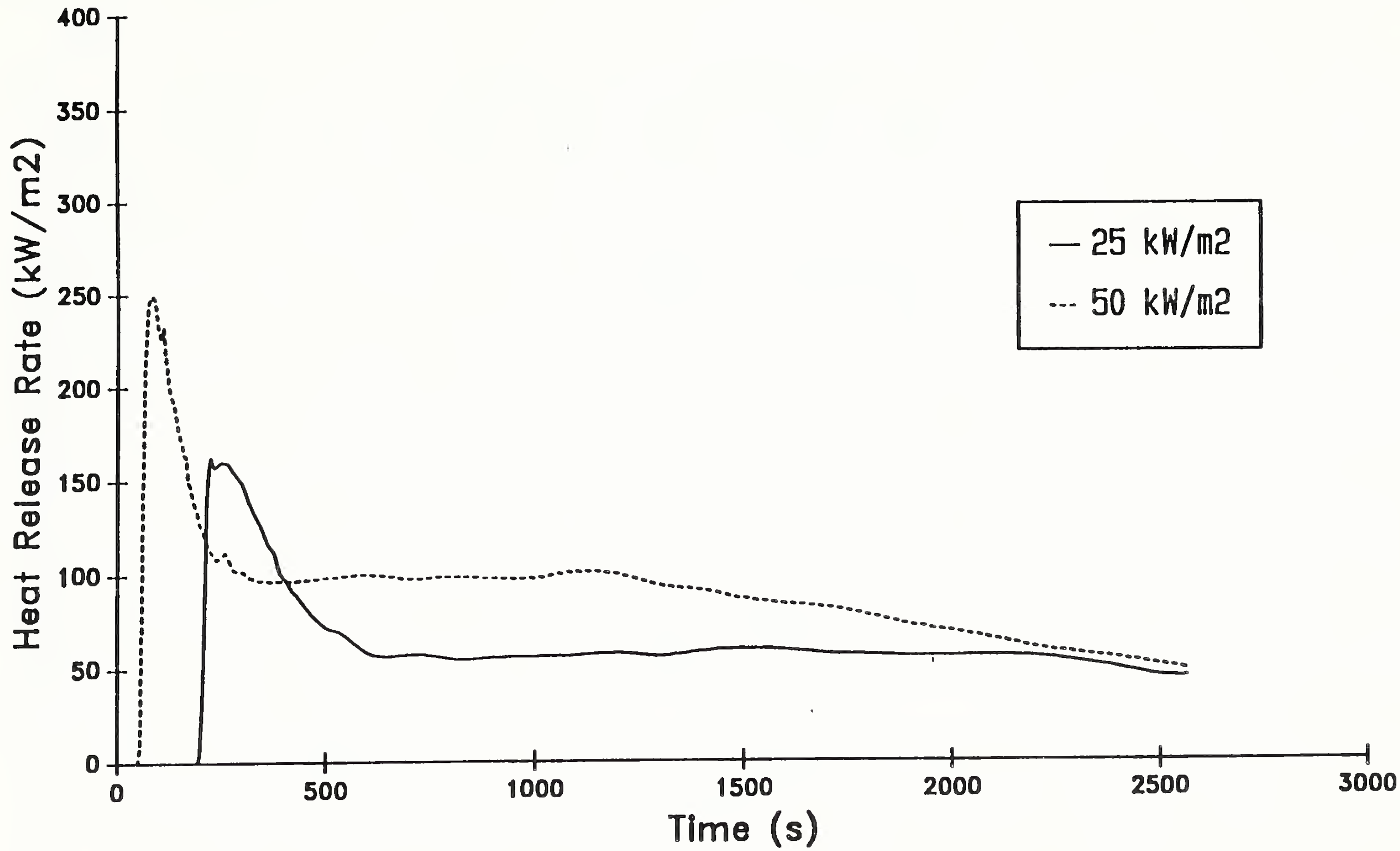

Figure 9. The rate of heat release for cable LSMSCU-44 in the vertical orientation at external irradiances of 25 and 50 kW/m^2.

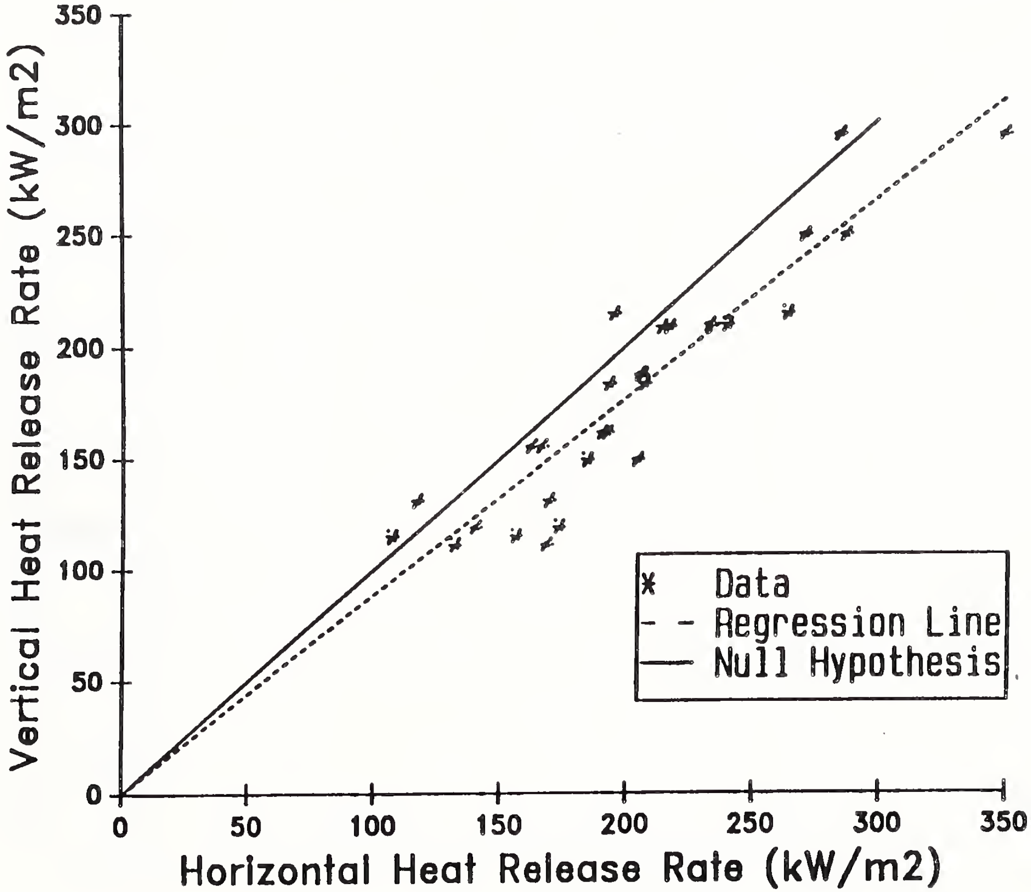

Figure 10. Comparison of peak heat release rate data for cable samples mounted in the vertical and horizontal orientations.

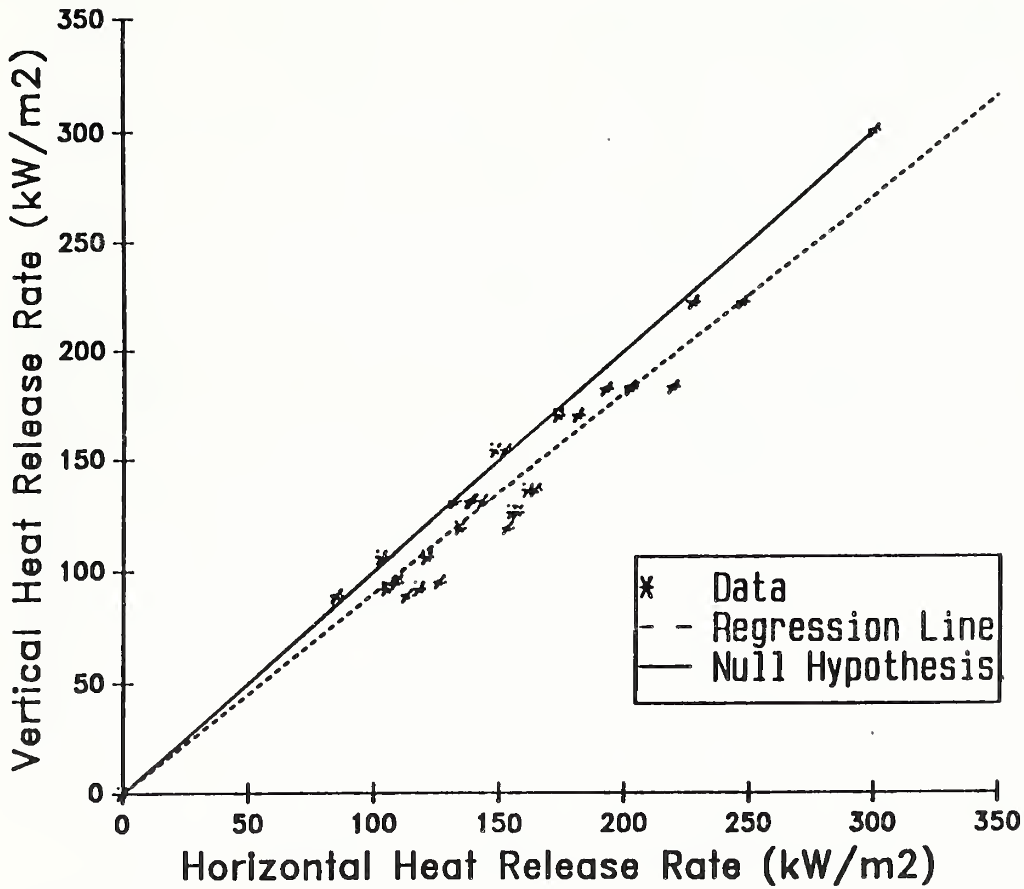

Figure 11. Comparison of 60 s average heat release rate data for cable samples mounted in the vertical and horizontal orientations.

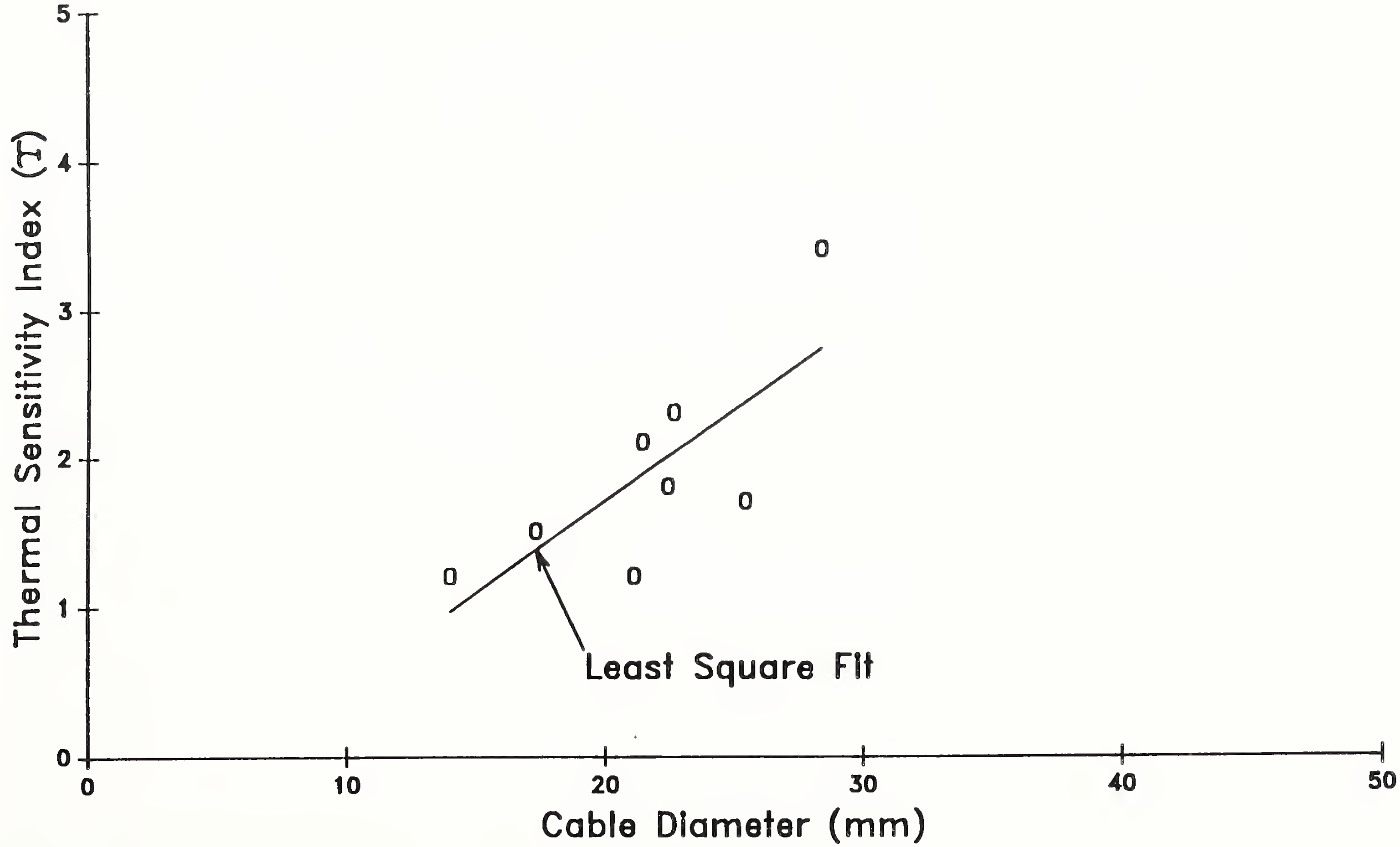

Figure 12. The relationship between the Thermal Sensitivity Index, T, and cable diameter for cross-linked polyolefin jacketed cables.

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Cone Calorimeter tests were performed on eight multi-conductor electrical cables. Measurements of ignition delay time, heat release rate, mass loss rate, and gas and smoke generation rates were made in the vertical (2 irradiance levels) and horizontal (3 irradiance levels) orientations. It was found that comparable ignition delay times were observed for all of the cross-linked polyolefin jacketed cables. The PVC jacketed cable had a substantially lower ignition delay time. All of the cables exhibited an ignition delay time dependence on external irradiance proportional to $1/q^2$. Sample orientation did not significantly effect the ignition delay time. Heat release rate measurements showed that cables burned in multiple stages. Each stage of burning was associated with the decomposition of a different layer of the cable assembly. For some cables, at low external irradiances (25 kW/m^2) only the outer jacket of the cable burned. At higher irradiances (above 50 kW/m^2), the outer jacket burst open exposing the interior cable materials and secondary heat release rate peaks resulted. Changes in the cable components actually burning were reflected in variations in mass loss, gas, and smoke generation rates as well as small changes in the effective heat of combustion. HBr and HCl were detected during the burning of some of the cables. The production of HCN was detected at some point during the combustion of most of these cables.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Cables; combustion; cone calorimeters; flammability; ignition delay time; heat release rate; gas yield; smoke yield.

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