Understanding the Hazards of Grouped Electrical Cables

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Abstract
CHRISTIFIRE (Cable Heat Release, Ignition, and Spread in Tray Installations during FIRE) is a U.S. Nuclear Regulatory Commission Office of Research program to quantify the mass and energy released from burning electrical cables. This type of quantitative information will be used to develop more realistic models of cable fires for use in fire probabilistic risk assessment (PRA) analyses. The experimental program has two main thrusts—bench-scale measurements of small samples of burning cables and full-scale measurements of the heat release and fire-spread rates of cables burning within typical ladder-type trays. The bench-scale measurements include micro-calorimetry of cable components, effluent characterization using absorption spectroscopy, and measurements of the heat release rate using a cone calorimeter. The full-scale measurements include the burning of a variety of cables within a typical tray under radiant panel heating, and full-scale, multiple tray fires. The outcome of the experiments is to be used by a variety of fire models, ranging from simple correlations to computational fluid dynamics.

Introduction
Electrical cables perform numerous functions in nuclear power plants. Power cables supply electricity to motors, transformers, heaters, and light fixtures; control cables connect plant equipment such as motor-operated valves and motor starters to remote initiating devices (e.g., switches, relays, and contacts); instrumentation cables transmit low-voltage signals between input devices and readout display panels. Nuclear plants typically contain hundreds of kilometers of electrical cables. The *in situ* fire fuel load is clearly dominated by electrical cable insulating materials in most areas of a plant. These electrical cables will be found in both the cable routing raceways and in the electrical control cabinets. In a postulated fire scenario, they can be an ignition source, an intervening combustible, and/or a device that can potentially lose functionality. These cables are made up of a variety of thermoplastic and thermoset materials. The primary characteristics that distinguish one cable type from another with respect to fire behavior include cable jacket formulation, conductor insulator formulation, multiple versus single-conductor, conductor size, and flammable to nonflammable material weight ratios.

Electrical cables have been responsible for, or contributed to, a number of fires in commercial nuclear plants over the years. In 1975, a serious fire involving electrical cables occurred at the Browns Ferry Nuclear Power Plant operated by the Tennessee Valley Authority [1]. The fire caused damage to more than 1,600 cables resulting in loss of all Unit 1 emergency core cooling system equipment. The damage was extensive because of the flammability of the cables, including ease of ignition, and flame spreading.

The burning behavior of cables in a fire depends on a number of factors, including their constituent materials and construction, as well as their location and installation geometry. Burning cables can propagate flames from one area to another or they can add to the amount of fuel available for combustion and can liberate smoke containing toxic and corrosive gases. The lower the heat flux required to ignite the electrical cables, the greater the fire hazard in terms of ignition and flame spread. Electrical cables exposed to fire can lose physical integrity (i.e., melting of the insulation) and insulation resistance, leading to electrical breakdown such as short-circuiting or the spread of fire to other cables or combustibles.

The amount of experimental evidence and analytical tools available to calculate the development and effects of cable tray fires is relatively small when compared to the vast number of possible fire scenarios that can be postulated for nuclear plants in the U.S. Many of the large-scale fire tests conducted on cables are qualification tests in which the materials are tested in a relatively large-scale configuration and qualitatively ranked on a comparative basis. This type of test typically does not address the details of fire growth and spread, and does not provide any useful data for model calculations. Very few of these tests attempt to characterize the fire itself in more than a very superficial way.

There have been a variety of studies focused on small scale material characterization tests. Many investigators have questioned the degree to which small-scale test results reflect true fire behavior, especially plastic materials. Until these small-scale test results have been more fully validated through larger-scale test data, caution must be exercised in the use of small-scale test results in the prediction of full-scale fire behavior.

The need for data about the fire hazards of cables also relates to the methods contained in NUREG/CR-6850, "Fire PRA Methodology for Nuclear Power Facilities"[2]. The fire PRA method requires data on heat release rates and fire spread from tray to tray. As mentioned above, the currently available data is limited, and there is a need for more data to reduce the uncertainty associated with these methods.

Project Objective

The CHRISTIFIRE (Cable Heat Release, Ignition, and Spread in Tray Installations during FIRE) experimental program is a U.S. Nuclear Regulatory Commission (US NRC) Office of Nuclear Regulatory Research (RES) initiated effort to quantify the mass and energy released from burning electrical cables. The project is a collaborative effort that includes the NRC Office of Nuclear Reactor Regulation (NRR) as peer reviewers and the National Institute of Standards and Technology (NIST) as the primary testing laboratory.

Several hundred samples of electrical cables were obtained by NIST for testing. Some of the cables had been used previously for a variety of experiments to assess their durability and sustainability. The U.S. NRC-sponsored project CAROLFIRE [3], [4], [5] has provided much needed information on the electrical failure mechanisms of cables in fire, including a relatively simple algorithm to predict the thermally-induced electrical failure (THIEF) of cables that is suitable for a variety of fire models. However, fire models still lack basic information about the heat release and spread rates of burning cables. CAROLFIRE demonstrated that ignition and electrical failure often occur within seconds of each other, but measurements were not made to quantify the burning behavior beyond the point of electrical failure.

CHRISTIFIRE addresses the burning behavior of cables in a fire rather than electrical functionality. In assessing the hazard to electrical cables within any given compartment of a plant, the first question to ask is when, and under what conditions, the cables will lose their functionality. The next question is will the cables burn and spread the fire, and if so, to what extent are other components in the compartment vulnerable to the increased heat produced by the burning cables. Fire models are used to answer both questions, but they cannot answer these questions without a considerable amount of information about the cable construction, material properties, and behavior in small and large-scale fire experiments.

The CHRISTIFIRE experimental program has two main thrusts – bench-scale measurements of the effluent from small samples of burning cables and full-scale measurements of the heat release and fire spread rate of cables burning within typical ladder-type trays. Both sets of measurements are designed to provide the necessary input data for numerical fire models that are typically used to assess the consequences of accidental fires within various compartments in a nuclear power plant. Unlike most standard fire tests involving cables, these experiments are not intended as qualification or classification tests. In fact, typical qualification tests focus on vertical cable trays, but CHRISTIFIRE involves mainly horizontal because these are most readily found in plants. Fires do not spread as rapidly over horizontal trays, but the rates can greatly depend on the proximity of a given tray to other trays or surrounding walls or ceiling.

Technical Approach

Given that there are innumerable permutations of cable types, trays, barriers, orientations and so forth, it is impossible to develop a testing program to evaluate all possible arrangements. However, if it can be shown that relatively inexpensive bench-scale experiments can be used to predict the outcome of large-scale experiments, and if the same bench-scale data can be used as input for fire models, the need for expensive large-scale testing decreases significantly. The simplest example of such an approach is the current estimation technique for heat release rate recommended in NUREG/CR-6850 [2] and NUREG-1805 [6], in which bench-scale heat release rate measurements using a device similar in design to the cone calorimeter are used for large-scale calculations. The drawback of the existing approach, however, lies mainly in the fact that it is based on only a handful of experiments performed under a single set of conditions.

The CHRISTIFIRE research program consists of experiments performed on a variety of length scales, from micro-scale chemical analyses to full-scale, realistic cable tray configurations. The approach borrows significantly from the European FIPEC program (Fire Performance of Electrical Cables [7]). TABLE 1 summarizes the experiments. The experiments can be roughly divided into two types – one to measure heat release and spread rates, the other to assess the composition of the cable materials and combustion products. From the point of view of a fire model, these experiments quantify the production rates of mass and energy for a tray of burning cables.

TABLE 1. Outline of Experimental Program

Scale	Description	Number of Tests	Related Standard or Test
Full	Horizontal Trays	16	FIPEC
Intermediate	Radiant Panel	33	None
Small	Cone Calorimeter	12 cables; 3 fluxes	ASTM D 6113
Small	Tube Furnace	12 cable samples	ISO/TS 19700
Micro	Micro-Calorimetry	12 cable samples	ASTM D 7309

Cables: Most of the cables used in the CHRISTIFIRE project were manufactured in the late 1970s and early 1980s. FIGURE 1 is a photograph of the different cables used. Most are multiple conductor control cables, consisting of an outer jacket enclosing individually insulated copper wires. For some there is additional filler material to maintain a circular cross section.

FIGURE 1. Photograph of cables used in CHRISTIFIRE

Exhaust Product Yields: The tube furnace (ISO/TS 19700, "Controlled equivalence ratio method for the determination of hazardous components of fire effluents") is a bench-scale device specifically designed to measure the composition of the effluent of a burning item. As shown in FIGURE 2, it consists of three main parts: (1) a quartz tube running through an electrically heated furnace; (2) a 30 L dilution and sampling chamber; and (3) a specimen boat and drive mechanism that can advance the specimen into the furnace at a controlled rate. Air is supplied at both the upstream end of the quartz tube and in the dilution and sampling chamber. By controlling the upstream air flow rate and the specimen feed rate, the equivalence ratio in the tube furnace can be adjusted to model several fire stages. The results reported here were performed under well-ventilated conditions. The average equivalence ratio was 0.53 with a standard deviation across all cases of 0.18.

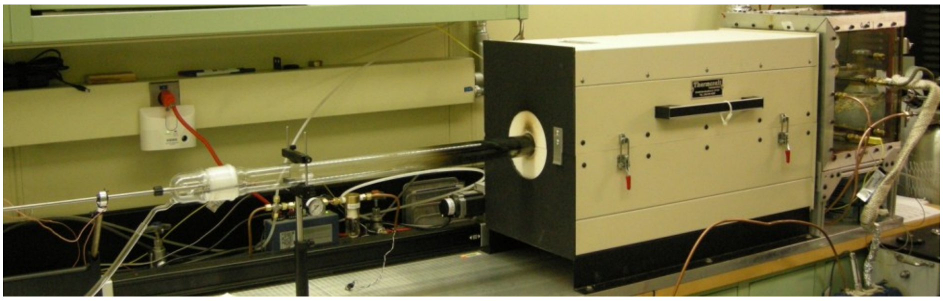

FIGURE 2. ISO/TS 19700 Tube Furnace.

Micro-Calorimetry: The Pyrolysis Combustion Flow Calorimeter (PCFC) was developed by Lyon, Walters and co-workers at the U.S. Federal Aviation Administration laboratories to measure quantities such as the Specific Heat Release Rate (W/g), Heat of Combustion (J/g) and Ignition Temperature (K) from very small (1 mg to 10 mg) specimens. The apparatus and measurement technique is now standardized as ASTM D 7309, *Standard Test Method for Determining the Flammability Characteristics of Plastics and Other Solid Materials Using Microscale Combustion Calorimetry* [8]. The PCFC technique utilizes traditional oxygen depletion calorimetry. The specimen is first heated at a constant rate of temperature rise (typically 0.5 K/s to 2 K/s) in a pyrolysis chamber and the degradation products are swept from the chamber by an inert gas. The gas stream is mixed with oxygen and enters a combustor at 900 °C where the decomposition products are completely oxidized. Oxygen concentrations and flow rates of the combustion gases are used to determine the oxygen depletion involved in the combustion process and the heat release rates are determined from these measurements.

Heat Release and Spread Rates: The cable samples were burned at three scales: full, intermediate, and bench-scale. The bench-scale experiments used the cone calorimeter (ASTM E 1354; ISO 5660-1) to measure the heat release rate (HRR) and the smoke production rate of a 10 cm by 10 cm (4 in by 4 in) single layer of cable segments. The intermediate-scale experiments made use of radiant panels to subject a roughly 1 m (3 ft) long section of cable within a 0.45 m (18 in) wide tray to a constant heat flux. Much like the cone calorimeter in design, the radiant panel apparatus provided a heat release rate per unit area of a more realistic arrangement of cables within a commonly used ladder-back tray. The full-scale tests consisted of three stacked, horizontal trays that were up to 3.6 m (12 ft) in length. These tests provided information on the vertical and horizontal spreading of a fire within a typical arrangement of trays.

Cone Calorimeter Experiments: The cone calorimeter is a widely-used device for measuring the heat release rate of a material sample under a constant imposed heat flux. In the FIPEC program, it was shown that various measurements within the cone correlated with large-scale test results. In the FIPEC program, a special specimen holder and procedure was developed specifically for the testing of cables. The modifications apply to the sealing of the cut cable ends, arrangement of the cable segments, insulation of the holder, and restraint of the sample. This special modification is now standardized in ASTM D 3116.

Radiant Panel Experiments: The apparatus consists of a single horizontal tray with varying amounts of cable exposed to an array of quartz-faced radiant panels. The tray is 1.2 m (4 ft) long and 0.45 m (18 in) wide. Six panels are used in two symmetric banks. The radiant panels are 25 cm by 30 cm (10 in by 12 in), run on 480 V AC, and produce a maximum radiant output of 4.8 kW each, or a maximum heat flux of 62 kW/m^2. See FIGURE 3 for photographs of the apparatus. Preliminary measurements demonstrated that this configuration can produce approximately 30 kW/m^2 over 1 m (3 ft) of the cable tray. The objective of these experiments was to compile a table of heat release rates per unit area for a variety of heat flux exposures and tray loadings. The heat flux exposures were typically between 15 kW/m^2 and 30 kW/m^2. For the loading, the NFPA National Electric Code, 2008 Edition, limits the total cross-sectional area of the cables within a 0.45 m (18 in) tray to 135 cm^2 (21 in^2). Testing generally involved loading levels between 25 % and 50 % of the limit, or approximately 1 to 2 rows of cables.

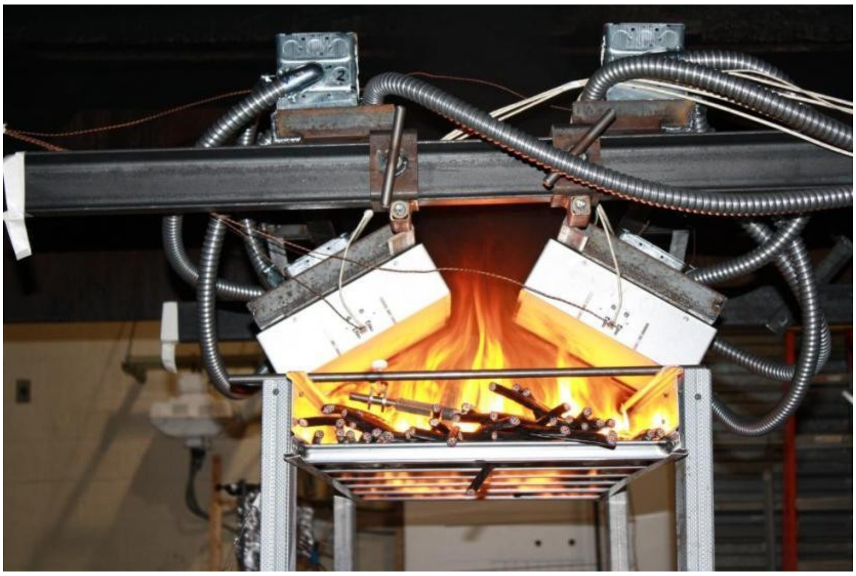

FIGURE 3. End view of radiant panel apparatus

Multiple Tray Experiments: The multiple tray (MT) experiments were composed of vertical stacks of three to seven cable trays. This configuration addresses the fairly common installation where 0.45 m (18 in) horizontal, ladder-backed trays are stacked over top of each other with roughly 0.3 m (1 ft) spacing. The purpose of these experiments was not to directly generate fire model input data, but rather to confirm that burning rate data collected at bench and intermediate-scales would enable a fire model to estimate the heat release and spread rates of the full-scale tests. FIGURE 4 shows a typical experiment. A small 0.3 m by 0.3 m (1 ft by 1ft) square, gravel-packed natural gas burner was placed 18 cm (7 in) below the lowest tray. The natural gas flow rate to this burner was calibrated to provide approximately 35 kW. The support rig and cable trays were placed upon four scales, each accurate to approximately 1 g. The heat release rate of the fire was measured in two ways. First, the amount of oxygen consumed by the fire was measured via oxygen consumption calorimetry instrumentation in the hood. Second, the measured mass loss rate was multiplied by the heat of combustion that was estimated using data from the small scale experiments.

FIGURE 4. Multiple Tray (MT) cable test apparatus.

Of these three sets of measurements, the intermediate scale is of greatest value for fire modeling. Although a cone calorimeter measurement is a commonly performed, relatively inexpensive method to measure the burning rate of a real material, the small size of the sample, especially an inhomogeneous mixture of different materials, makes it difficult to scale the measured heat release rate to larger scale. On the other hand, while the full-scale measurements do not have scaling limitations, it is more difficult to extract a meaningful fire model input from them. In other words, the heat release rate of an array of burning cable trays cannot be directly applied in a model because the tray configuration will almost certainly be different in the model application than it is in the experiment.

The obvious question to ask is why bother with the cone calorimeter or full-scale measurements at all? In the case of the cone, the answer is cost. It is not possible to burn samples of every cable type used in nuclear plants throughout the United States, past, present and future. There will always be a need to assess the burning behavior of an old or new cable. It would be impractical to perform intermediate or full-scale experiments for this purpose. If it can be shown that the burning rate measured in the cone scales with the intermediate scale results, and if it can be shown that the intermediate scale results can be used to predict the full-scale results, then the single cone measurement can be used for fire model analysis assuming a certain scaling factor. Past experimental programs to assess cable burning behavior have almost all used more or less this same strategy, although many lacked the critical intermediate-scale experiments which made it more difficult to correlate the bench-scale and full-scale results.

Results
This section presents selected results of the experimental test series with an emphasis on just two cables – one a thermoplastic and the other a thermoset. The term "thermoplastic" is applied to cables that tend to melt and drip upon heating. Typical thermoplastic cables are made of polyethylene and/or polyvinyl chloride. "Thermoset" cables tend to char upon heating, and are often constructed of materials like cross-linked polyethylene (XLPE). The purpose of the results shown in this section is to highlight the important differences between these two major cable types. The selected thermoset and thermoplastic cables, identified as #700 and #701, respectively, have similar weight, appearance and functionality.

Micro-Calorimetry: FIGURE 5 presents the results of the analysis of the insulation material for a typical thermoset (#700) and thermoplastic (#701) cable. The curves display the heat release rates per unit mass of a small sample heated up at a rate of 1 K/s. The parameters in the figure are the calculated pre-exponential factors, *A*, activation energies, *E*, and "peak" temperatures of an assumed two-reaction decomposition scheme, derived using methodology described by Lyon [9]. The area underneath the curves represents the heat of combustion multiplied by the heating rate. The dashed curve indicates the experimental measurement, and the solid curve indicates the results of the kinetic analysis. Of importance here is the difference in the temperature at which the material burns. The thermoplastic material typically burns at temperatures starting at approximately 300 °C, whereas the thermoset material does not begin to burn in earnest until about 450 °C.

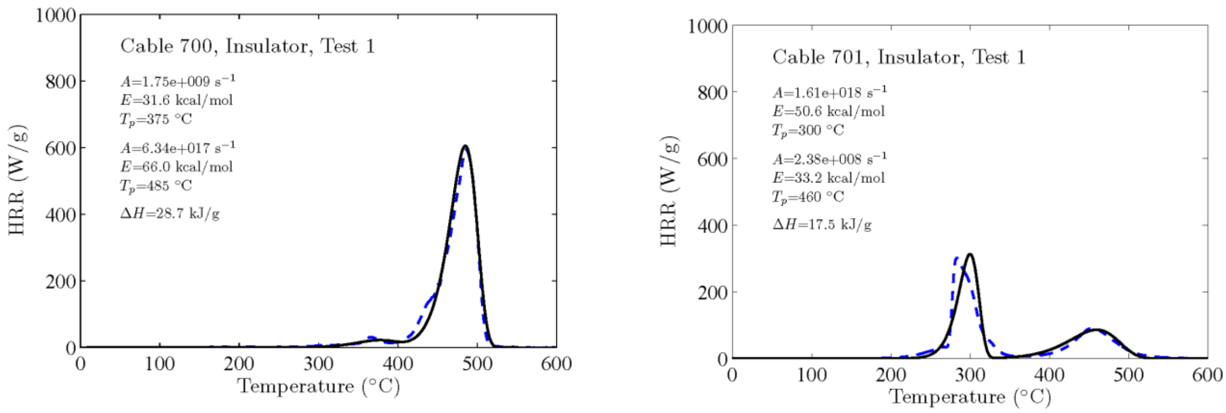

FIGURE 5. MCC results for a typical thermoset (left) and thermoplastic (right) cable.

Tube Furnace: FIGURE 6 presents the results of the effluent analysis for the cable samples. Notable differences appear in the yield of soot, CO, and HCl, but there is no indication that the relative yields of these species are related to the overall burning rates. Note that Cable 700 produces little HCl, but Cable 701 does. The insulation and jacket material of Cable 700 is made of cross-linked polyethylene, whereas Cable 701 is a mixture of poly-vinyl chloride and other materials. However, several other cables whose basic material description did not specifically mention chlorine as a component also yielded similar quantities of HCl.

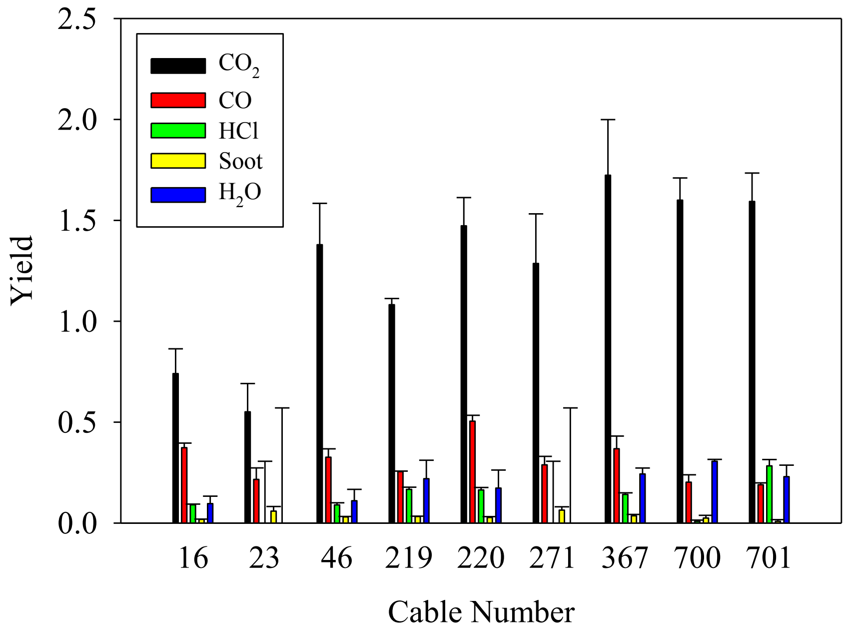

FIGURE 6. Yields (g/g) of major combustion products.

Cone Calorimeter: FIGURE 7 presents cone calorimeter results (three replicate tests) for a typical thermoset and thermoplastic cable. The burning rate per unit area of a single row of the thermoplastic cable is greater than the thermoset by roughly 35 %. Note that the vertical dashed lines on the plots indicate the times at which 10 % and 90 % of the total energy has been released. The average burning rate is derived by averaging over the time period in between.

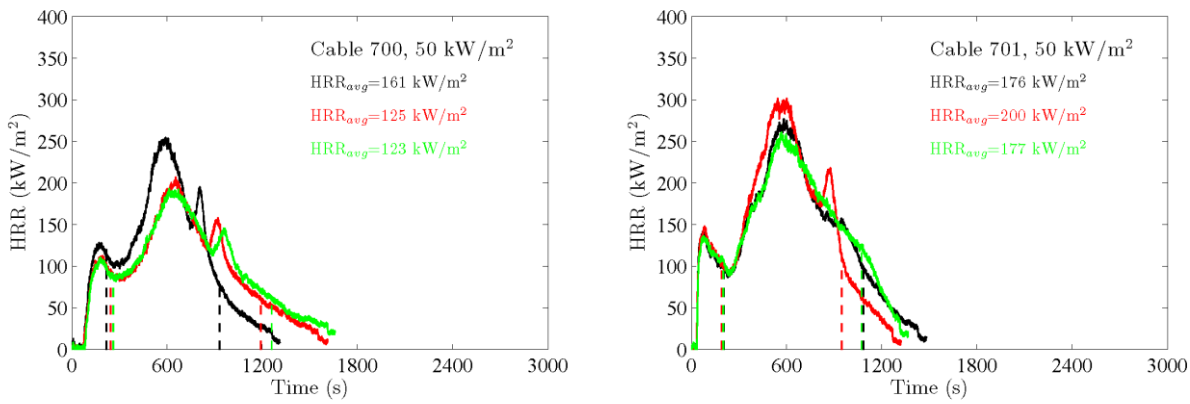

FIGURE 7. Cone calorimeter results for a thermoset (left) and thermoplastic (right) cables. The heat flux of 50 kW/m^2 represents the power of the cone heater. The HRR values represent the heat released per unit area of sample for the three replicate experiments.

Radiant Panel Tests: FIGURE 8 presents results of the Radiant Panel test series for all of the cables tested. A very rough generalization of the data indicates that thermoset cables burn in a range from 100 kW/m^2 to 200 kW/m^2, whereas thermoplastics burn from 200 kW/m^2 to 350 kW/m^2. These ranges are fairly broad due to differences in the specific cable materials and construction, and also differences in the exposing heat flux. Note that in most cases, the measured heat release rate increased with increasing imposed heat flux. However, in some cases, the value did not exhibit this trend. The reason for this has more to do with the method of extracting the average value from a time-dependent burning history than with anything physical. Also, the way the cables were positioned in the tray did sometimes impact the burning pattern.

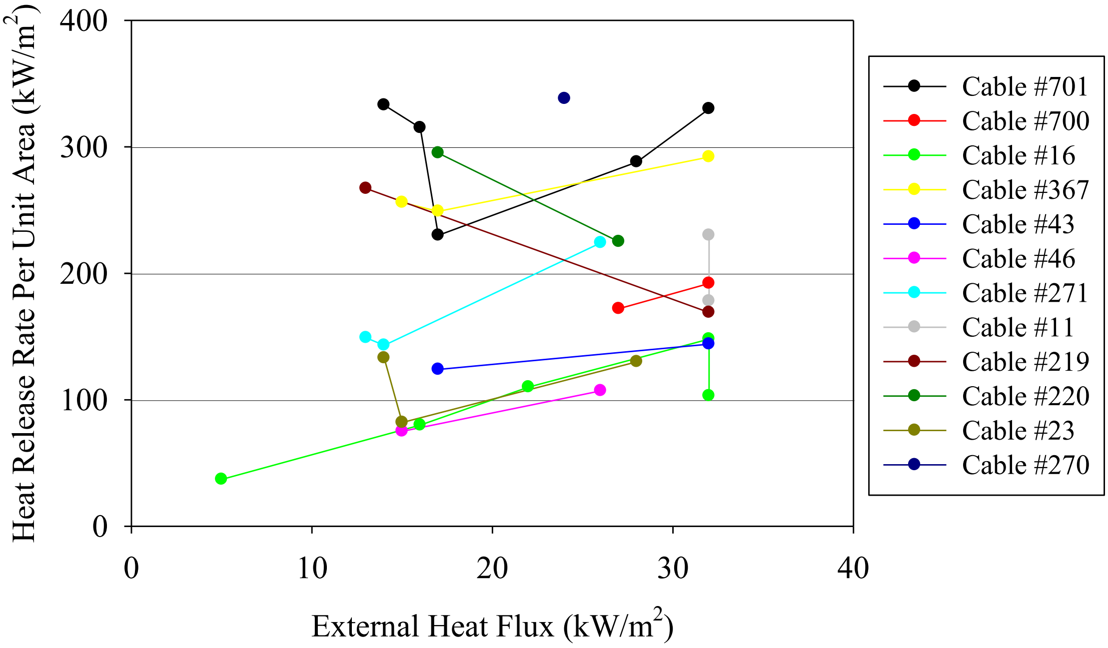

FIGURE 8. Summary of the radiant panel heat release rates.

Multiple Tray Test involving a Thermoset Cable: FIGURE 9 shows a multiple tray experiment consisting of three trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long and contained 40 cables, all #700. The cables were packed loosely. The burner under the bottom tray was maintained at about 40 kW and turned off following the observation of sustained burning in Tray 2. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape. The damage to the cables was relatively minor. The cables in each tray burned over roughly 1 m (3 ft) in length.

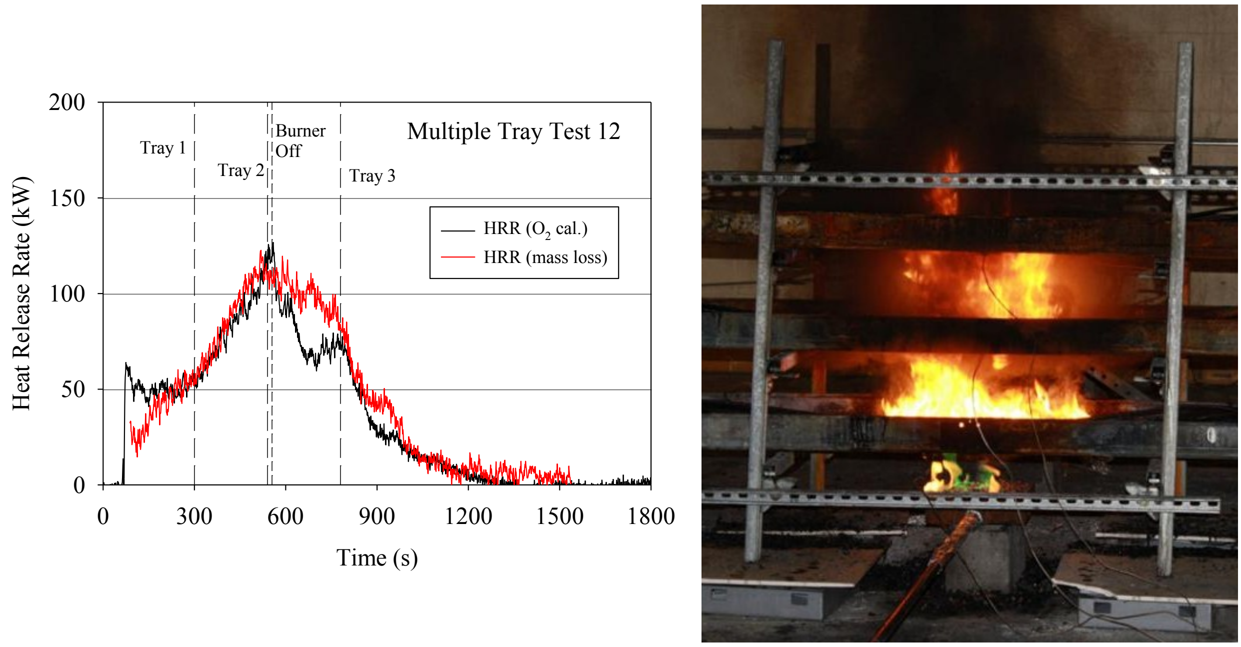

FIGURE 9. Results of a multiple tray test involving a thermoset cable. The vertical lines indicate the time when each tray becomes fully involved in the fire. Tray 1 refers to the lowest tray.

Multiple Tray Test involving a Thermoplastic Cable: FIGURE 10 presents the results of an experiment involving four trays containing Cable 701. The fire spread to the ends of each tray, following a V-pattern by which the cables in front of the flames were pre-heated by the fire in the tray above. There was virtually no solid residue left after the experiment, only the copper conductors remained.

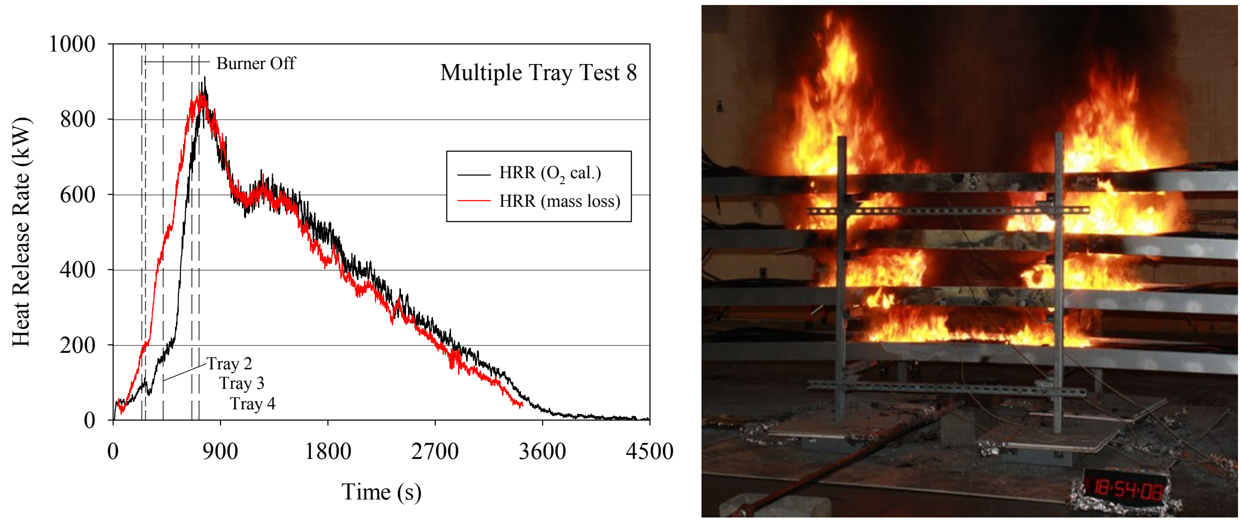

FIGURE 10. Results of a multiple tray test involving a thermoplastic cable. The vertical lines indicate when each tray became fully involved in the fire. Tray 1 refers to the lowest tray. Note that the involvement of Tray 1 coincided with the extinguishment of the burner.

Discussion

The results of the multiple tray experiments involving the two types of cables (#700 and #701) are significantly different, mainly in the peak heat release rate. The cables are similar in size and construction. The measured burning rate per unit area of the thermoplastic cable in the radiant panel apparatus and the cone calorimeter was greater than the thermoset cable by approximately 30 %, but the peak heat release rate of the thermoplastic cables in the multiple tray experiments was greater by factors ranging from 3 to 8. The reason for this is the fact that the thermoplastic cable has a significantly lower burning temperature, as measured in the micro-calorimeter, allowing a fire to grow and spread more rapidly.

Conclusion

The CHRISTIFIRE testing program is expected to continue through the spring of 2010. The final report is expected to contain a comparison of burning rates of cables at different scales, as well as an assessment of the extent to which bench-scale measurements are predictors of full-scale fires. In this regard, the program is similar to various other studies. In addition, the program is expected to provide input data for fire models of different levels of complexity, from simple empirical models all the way to computational fluid dynamics (CFD). Some of the measurements, like the HRR of the full-scale experiments, might be used directly in simpler models, whereas some, like the micro-calorimetry, might be used as part of a more complex model.

Acknowledgements

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