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NIST TN 2320

Thermal Exposure of Objects Near Burning Electrical Enclosures

Kevin McGrattan
Isaac Leventon

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Kevin McGrattan
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Fire Research Division
Engineering Laboratory

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Abstract

This report documents a series of fire experiments performed within steel electrical enclosures and on open “ladder back” cable trays. The first objective is to measure the heat release rates and qualitatively understand the burning behavior of circuit breaker fires within closed steel enclosures when ignited by a source representative of a high energy arc fault (HEAF). The second objective of this report is to quantify the thermal exposure of electrical cables that typically are installed in trays above an enclosure.

Keywords

Circuit Breaker; Electrical enclosures; Electrical fires; High Energy Arc Fault (HEAF); Switchgear.

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1. Introduction

Electrical switchgear enclosures housing equipment such as circuit breakers and motor controls are a common source of fire in industrial settings, and the heat release rate (HRR) and damage caused by these fires are important considerations in facility risk assessments. This report describes measurements of the HRR of circuit breakers within electrical enclosures as well as the internal temperature of electrical cables and other equipment outside of the enclosure exposed to the heat of fires within.

Previous experiments have been conducted to determine HRR probability distributions for electrical enclosure fires [1]. Analysis was then conducted to refine these results to consider specific electrical enclosure characteristics (e.g., classifying electrical enclosures in terms of function, size, contents/fuel loading, and ventilation) [2]. In 2020, a revised set of parameters was provided [3] to address both the fire growth and the suppression response. Further experiments were conducted to measure the HRR for enclosures with limited ventilation [4] and to quantify the impact of material composition (of combustible solids commonly found in power plants) on ignitability and fire growth behavior [5].

To date, there are few measurements[1] of the HRR of circuit breaker fires in electrical enclosures, which have been observed to grow and continue burning for tens of minutes after high energy arc fault (HEAF) events. Thus, the experiments described in this report (Section 3) seek to quantify the peak HRR, time to peak HRR, and duration of circuit breaker fires in steel electrical enclosures. The second focus of this report (Section 4) summarizes the results of experiments designed to quantify the thermal exposure of electrical cables that typically are installed in trays above an enclosure.

The experiments described in this report are part of a broader test series, hence the first experiment presented is identified as Experiment 33. Results from the earlier 32 experiments are presented in NIST Technical Note 2232 [4].

Also, the uncertainty of a measurement presented in this report is typically expressed as a relative expanded uncertainty, sometimes referred to as a 95 % or “two-sigma” confidence interval. This uncertainty includes both an *epistemic* component, i.e. the measuring device has an accuracy and precision reported by the manufacturer based on its operating principles and calibration, and an *aleatoric* component, i.e. there are random variations in repeated trials of an experiment.

[1] See Reference [6] which includes a description of some experiments in which the HRR of a fire initiated by a high energy arc fault was measured.

2. A Surrogate Target for Assessing Electrical Cables Exposed to Fire

The objective of experiments involving fires within electrical enclosures is not necessarily to assess the viability of the enclosure itself or the equipment contained within, but rather to assess the vulnerability of surrounding equipment and the likelihood of spreading the fire beyond its point of origin. The equipment most likely to be located near an enclosure are electrical cables. The fragility of electrical cables exposed to the heat of a fire is largely a function of the cable's inner temperature; that is, the temperature underneath its protective jacket where the metallic conductors rapidly spread the heat. Of course, electrical failure or ignition do not occur precisely at any one temperature, but research suggests [7] that the median failure temperature for most cables is between 200 °C and 400 °C (392 °F and 752 °F). It is typically assumed in risk assessments that electrical failure and ignition occur at similar temperatures, most likely because electrical arcing provides an igniting spark.

For the experiments described in this report, it was not possible to include every possible type of cable. This is a common problem in fire science, and it has become common practice to use simple, often metallic, objects to represent a wider range of objects that might be subjected to the heat of a fire. For example, Putorti et al. [8] used copper and tungsten disks to assess the thermal flux from enclosures subjected to high energy arc faults (HEAF). For the current experiments, a 6061 aluminum alloy rod, approximately 15 cm (6 in) in length and 13 mm (0.5 in) in diameter has been chosen to represent a cable of comparable diameter. Aluminum has been chosen as the metal because its specific heat is comparable to the bulk specific heat of a typical electrical cable containing a mix of polymers and metal conductors, usually copper.

A useful way to compare the aluminum rod with a cable is by way of its *heat capacity*, expressed as the product of the density, specific heat, and cross sectional area, ρcA, in units of kJ/(K m); that is, the amount of energy required to raise a 1 m segment 1 K. The heat capacity of the aluminum rod is approximately 0.31 kJ/(K m). This value can be compared to that of the two cables that have been used in the ignition experiments described below. The one referred to as the "thermoplastic" cable has polyethylene insulation covering its seven 12 AWG[2] copper conductors. Its jacket is approximately 1.9 mm (0.075 in) thick polyvinyl chloride (PVC). The cable is approximately 15.9 mm (0.63 in) in diameter and has a mass of 0.38 kg/m. It is approximately 55 % by mass copper, 27 % jacket, 10 % insulation, and 8 % filler. Using nominal values of the specific heats of these materials, its thermal capacity is calculated to be approximately 0.36 kJ/(K m). The cable referred to as the "thermoset" has cross-linked polyethylene insulation covering its twelve 18 AWG copper conductors. Its jacket is approximately 1.5 mm (0.06 in) thick chlorosulfonated polyethylene (CSPE). The cable is approximately 12.7 mm (0.5 in) in diameter and has a mass of 0.25 kg/m. It is approximately 37 % by mass copper, 33 % jacket, 29 % insulation, and 1 % filler. Its thermal capacity is approximately 0.22 kJ/(K m).

[2] American Wire Gauge

Figure 1 displays the measured[3] temperature of an aluminum rod and two cables cut into 15 cm (6 in) segments when placed in a convection oven whose temperature is set to a nominal value of 300 °C (572 °F). A 3 mm (1/8 in) hole was drilled 7.5 cm (3 in) along the central axis of the aluminum rod and a single thermocouple was inserted within. For the cable segments, a small incision was made in the cable jacket and a single thermocouple was inserted between the conductors approximately halfway along its length. The incision was sealed with noncombustible tape.

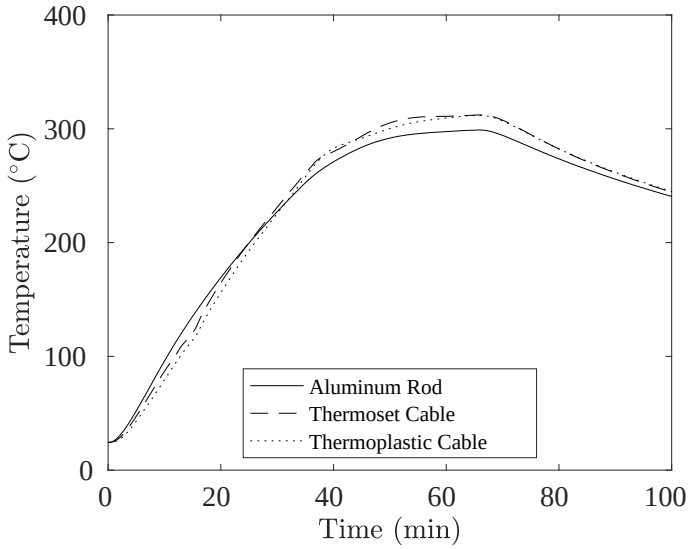


Fig. 1. Measured temperatures of a 13 mm (0.5 in) aluminum rod and two representative cable segments in a convection oven.

The measured temperatures of the rod and cable segments are fairly comparable, suggesting that the aluminum rod mimics the cable segments until the cable polymers begin to pyrolyze at approximately 300 °C. However, in the experiments described below, the temperature of the aluminum rod tended to increase at a slightly faster rate than instrumented cables located at the same location. There are several reasons for this. First, the cables were cut into lengths on the order of 3 m to 4 m (9 ft to 12 ft) and placed in a ladder-back cable tray. Only a small fraction of the cable was exposed to the direct heat of the fire plume, and its copper conductors would have distributed the heat along its entire length. The aluminum rod, on the other hand, is cut to a length of 15 cm; thus, the heat is "trapped" and does not dissipate laterally. Second, the cables were set next to one another in the tray such that some fraction of the surface area would have been shielded from the convective and radiative heating of the fire. The rods were typically more exposed.

Given that the aluminum rods are not perfect surrogates for cables, why use them at all?

[3]Omega Engineering reports that the expanded uncertainty of its Type K thermocouple is ± 0.75 % of the measured absolute temperature.

It is not difficult to affix thermocouples within unenergized cables, and, indeed, this was done as part of the test protocol. The principal reason for the aluminum rods is to facilitate comparisons with numerical models. Regardless of the level of detail in the underlying physics, fire models typically treat a cable as a cylinder that is heated uniformly at the surface and which undergoes one-dimensional heating in the radial direction. There is no lateral heat conduction and typically there are no nearby obstructions. It is certainly possible to model a tray full of cables using a complex three-dimensional heat conduction algorithm, but such a calculation is time-consuming, difficult to embed within existing models, and requires detailed thermo-physical data of all the cables that might be in a given tray. It is far more tractable to perform a simple one-dimensional heat transfer calculation based on computed conditions in the vicinity of the cable tray. The computed surrogate temperatures can also be easily scaled should the actual cables be larger or smaller in diameter to the nominal 13 mm (0.5 in) chosen in this study.

The temperature measurements described in this report are to be used to validate numerical models that will then be used to consider many other enclosure-cable tray configurations that could not be physically tested. The purpose of this modeling is to predict the thermal conditions in the vicinity of equipment surrounding a burning electrical enclosure. The aluminum rods provide a far better “target” with which to assess the model predictions. In essence, the aluminum rod is a device that measures the amount of heat that would be absorbed by an actual cable of comparable diameter. Making this measurement with the cable itself is, ironically, more difficult because of the fact that the cable allows the absorbed heat to be conducted along its length.

3. Circuit Breaker Heat Release Rate Measurements

Four low-voltage circuit breaker enclosures built by ABB, an international manufacturer of electrical equipment, were shipped to the National Fire Research Laboratory (NFRL) at NIST in September 2023. These enclosures were donated by the German nuclear safety organization Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) from a decommissioned nuclear power plant in Germany, and contain low-voltage circuit breakers and various types of panel wires, cables, and instrumentation. One configuration consisted of three vertical sections that were bolted together, as shown in Fig. 2, and one configuration was detached.



Fig. 2. Photograph of the ABB enclosure. The breaker is located in the middle compartment of each vertical column. Wiring and other electrical equipment is located mainly in the compartment above, and the compartment below is largely empty. Each of the three vertical columns is largely the same.

Two additional circuit breaker enclosures, manufactured by Westinghouse, were shipped to NIST in December 2023. Each enclosure houses six low-voltage breakers. One of the enclosures is shown in Fig. 3, where the lowest level breaker has been removed and replaced with a gas burner for the experiment. The uppermost compartment contains wiring and instrumentation.



Fig. 3. Photograph of the Westinghouse enclosure. Each vertical column contains three breakers in the lowest three compartments, with instrumentation in the uppermost compartment. A gas burner has replaced the lowest level breaker in the right vertical column.

3.1. Description of Experiments

For the experiments involving either the ABB or Westinghouse enclosures, one or more circuit breakers with nominal dimensions of 30 cm by 40 cm by 30 cm (12 in by 16 in by 12 in) and masses of approximately 50 kg (110 lb) are the primary combustibles whose non-metallic mass consists of polymeric insulating materials such as glass-polyester and thermoset composite resins. Additionally, plastic wire harnesses, panel wire, and circuit boards are located, typically, in the compartment above the breaker, as seen in Fig. 4. There are, typically, only a few jacketed, multi-conductor cables located within the upper compartment. In these experiments, some cables were added to the upper compartment to make up for those that were removed prior to shipment to NIST.

The compartment below the breaker is largely devoid of combustible materials. No attempt was made to remove and weigh all of the combustible materials because doing so would have potentially changed its burning behavior. However, representative samples of the most common non-metallic components such as wire insulation, switches, and circuit boards were removed prior to the experiments to determine their heat of combustion (see Section 3.2.1). Estimates of the total combustible mass in each compartment were



Fig. 4. Photograph of instrumentation above the breaker. A few cables have been added to replace those removed previously.

then made by dividing the integral of the HRR with time (kJ) by the measured heat of combustion (kJ/kg). These results are presented in Section 3.2.

The breakers were ignited using a nominally 30 cm (12 in) square natural gas burner positioned approximately 20 cm (8 in) beneath the circuit breaker, as shown in Figs. 3 and 5. The burner's HRR[4] was set to approximately 100 kW. After sustained ignition of the circuit breaker was observed, the burner was turned off and the enclosure fire was allowed to continue burning until the measured HRR decreased below 10 kW, at which point the small remaining fires were extinguished.

Sheathed thermocouples[5] were installed approximately 15 cm (6 in) below the ceiling of each compartment to provide a measurement of the gas temperature within. Thermocouples were also embedded within electrical cable segments and aluminum rods (see Section 2) that were placed directly above each circuit breaker. The cable target is a 7-conductor thermoplastic electrical cable segment and the aluminum target is a 6061 alu-

[4]The relative expanded uncertainty (95 % confidence interval) of the HRR measurement under the hood used in these experiments is 4 % for natural gas and 7 % for "generic combustibles" [9].

[5]Type K, sheath diameter 3 mm (1/8 in), expanded uncertainty ± 0.75 % of the measured absolute temperature.



Fig. 5. Position of the burner under the breaker in Test 34.

minum alloy rod, both approximately 15 cm (6 in) in length and 13 mm (0.5 in) in diameter. Throughout this report, these surrogate targets are referred to as slug calorimeters, or simply "slugs," a term commonly used in the fire science community to describe objects such as these.

Photographs of the enclosures used in this project are shown in Figs. 2 and 3. Each enclosure is approximately 2.2 m (87 in) tall, 0.4 m (16 in) wide, and 1.0 m (40 in) deep. Some of the enclosures have ventilation panels near the top and bottom, and all have seams and small openings to accommodate wiring, bus bars, door panels, and so on. No attempt was made to seal these various gaps and openings except in Experiment 34 where a burned out instrument panel was covered by a steel plate, and in Experiment 35, where a hole in the top of the enclosure was covered by a steel plate.

3.2. Experimental Results

The measurements of the HRR of the breakers were made in October of 2023 and January of 2024. Nominal results are listed in Table 1 and details can be found on the following pages. For each experiment, the nominally 100 kW natural gas burner was sustained until it appeared that the breaker had begun to burn. For the first two experiments, the burner was sustained longer than necessary, as evidenced by Exp. 35 where the breaker was able

to sustain a fire after four minutes of exposure from the burner.

Overall, the breakers within the ABB enclosures sustained a fire beyond the time when the burner was extinguished. However, the Westinghouse breakers did not appear to burn without the aid of the gas burner, even though, after the experiment, the non-metallic materials within the breaker clearly showed evidence of having pyrolized. In short, the pyrolysis was not followed by flaming combustion.

The "Peak HRR" in Table 1 indicates the maximum value of the HRR of the enclosure contents; that is the total HRR minus that of the natural gas burner. The "Total HR" (Total Heat Release) is the total energy released less the burner's energy; that is, the energy of the contents alone. The "Mass Consumed" is the Total HR divided by an estimated[6] heat of combustion of 20 MJ/kg for the combustible materials within the enclosure. The peak "slug" and gas temperatures are comparable and represent uniform conditions within the burning breaker and instrument compartments.

Table 1. Summary of Experimental Results. The uncertainty of the HRR is ± 7 %. The uncertainty of the temperature is ± 0.75 % of its absolute value. The listed times are rounded to the nearest minute.

Exp. No.	Make	Peak HRR [kW]	Total HR [MJ]	Mass Consumed [kg]	Time to Peak [min]	Burner Duration [min]	Peak Slug Temp. [°C]	Peak Gas Temp. [°C]
33	ABB	250	387	19.4±4.9	11	10	770	860
34	ABB	140	192	9.6±2.4	9	8	680	700
35	ABB	200	230	11.5±2.9	20	4	680	670
40	West.	30	60	3.0±0.8	28	60	160	650
41	West.	100	280	14.0±3.5	40	60	150	700

The breaker that was burned in Exp. 35 was weighed before and after the experiment. Its original mass was 47.8 kg and its final mass was 44.1 kg. The uncertainty of the load cell is approximately 1 g, which is far exceeded by the uncertainty due to extracting the burned breaker from the enclosure and separating out materials that were or were not part of the original breaker. Thus, the estimated combustible mass of the breaker is taken as 3.7 kg $\pm$ 0.1 kg.

Using the measured mass loss of the breaker and the estimates of the mass consumed in the three experiments, it is possible to estimate the distribution of combustible mass in the lower, middle, and upper compartments of the enclosure. In Exp. 33, the fire consumed the contents of a lower, middle and three upper compartments. In Exp. 34, the fire consumed

[6] The uncertainty of the estimated heat of combustion is difficult to quantify. The estimated value of 20 MJ/kg $\pm$5 MJ/kg is merely the average heat of combustion, ΔH_c, measured for various plastics found within the enclosure (weighted to account for the greater mass of combustible solids contained within the circuit breaker itself, which had relatively low ΔH_c; see Sec. 3.2.1).

a lower and middle compartment. In Exp. 35, the fire consumed a lower, middle, and upper compartment. Taking the combustible load of the middle compartment to be 3.7 kg, the estimated mass loss of the breaker, a least squares regression yields an estimate of 3.5 kg for the lower compartment and 2.7 kg for the upper. The 3.5 kg estimate for the lower compartment can be taken as all of the combustibles in the lower and middle compartment minus the breaker itself. These estimated combustible loads fall well within the uncertainty bounds for the total mass consumption listed in Table 1.

The HRR of a fire contained within a single compartment is limited by the air supplied through openings in the back and side of the enclosure and the opening in the front door of the compartment that is created when the instrument panel melts/burns away. For the enclosures tested, this opening is approximately 15 cm (6 in) wide by 30 cm (12 in) tall. A useful correlation [10] used in compartment fire modeling states that air is entrained into a flashed over compartment at a rate given by

$$\dot{m}_{\mathrm{a}} = 0.5 A \sqrt{H} \approx 0.0123 \text{ kg/s} \tag{1}$$

where H is the opening height (0.3 m) and A is the opening area (0.045 m^2). With this estimate, the HRR can be estimated

$$\dot{Q} = Y_{\mathrm{O}_2,\infty} E \dot{m}_{\mathrm{a}} \approx 37 \text{ kW} \tag{2}$$

where $Y_{\mathrm{O}_2,\infty} \approx 0.23$ is the oxygen mass fraction of air and $E \approx 13\,100$ kJ/kg is the approximate amount of energy released per unit mass of oxygen consumed.

Evidence for the estimated HRR associated with the opening of the instrument panel can be seen in Exp. 35 where the upper compartment opens up at approximately 19 min, at which time the HRR increases rapidly by approximately 40 kW. The increased ventilation through the front door adds to the existing ventilation through the back of the enclosure. Collectively, these openings supply the air needed to support an HRR of approximately 100 kW per compartment.

3.2.1. Material Property Measurements

Material samples were taken from the various circuit breakers to better understand their burning behavior using a Microscale Combustion Calorimeter[7] (MCC), an apparatus in which a specimen of known mass is thermally decomposed in nitrogen at a constant heating rate and then burned in oxygen to determine its heat of combustion. Samples were not identified by a specific material type (e.g., composition, and/or manufacturer/distributor name), rather they are labeled in series (No. 1 to No. 10) to correspond to each of the items identified in Fig. 6.

[7] This MCC used in this work was a Deatak MCC-3 equipped with a paramagnetic oxygen sensor and calibrated according to ASTM D7309 [11]

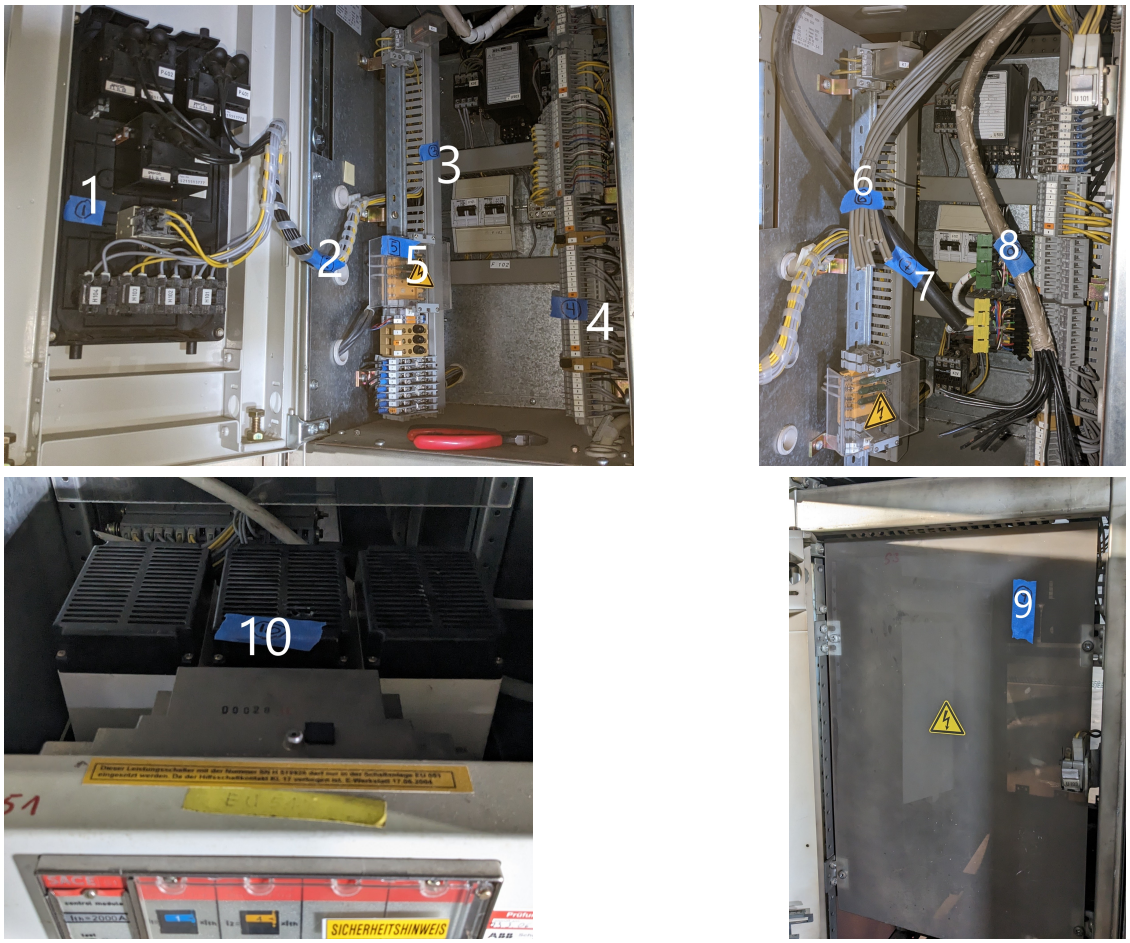


Fig. 6. Photographs of each of the ten components selected for MCC measurements.

MCC experiments were conducted in December, 2023. The material samples were subjected to a 80 mL/min nitrogen stream starting at a temperature of 75 °C, increasing linearly to 750 °C at a heating rate of 60 K/min. The pyrolyzed gases were combusted in an oxygen stream of 20 mL/min. Tests were repeated at least three times for each material. Nominal results are listed in Table 2. The mass-weighted average heat of combustion of the materials tested is approximately 20 MJ/kg. Also reported in this table are the onset temperature and Fire Growth Capacity, FGC. The FGC is a physically-based parameter for early stage fire growth, derived from a simple burning model, that has been shown to rank commercial materials according to their behavior in bench scale flame and fire tests [12]. The onset temperature is approximated by the temperature at which 5 % of total heat release is measured, consistent with the definition of the FGC. Details of these calculations are provided elsewhere [12, 13].

Table 2. MCC Measurements. The relative expanded uncertainty in the reported Heat of Combustion is approximately 6 % of the measured value. The primary components of this uncertainty estimate include: (1) the relative expanded uncertainty of the heat released per unit mass of oxygen consumed, 5 % [14]; (2) the relative expanded uncertainty of the system flow rate, 2 %; and (3) test repeatability, 2 % or 2 standard deviations of replicate measurements. The relative expanded uncertainty in the solid residue yield is 2 %, primarily due to stochastic variations in values measured in repeated tests. The expanded uncertainty of the temperature measurements is ± 0.75 % of the measured absolute value.

Matl. No.	Heat of Combustion (kJ/g)	Solid Residue Yield (g/g)	Onset Temperature (°C)	Fire Growth Capacity (FGC) (J/(g K))
3	13.9	0.29	315[a]	80
4	30.8	0.02	388	376
5	25.7	0.00	354	465
6	28.3	0.10		
7	22.1	0.40	248	111
8	9.6	0.02	257	78
9	27.1	0.24	507	310
10	17.9	0.57	204	67

[a] Material 3 decomposes through a multi-step reaction, approximately 10% of total heat release occurs in reaction step 1; onset temperature of second main reaction step is approximately 425 °C.

3.2.2. Experiment 33

The HRR and gas/target temperatures are shown in Fig. 7. Referring to the photographs shown in Fig. 8, the natural gas burner was positioned near the top of the lower left compartment of the enclosure, approximately 20 cm (8 in) below the breaker located in the middle left compartment. The fire ignited the breaker after approximately 2 min and then spread to the compartment above. The fire then spread to the two adjacent compartments along the top of the enclosure. The gas temperatures shown in Fig. 7 indicate that the fire spread from one compartment to the next in approximately 10 min. The compartments are separated by two steel walls.

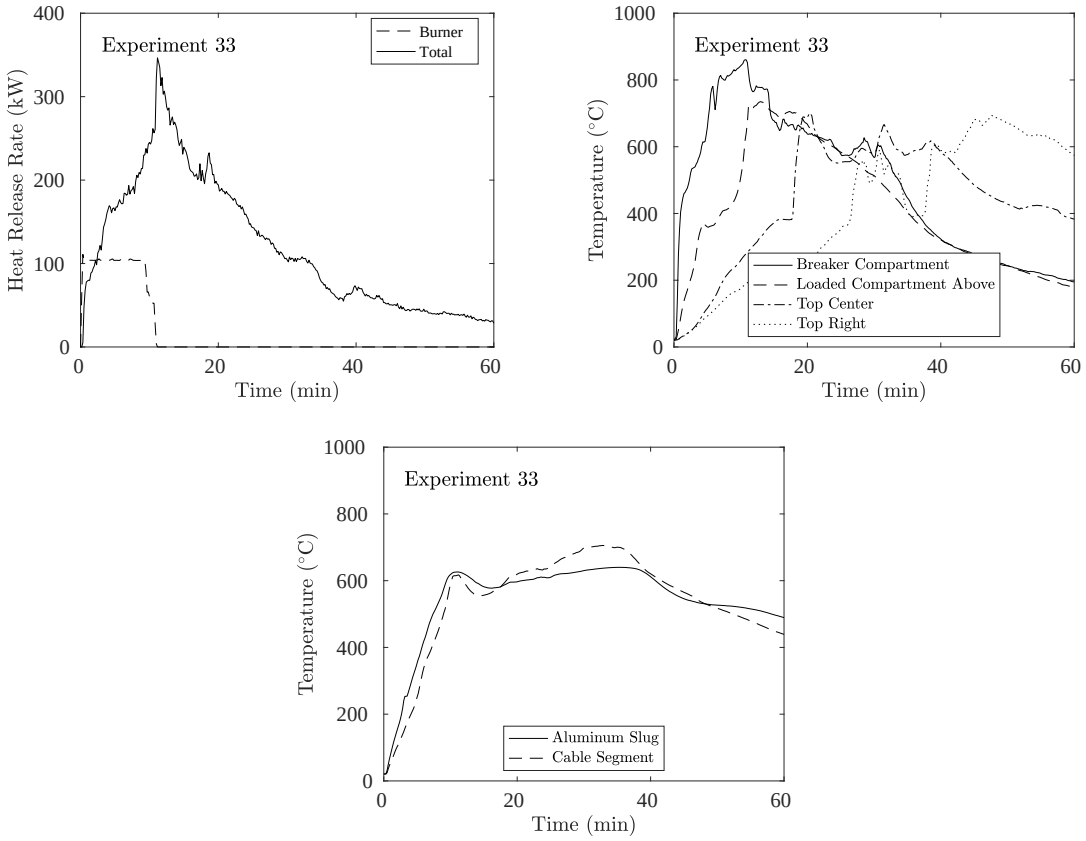


Fig. 7. Heat release rate (upper left), gas temperatures (upper right), and slug/cable temperatures (bottom) for Exp. 33. The curve labeled “Burner” in the upper left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry. The gas temperatures were recorded near the ceiling of the middle left compartment housing the breaker (“Breaker Compartment”), the upper left compartment housing miscellaneous wiring and plastics (”Loaded Compartment Above”), and the upper central and upper right compartments housing similar materials (“Top Center” and “Top Right”). In the bottom plot, the “Aluminum Slug” and thermoplastic “Cable Segment” were placed atop the breaker.

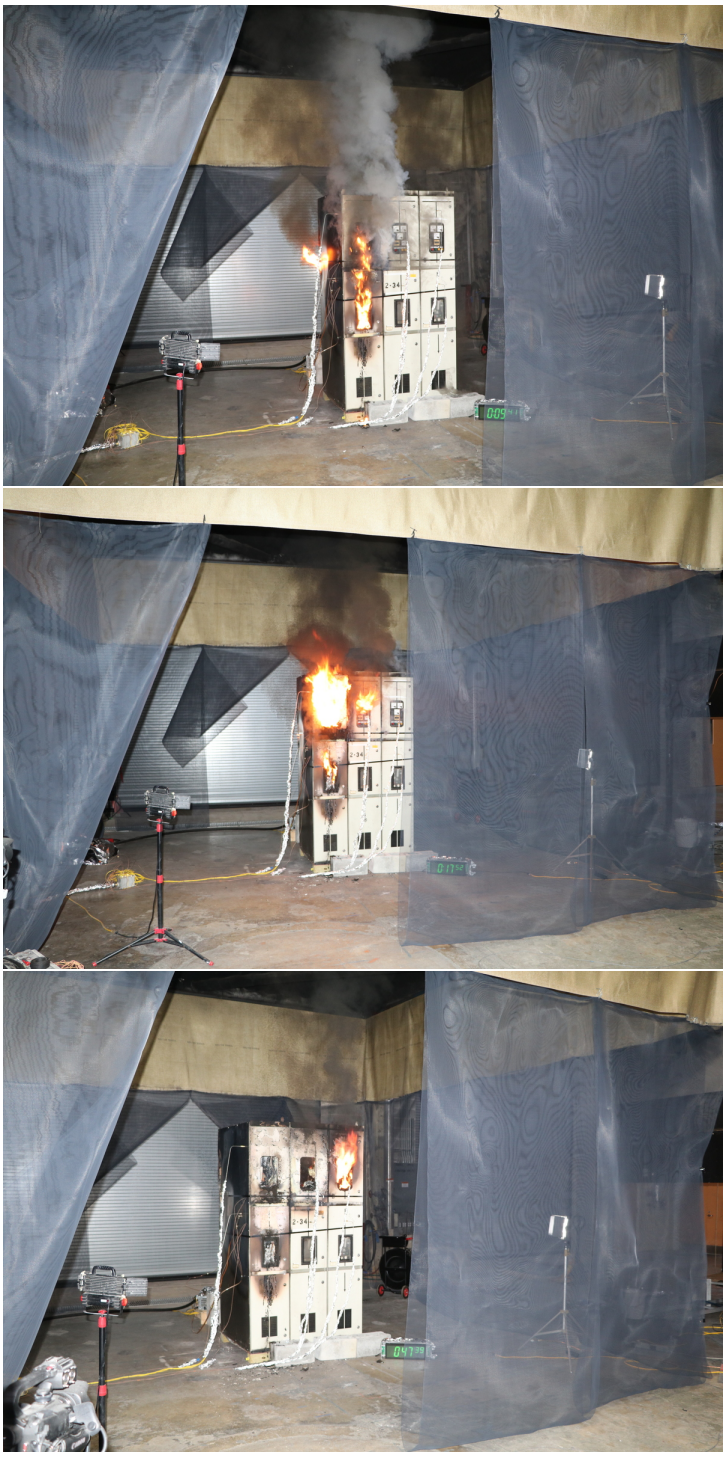


Fig. 8. Photographs of Experiment 33, 9 min, 17 min, and 47 min (top to bottom) after ignition of the burner which was located in the lower left compartment.

3.2.3. Experiment 34

The fire in Exp. 33 consumed all of the combustibles in the upper compartments of the large enclosure. However, the breakers in the center and right columns remained intact. For Exp. 34, the burner was placed beneath the breaker on the right side of the enclosure (see Fig. 10) with the aim of measuring its HRR with no combustibles in the compartment above. The gas temperature in the compartment above reaches only approximately 400 °C because there is no significant fire in this compartment, only the heat from the fire below.

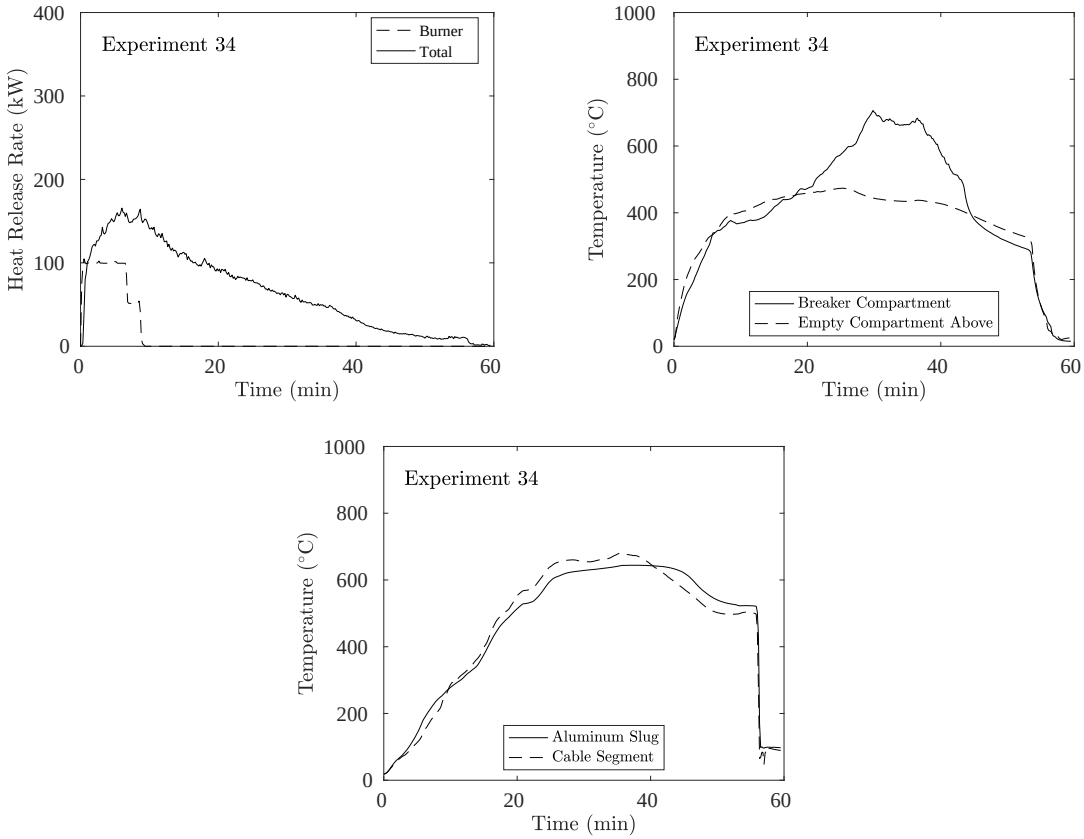


Fig. 9. Heat release rate (upper left), gas temperatures (upper right), and slug/cable temperatures (bottom) for Exp. 34. The curve labeled “Burner” in the upper left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry. The gas temperatures were recorded near the ceiling of the middle right compartment housing the breaker (“Breaker Compartment”), and the upper right compartment with the burned out remnants from Experiment 33 (”Empty Compartment Above”). In the bottom plot, the “Aluminum Slug” and thermoplastic “Cable Segment” were placed atop the breaker.

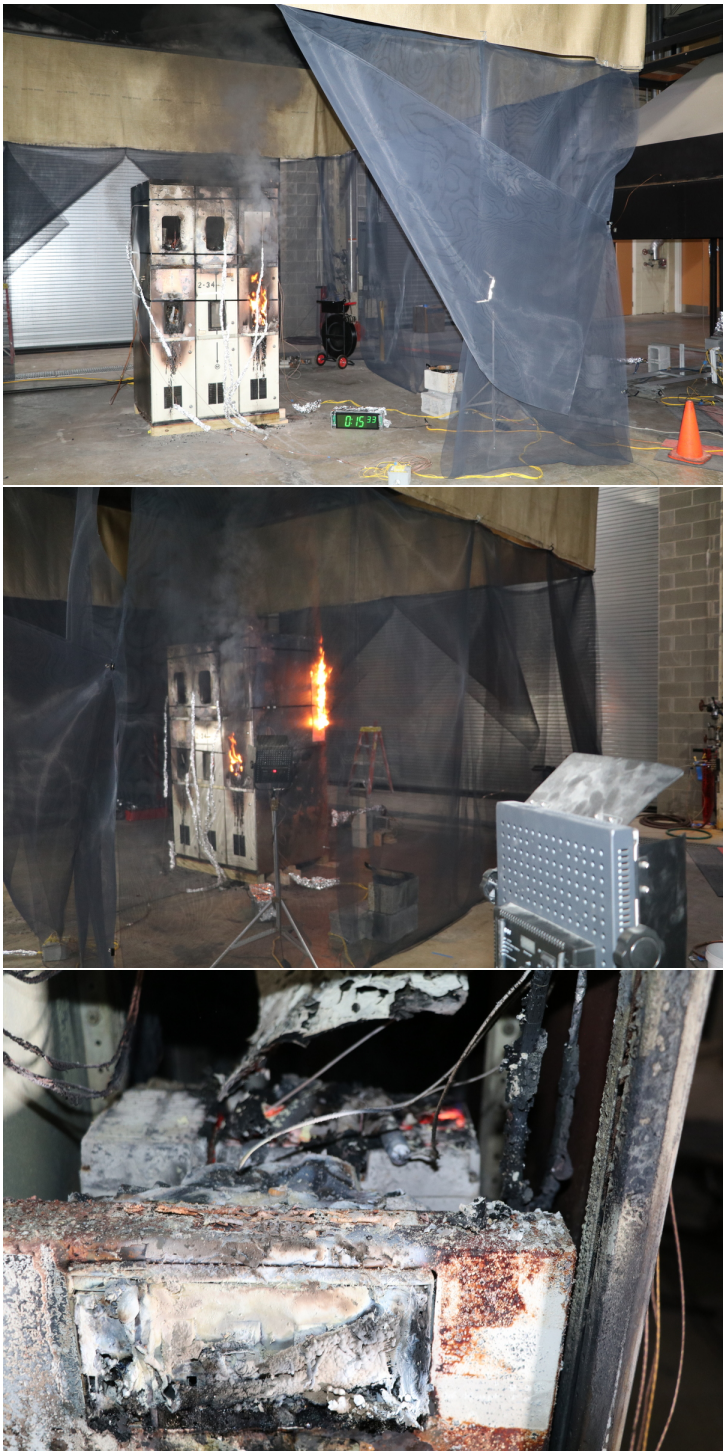


Fig. 10. Photographs of Exp. 34, 15 min, 30 min, and 60 min (top to bottom) after ignition of the burner which was located in the lower right compartment. The bottom photograph shows the breaker after the experiment continues to glow red due to the heat trapped within.

3.2.4. Experiment 35

Figure 11 displays the HRR and gas/target temperatures for Exp. 35. Referring to Fig. 12, this experiment was conducted within the single-column ABB breaker enclosure, where the burner was positioned as in the previous experiments. The breaker ignited within 4 min at which time the burner was turned off. The total HRR dropped to about 50 kW at this time and then slowly increased as the fire spread from the breaker to the compartment above after approximately 18 min from the start of the experiment.

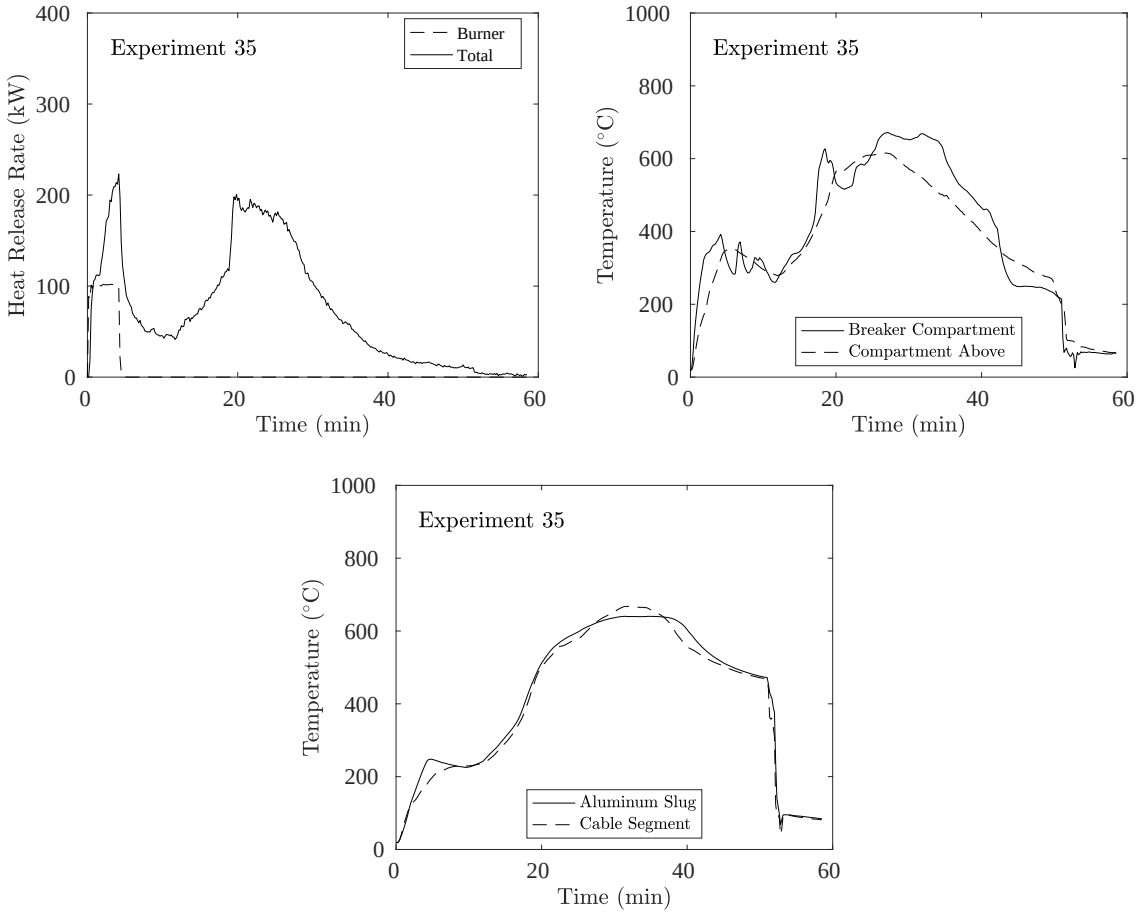


Fig. 11. Heat release rate (upper left), gas temperatures (upper right), and slug/cable temperatures (bottom) for Exp. 35. The curve labeled “Burner” in the upper left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry. The gas temperatures were recorded near the ceiling of the middle compartment housing the breaker (“Breaker Compartment”), and the upper compartment filled with miscellaneous wiring and plastics (”Compartment Above”). In the bottom plot, the “Aluminum Slug” and thermoplastic “Cable Segment” were placed atop the breaker.

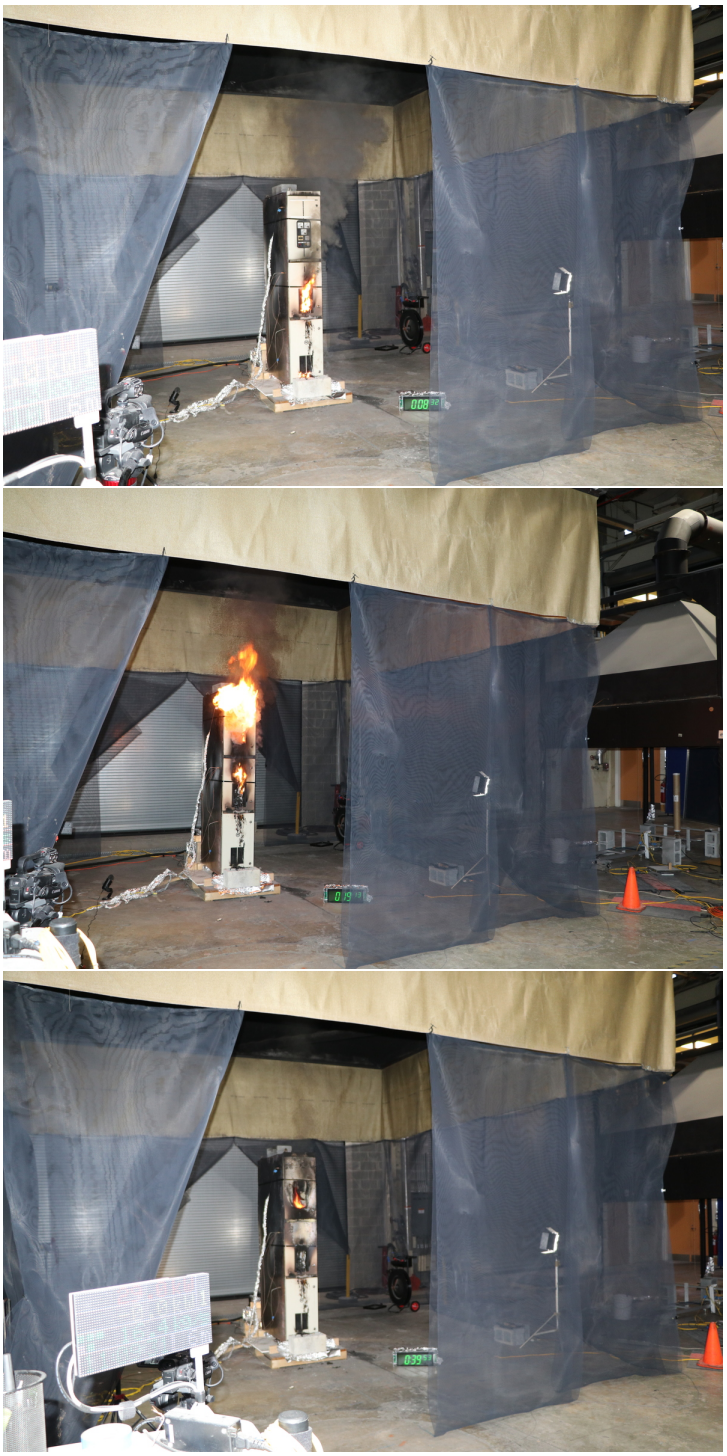


Fig. 12. Photographs of Exp. 35, 8 min, 19 min, and 39 min (top to bottom) after ignition of the burner which was located in the lower compartment.

3.2.5. Experiment 40

Figure 13 displays the HRR and key temperatures of Experiment 40. Referring to Fig. 14, the gas burner was positioned within the lower right compartment of a Westinghouse low-voltage breaker enclosure. Breakers occupied the two compartments above, and the compartment above that was filled with approximately 0.8 kg of panel wire. A 30 cm (12 in) wide tray containing 12 thermoplastic cables was placed approximately 30 cm (12 in) above the top of the enclosure. Thermocouples were inserted into three cables within the tray, and instrumented aluminum rods ("slugs") were placed alongside the instrumented cables. A single sheathed thermocouple was placed at the front of each compartment. All doors on the left side of the enclosure remained closed during the experiment except the one containing the burner.

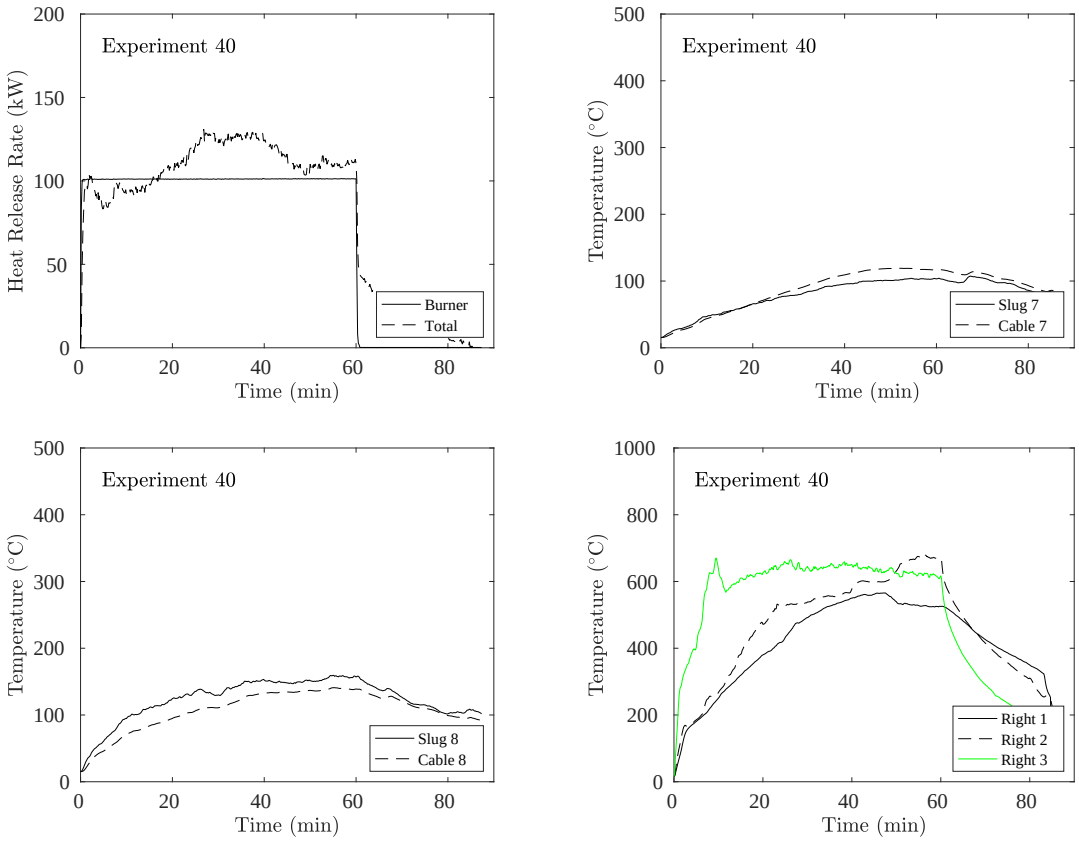


Fig. 13. The curve labeled "Burner" in the upper left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry. The curves labeled "Slug X" and "Cable X" are temperatures of cables and aluminum rods (slugs) in the cable tray above the enclosure. All were placed above the location of the fire, but those labeled with a 7 were to the rear of the tray; 8 to the front. The gas temperatures shown in the lower right plot refer to the lower breaker compartment ("Right 3"), upper breaker ("Right 2"), and top compartment with panel wire ("Right 1").



Fig. 14. Photographs of Experiment 40. (Top) The burner in position below the breaker. (Middle) The fire at 7 min, 26 s after ignition. (Bottom) The breaker after the experiment.

3.2.6. Experiment 41

Figure 15 displays the HRR and key temperatures of Experiment 41. Referring to Fig. 16, the gas burner was positioned within the lower left compartment of a Westinghouse low-voltage breaker enclosure. Breakers occupied the two compartments above, and the compartment above that was filled with approximately 1.0 kg of panel wire. A 30 cm (12 in) wide tray containing 12 thermoplastic cables was placed approximately 30 cm (12 in) above the top of the enclosure. Thermocouples were inserted into three cables within the tray, and instrumented aluminum rods ("slugs") were placed alongside the instrumented cables. A single sheathed thermocouple was placed at the front of each compartment. All doors on the left side of the enclosure remained open during the experiment.

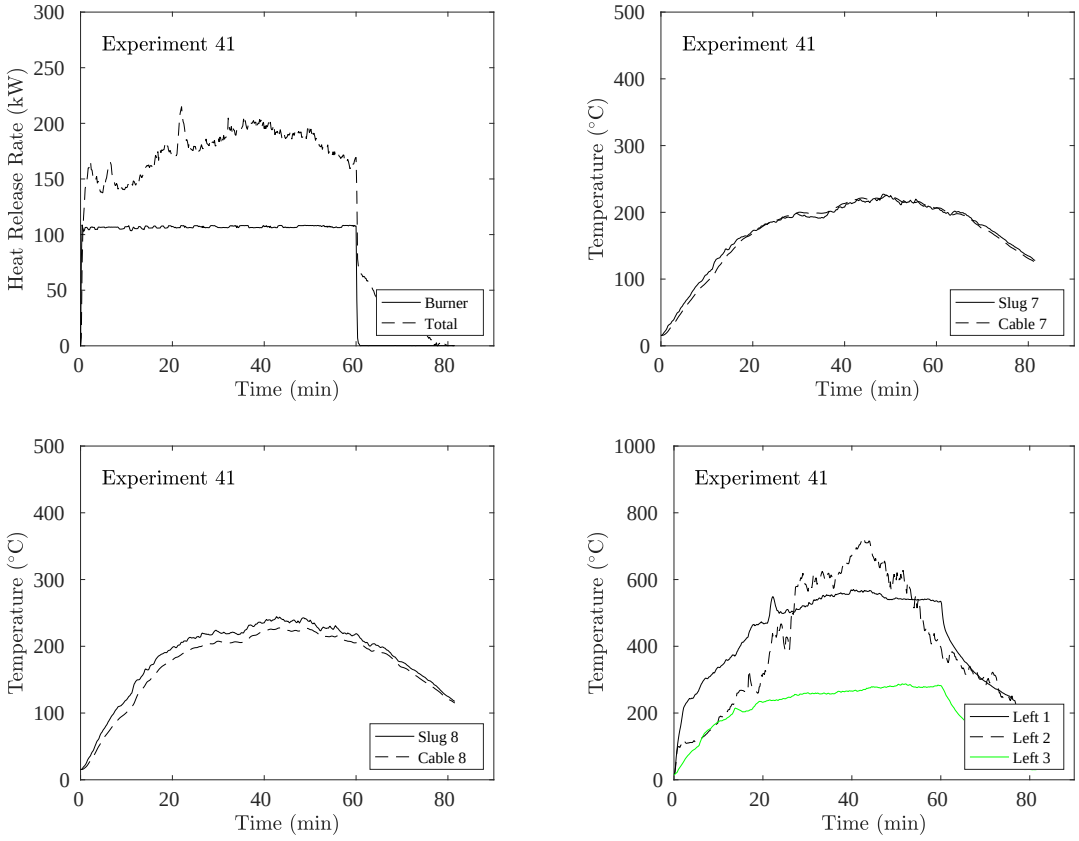


Fig. 15. The curve labeled "Burner" in the upper left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry. The curves labeled "Slug X" and "Cable X" are temperatures of cables and aluminum rods (slugs) in the cable tray above the enclosure. All were placed above the location of the fire, but those labeled with a 7 were to the rear of the tray; 8 to the front. The gas temperatures shown in the lower right plot refer to the lower breaker compartment ("Left 3"), upper breaker ("Left 2"), and top compartment with panel wire ("Left 1").



Fig. 16. Photographs of Experiment 41. The top photograph shows the fire at 5 min, 20 s. The middle photograph shows the material burning in the uppermost compartment at 21 min, 22 s. The bottom photograph shows burning plastic insulation material at the rear of the enclosure after the fires in the front compartments had largely burnt out.

4. Thermal Exposure of Cables Above a Burning Electrical Enclosure

Three types of experiments were conducted to assess the thermal exposure of electrical cables above a burning enclosure:

1. Single trays of cables were positioned above a gas burner.
2. Plume temperatures were measured above vents in a burning electrical enclosure.
3. Cable trays were exposed to fire plumes above burning enclosures.

Two types of cables were used in these experiments. The one referred to as the "thermoplastic" cable has polyethylene insulation covering its seven 12 AWG[8] copper conductors. Its jacket is approximately 1.9 mm thick polyvinyl chloride (PVC). The cable is approximately 15.9 mm (0.63 in) in diameter and has a mass of 0.38 kg/m. It is approximately 55 % by mass copper, 27 % jacket, 10 % insulation, and 8 % filler; its thermal capacity is approximately 0.36 kJ/(K m).

The cable referred to as the "thermoset" has cross-linked polyethylene insulation covering its twelve 18 AWG copper conductors. Its jacket is approximately 1.5 mm thick chlorosulfonated polyethylene (CSPE). The cable is approximately 12.7 mm (0.5 in) in diameter and has a mass of 0.25 kg/m. It is approximately 37 % by mass copper, 33 % jacket, 29 % insulation, and 1 % filler; its thermal capacity is approximately 0.22 kJ/(K m).

4.1. Single Tray Ignition Study

In these experiments, a single 45 cm (18 in) wide tray containing either thermoplastic or thermoset cables was positioned above a nominally 30 cm (12 in) square natural gas burner with an HRR of approximately 40 kW. Some of the cables had Type-K thermocouple embedded with an aluminum rod ("slug") positioned alongside. The purpose of the experiments was two-fold: (1) to provide measurements of internal cable temperature and ignition time, and (2) to assess the use of the aluminum slugs as a surrogate for actual cables in testing of this sort.

[8] American Wire Gauge

4.1.1. Experiment 36

A nominally 45 cm (18 in) wide tray containing 13 thermoplastic cables was placed approximately 36 cm (14 in) above a nominally 30 cm square 40 kW natural gas burner. Thermocouples were inserted into the center of three cables above the burner, and instrumented aluminum rods ("slugs") were placed alongside the instrumented cables. The figures below show the HRR of the gas burner and the total HRR of the burner and cables, along with the internal temperatures of the cables and slugs. The cable ignited at approximately 3 min.

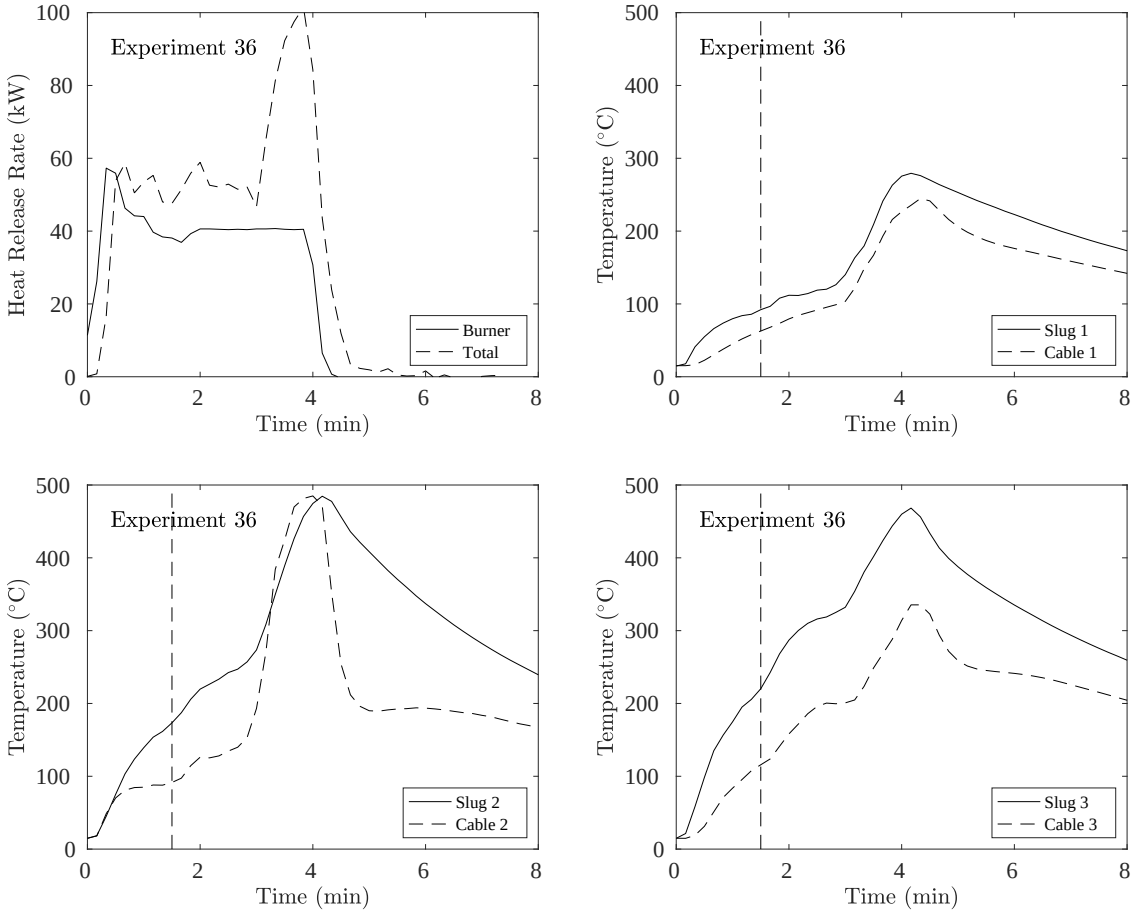


Fig. 17. Heat release rate (upper left) and internal cable and slug temperatures above a 40 kW burner. The curve labeled "Burner" in the upper left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry. The vertical dashed line indicates cable ignition.



Fig. 18. Photographs of Experiment 36. The opt photograph shows the arrangement of cables and instrumentation. The middle photograph shows the fire just at the point of cable ignition. The bottom photograph shows the burning cables at approximately the same time.

4.1.2. Experiment 37

A nominally 45 cm (18 in) wide tray containing 13 thermoplastic cables was placed approximately 56 cm (22 in) above a nominally 30 cm square 40 kW natural gas burner. Thermocouples were inserted into three cables above the burner, and instrumented aluminum rods ("slugs") were placed alongside the instrumented cables. The figures below show the HRR of the gas burner and the total HRR of the burner and cables, along with the internal temperatures of the cables and slugs. The cables ignited at approximately 4 min.

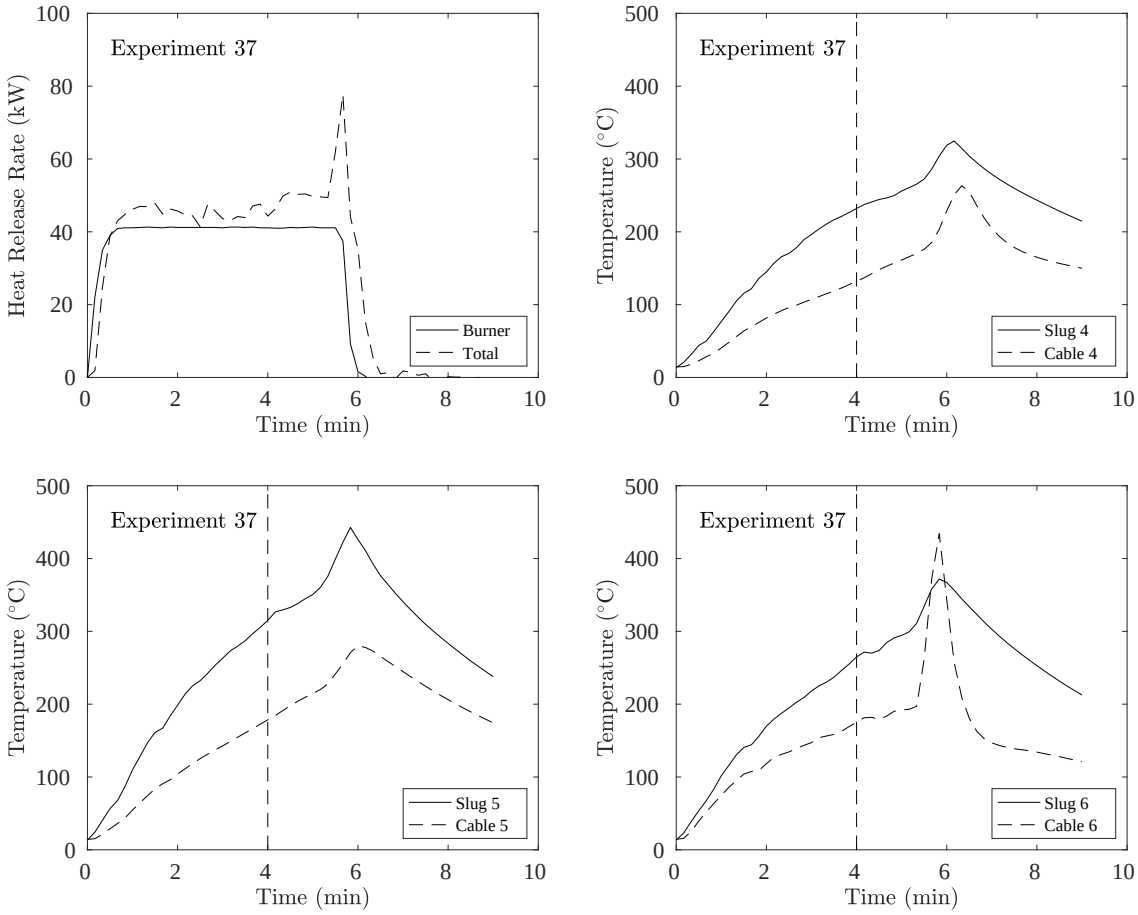


Fig. 19. Heat release rate (upper left) and internal cable and slug temperatures above a 40 kW burner. The curve labeled "Burner" in the upper left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry. The vertical dashed line indicates cable ignition.

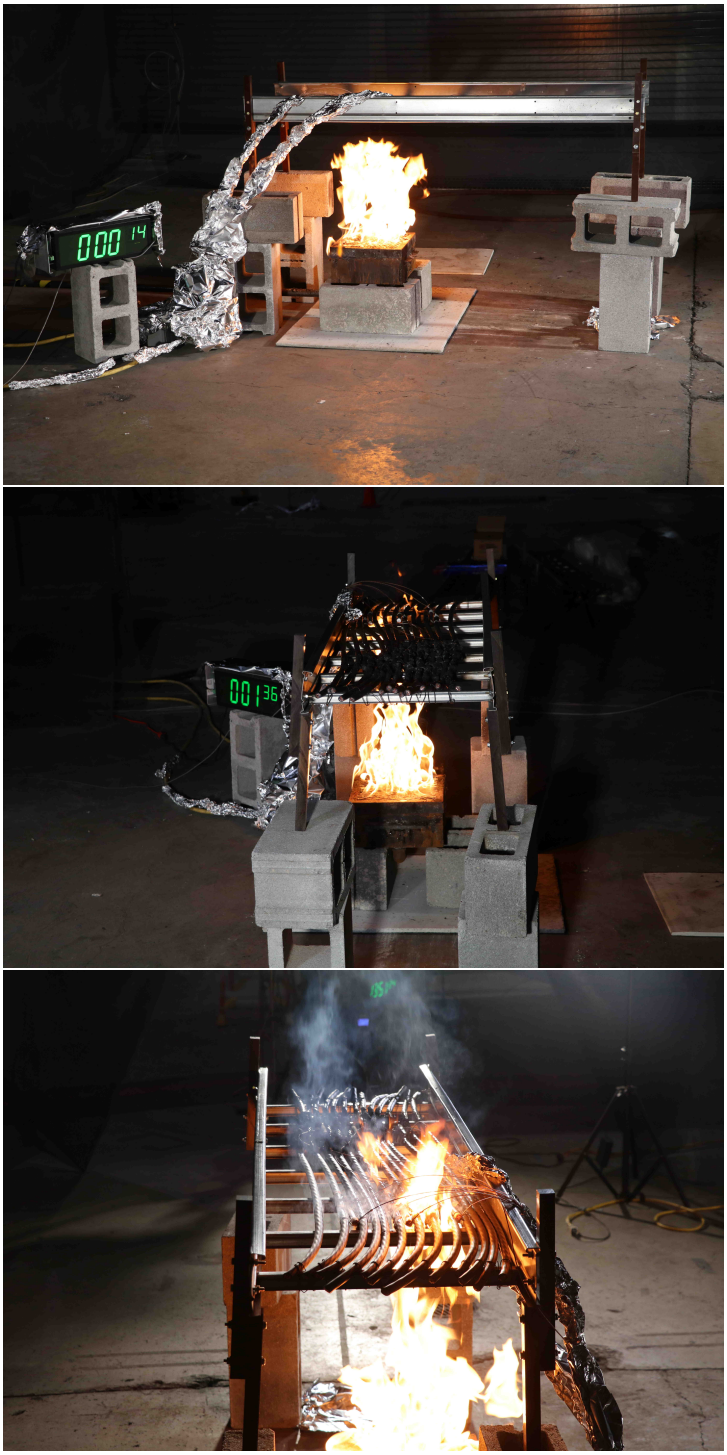


Fig. 20. Photographs of Experiment 37. The top photograph shows the fire 14 s after the burner was ignited. The middle photograph shows the fire at 1 min, 36 s. The bottom photograph shows the cables igniting at approximately 4 min.

4.1.3. Experiment 38

A nominally 45 cm (18 in) wide tray containing 12 thermoset cables was placed approximately 56 cm (22 in) above a nominally 30 cm square 40 kW natural gas burner. Thermocouples were inserted into three cables above the burner, and instrumented aluminum rods ("slugs") were placed alongside the instrumented cables. The figures below show the HRR of the gas burner and the total HRR of the burner and cables, along with the internal temperatures of the cables and slugs. The cables did not ignite.

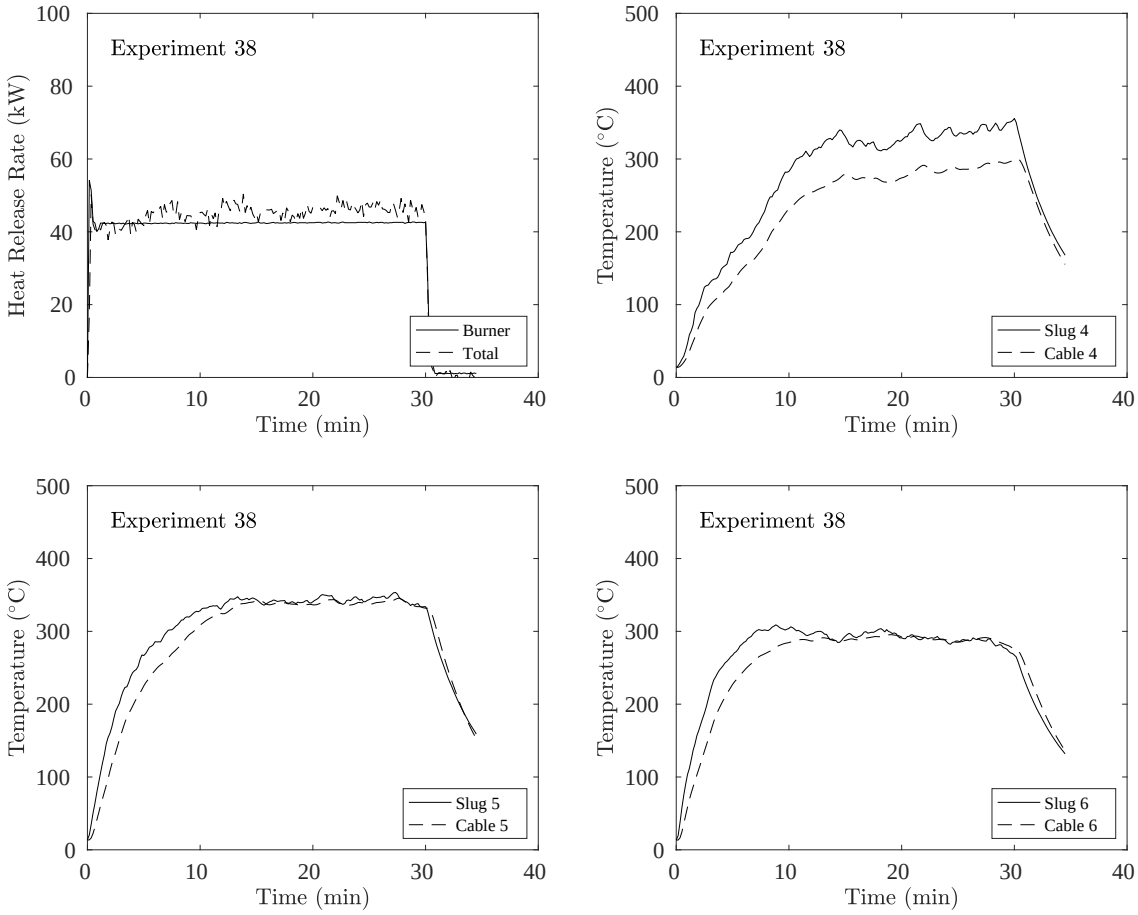


Fig. 21. Heat release rate (upper left) and internal cable and slug temperatures above a 40 kW burner. The curve labeled "Burner" in the upper left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.

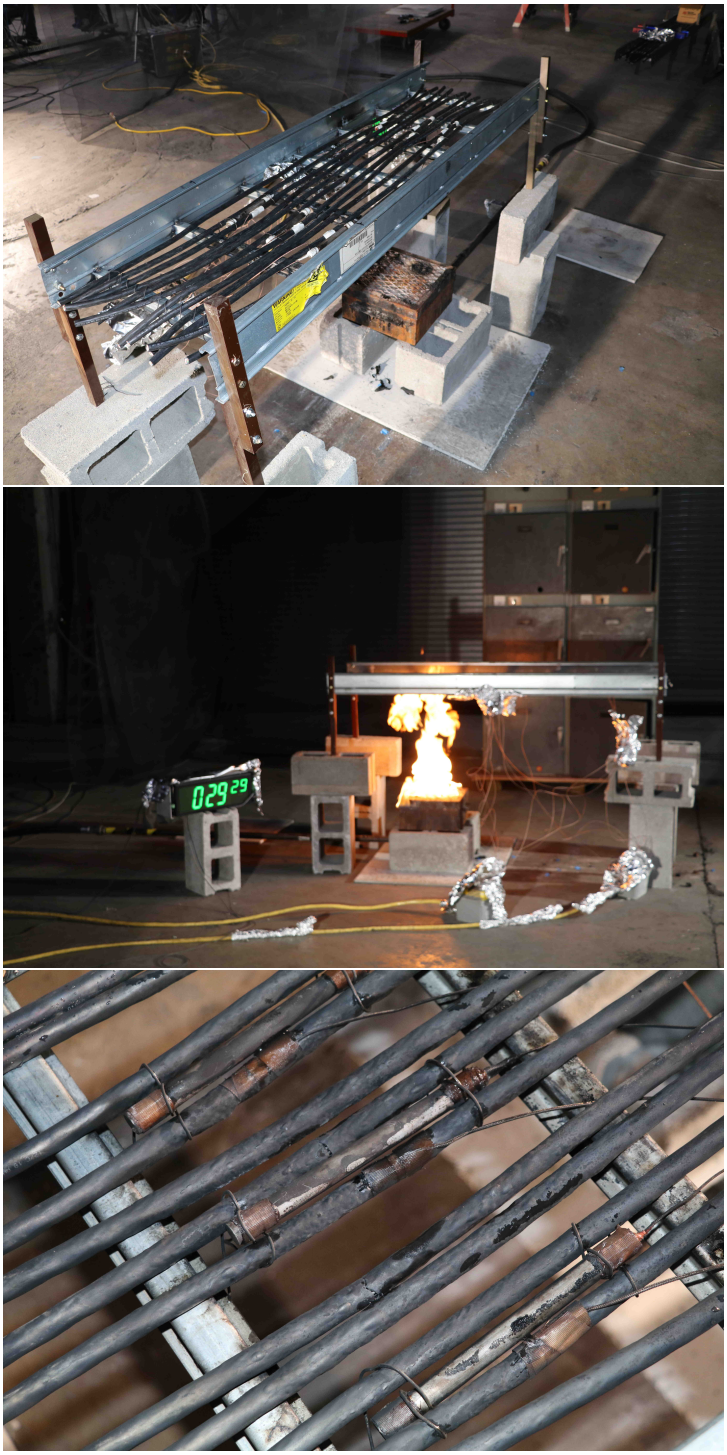


Fig. 22. Photographs of Experiment 38. The top photograph shows the cable trays elevated an extra 20 cm (8 in) on cement blocks. The middle photograph shows the fire at 29 min, 29 s. The bottom photograph shows the scorched cable jackets. The cables did not ignite.

4.1.4. Experiment 39

A nominally 45 cm (18 in) wide tray containing 12 thermoset cables was placed approximately 36 cm (14 in) above a nominally 30 cm square 40 kW natural gas burner. Thermocouples were inserted into three cables above the burner, and instrumented aluminum rods ("slugs") were placed alongside the instrumented cables. The figures below show the HRR of the gas burner and the total HRR of the burner and cables, along with the internal temperatures of the cables and slugs. The cables ignited at approximately 1 min, 10 s.

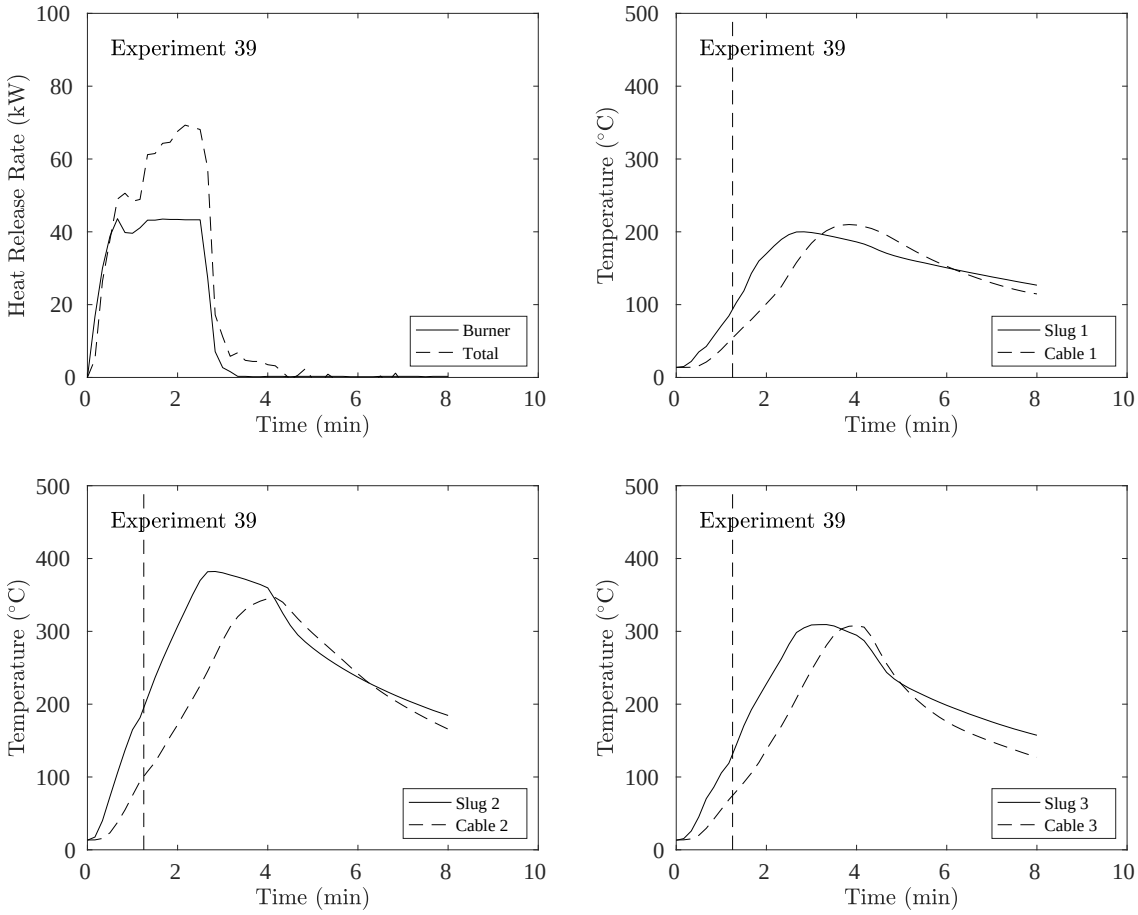


Fig. 23. Heat release rate (upper left) and internal cable and slug temperatures above a 40 kW burner. The curve labeled "Burner" in the upper left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry. The vertical dashed line indicates cable ignition.

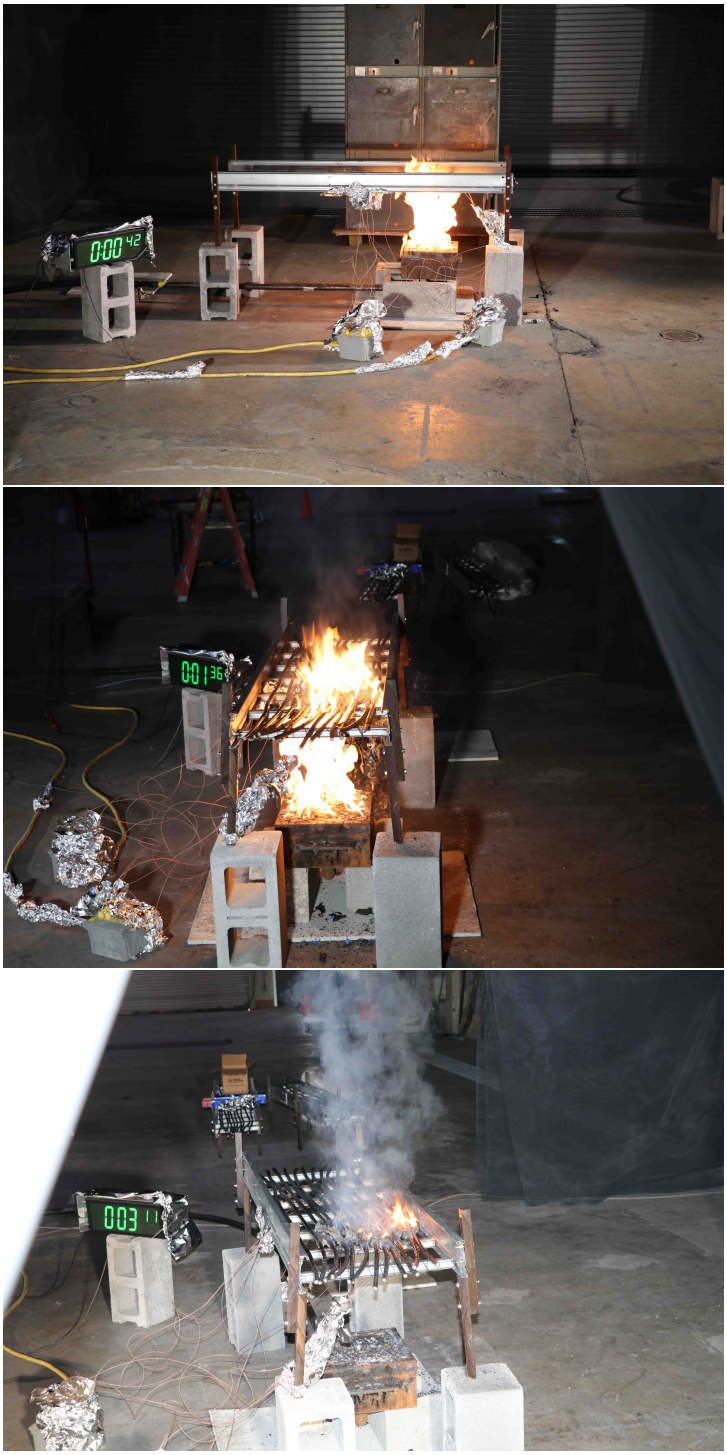


Fig. 24. Photographs of Experiment 39. The top photograph shows the fire impinging on the cables. The middle photograph shows the burning cables just after ignition. The bottom photograph shows the cables a few minutes after ignition and just before self-extinguishing.

4.1.5. Experiment 45

A nominally 45 cm (18 in) wide tray containing 34 thermoset cables was placed approximately 36 cm (14 in) above a nominally 30 cm square 40 kW natural gas burner. Thermocouples were inserted into two cables above the burner, and instrumented aluminum rods ("slugs") were placed alongside the instrumented cables. The figures below show the HRR of the gas burner and the total HRR of the burner and cables, along with the internal temperatures of the cables and slugs. A small flame appeared in one location above the layer of cables at about 50 min, but the flame did not spread or lead to a wider, sustained ignition. Even though the cables did not fully ignite after an exposure of 1 h, but there was extensive damage and exposure of the copper wires.

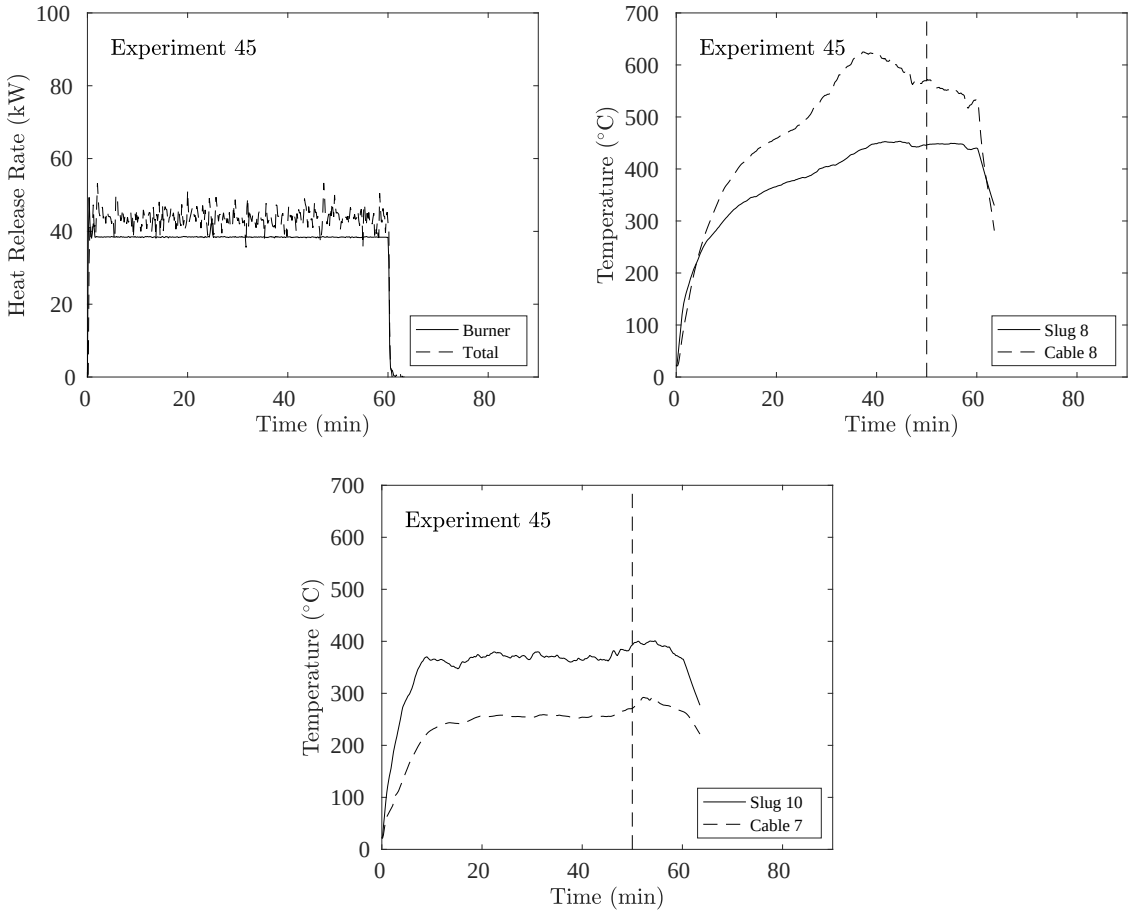


Fig. 25. Heat release rate (upper left) and internal cable and slug temperatures above a 40 kW burner. The curve labeled "Burner" in the upper left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry. The vertical dashed line indicates cable ignition.



Fig. 26. Photographs of Experiment 45. The top photograph shows the initial cable layer and instrumentation. The middle photograph shows the fire at 42 min, 46 s. The bottom photograph shows the damaged cables.

4.1.6. Experiment 46

This experiment is similar to Exp. 45 except that every seventh cable has been removed, leaving 30 rather than 34 across the width of the tray. The figures below show the HRR of the gas burner and the total HRR of the burner and cables, along with the internal temperatures of the cables and slugs. The cables ignite at approximately 12 min.

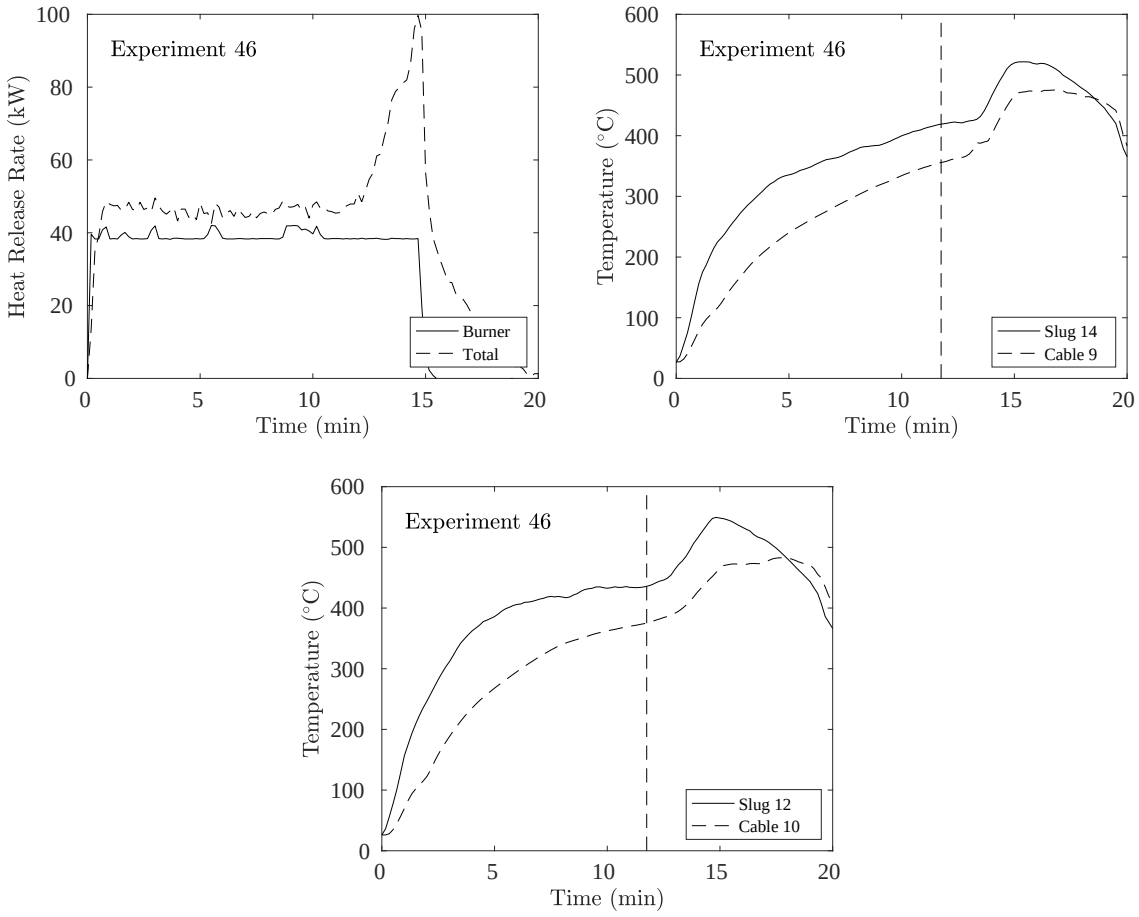


Fig. 27. Heat release rate (upper left) and internal cable and slug temperatures above a 40 kW burner. The curve labeled “Burner” in the upper left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry. The vertical dashed line indicates cable ignition.

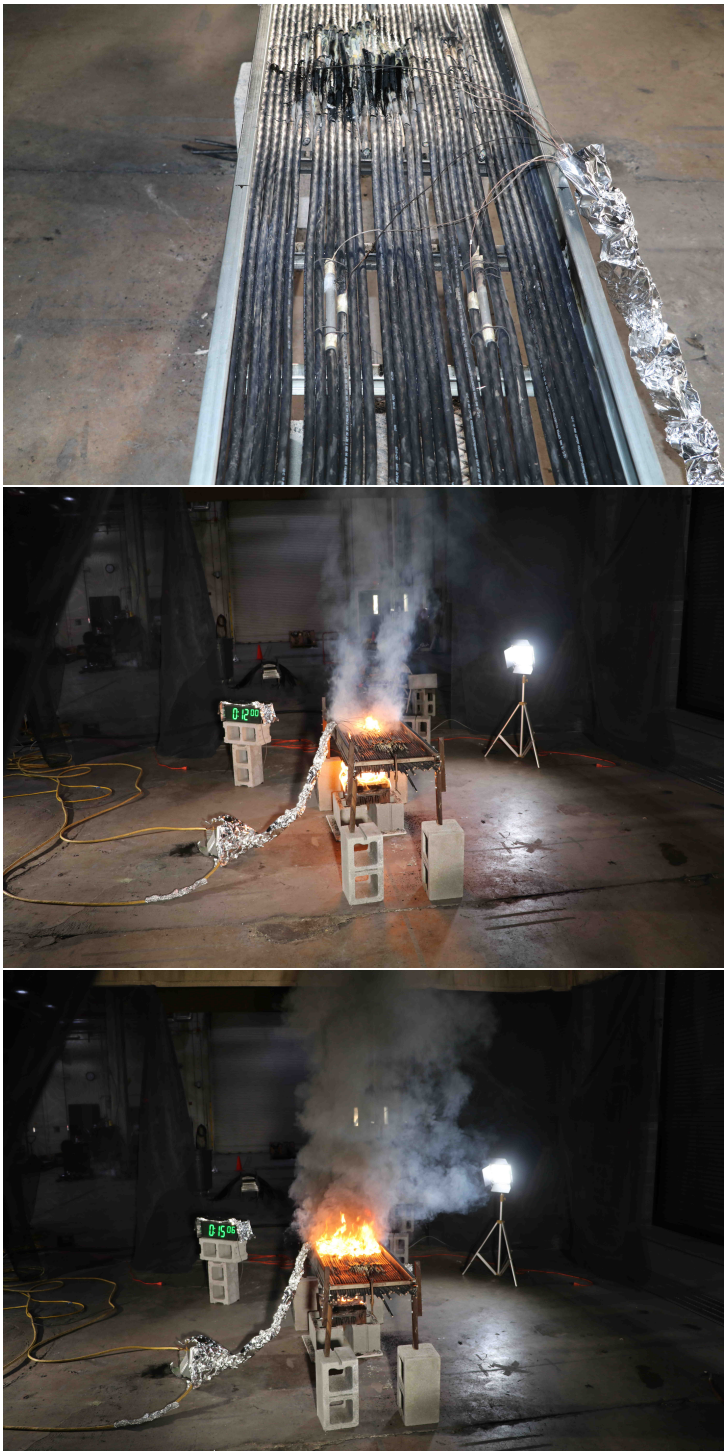


Fig. 28. Photographs of Experiment 46. The top photograph shows the arrangement of cables and instrumentation. The middle photograph shows the cables igniting at approximately 12 min. The bottom photograph shows the cables steadily burning at 15 min, 6 s.

4.1.7. Experiment 47

A nominally 45 cm (18 in) wide tray containing 30 thermoplastic cables was placed approximately 36 cm (14 in) above a nominally 30 cm square 40 kW natural gas burner. Thermocouples were inserted into two cables above the burner, and instrumented aluminum rods ("slugs") were placed alongside the instrumented cables. The figures below show the HRR of the gas burner and the total HRR of the burner and cables, along with the internal temperatures of the cables and slugs. The cables ignited in less than 1 min.

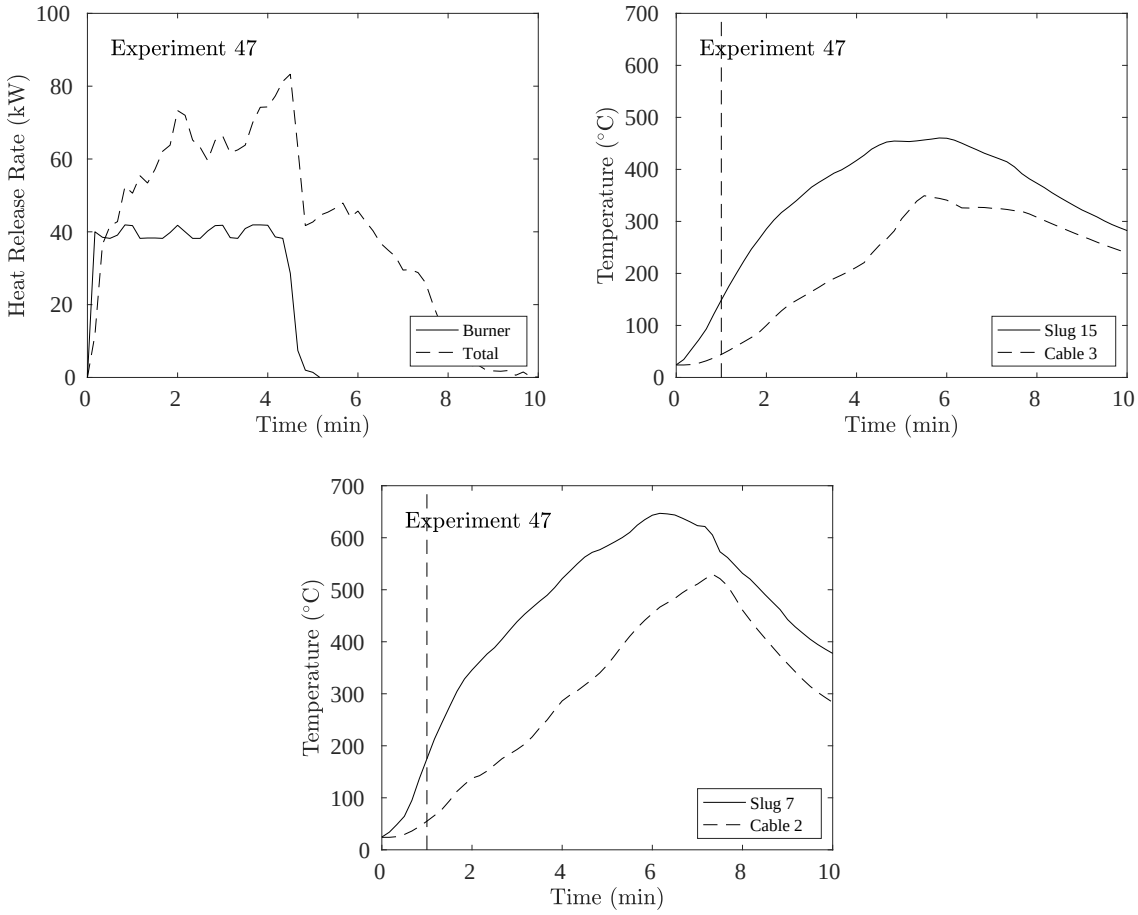


Fig. 29. Heat release rate (upper left) and internal cable and slug temperatures above a 40 kW burner. The curve labeled "Burner" in the upper left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry. The vertical dashed line indicates cable ignition.

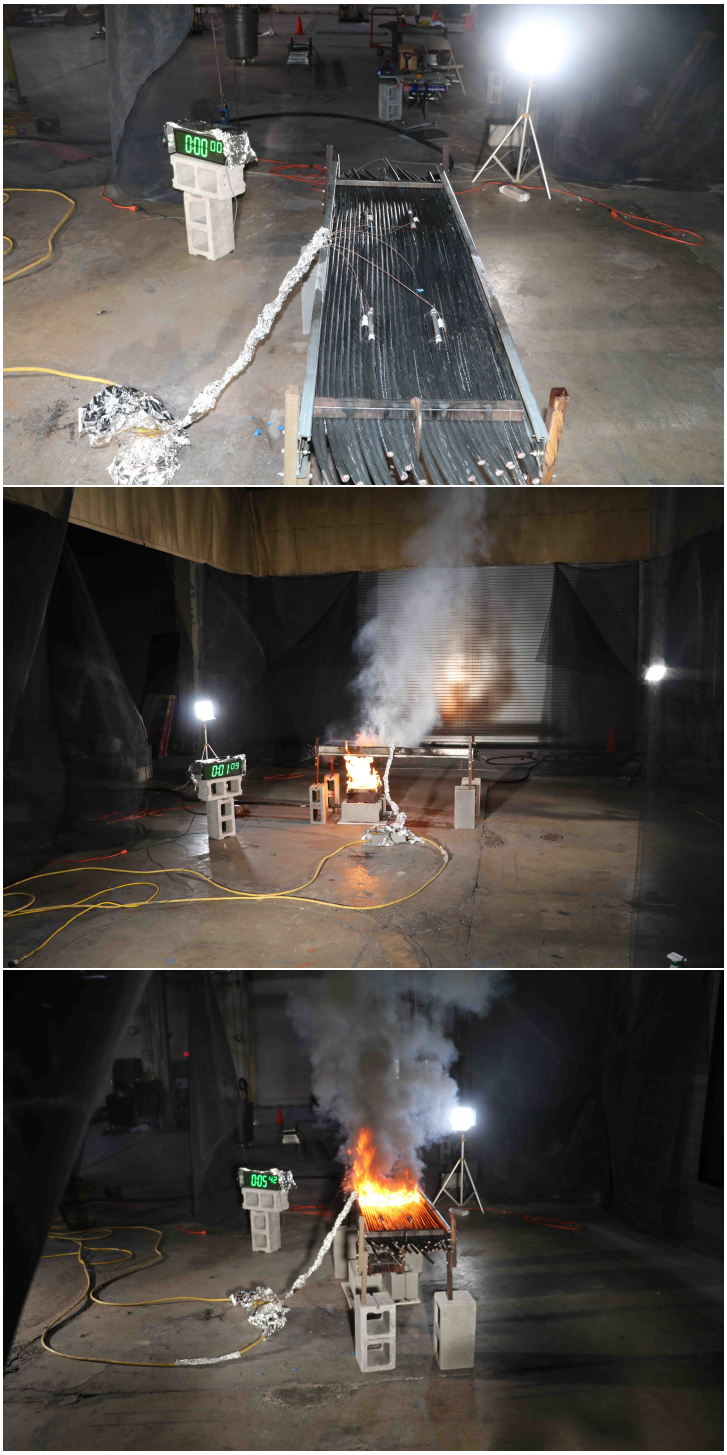


Fig. 30. Photographs of Experiment 47. The top photograph shows the cable and instrumentation placement. The middle photograph shows the cables burning at 1 min, 9 s, just after ignition. The bottom photograph shows the fire at 5 min, 42 s, after the burner has been extinguished.

4.1.8. Experiment 48

Experiment 48 was the same as Exp. 47 except that the tray was increased to 56 cm (22 in) above the burner. The figures below show the HRR of the gas burner and the total HRR of the burner and cables, along with the internal temperatures of the cables and slugs. The cables ignited at approximately 3 min.

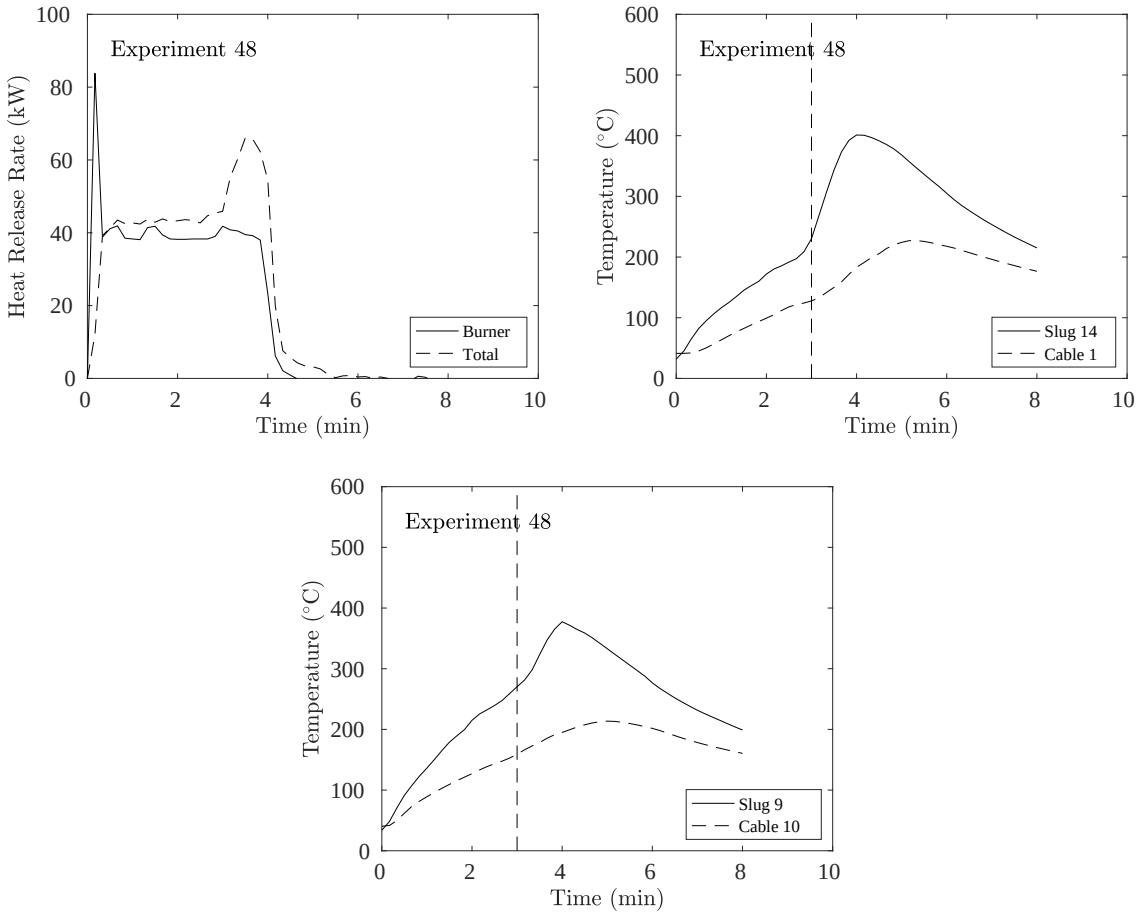


Fig. 31. Heat release rate (upper left) and internal cable and slug temperatures above a 40 kW burner. The curve labeled “Burner” in the upper left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry. The vertical dashed line indicates cable ignition.



Fig. 32. Photographs of Experiment 48. The top photograph shows the fire 1 min, 3 s after burner ignition. The middle photograph shows cable ignition just after 3 min. The bottom photograph shows steady burning at 3 min, 28 s.

4.1.9. Summary

Table 3. Ignition time of cables set above a 40 kW natural gas burner.

Exp. No.	Make	Cable Packing	Cable Height (cm)	Ignition Time (min:s)
36	TP	Loose	36	1:30
37	TP	Loose	56	4:00
38	TS	Loose	56	—
39	TS	Loose	36	1:30
45	TS	Tight	36	50:00
46	TS	Tight	36	12:00
47	TP	Tight	36	1:00
48	TP	Tight	56	3:00

4.2. Measuring the Gas Temperature above a Burning Enclosure

Following the HRR measurements in Experiments 40 and 41, the same Westinghouse enclosure was used in experiments aimed at measuring the fire plume temperature outside of a near-ceiling vertical vent. These were difficult measurements to perform because it is difficult to predict the trajectory of the plume centerline. Nevertheless, it can be seen in Experiments 42 through 45 that temperatures above a vertical vent can reach values of 400 °C to 500 °C (750 °F to 930 °F), high enough to ignite cables given enough time, a subject which is the focus of Experiments 49 through 64.

4.2.1. Experiment 42

A nominally 30 cm (12 in) square natural gas burner was positioned in the mostly empty space at the rear of the breaker enclosure used in Experiments 40 and 41. The HRR of the burner was ramped up to 200 kW following an approximate t-squared profile. Six sheathed thermocouples were positioned above the upper rear vent in an attempt to measure the plume temperature. The plume did not follow the expected pattern and the tips of the thermocouples were not exposed to the peak temperatures within the plume. Thus, this experiment is of marginal value for assessing the threat to overhead targets.

The figures below show the HRR of the gas burner, along with the temperatures measured by the sheathed thermocouples above the enclosure.

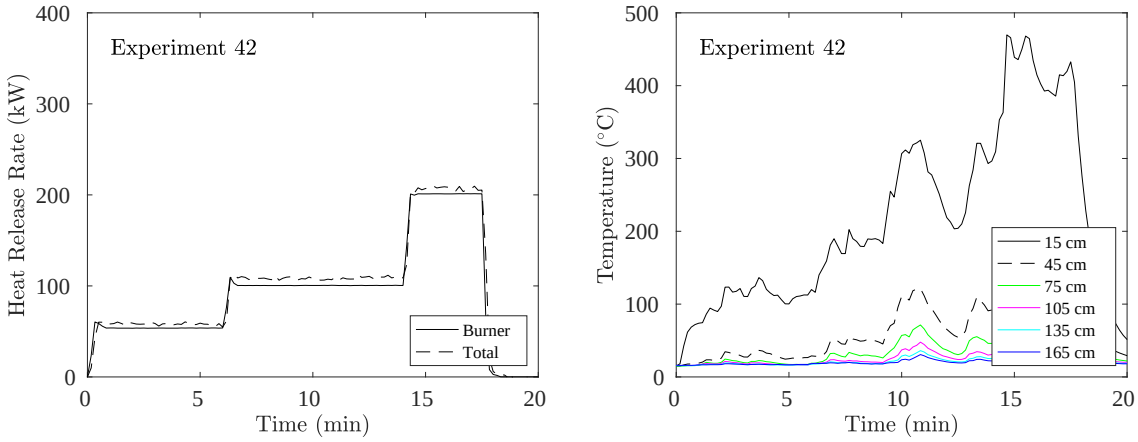


Fig. 33. Heat release rate (left) and sheathed thermocouple temperatures (right) above a burning breaker enclosure. The HRR measurement is based on natural gas consumption (“Burner”) and oxygen-consumption calorimetry (“Total”).



Fig. 34. Photographs of Experiment 42. The burner is on the right side of the enclosure and the photographs show the fire at approximately 50 kW (top), 100 kW (middle), and 200 kW (bottom). A vertical array of sheathed thermocouples sits at the upper edge of the enclosure. The cable tray in the background was left over from a previous experiment and played no role in this experiment.

4.2.2. Experiment 43

A nominally 30 cm (12 in) square natural gas burner was positioned in the mostly empty space at the rear of the breaker enclosure used in Experiments 40 and 41. The HRR of the burner was ramped up to 300 kW following an approximate t-squared profile. Six aluminum rods ("slugs") and six sheathed thermocouples were positioned above the upper rear vent in an attempt to measure the plume temperature. Two of each instrument were positioned approximately 15 cm (6 in), 30 cm (12 in), and 60 cm (24 in) above the top of the enclosure, roughly flush with the rear door.

The figures below show the HRR of the gas burner and the total HRR of the burner, along with the temperatures measured by the sheathed thermocouples and aluminum rods above the enclosure. Note that the rod temperatures show less temporal variation because of increased thermal mass. These temperatures are a better indicator of those of actual cables that might be located in the vicinity.

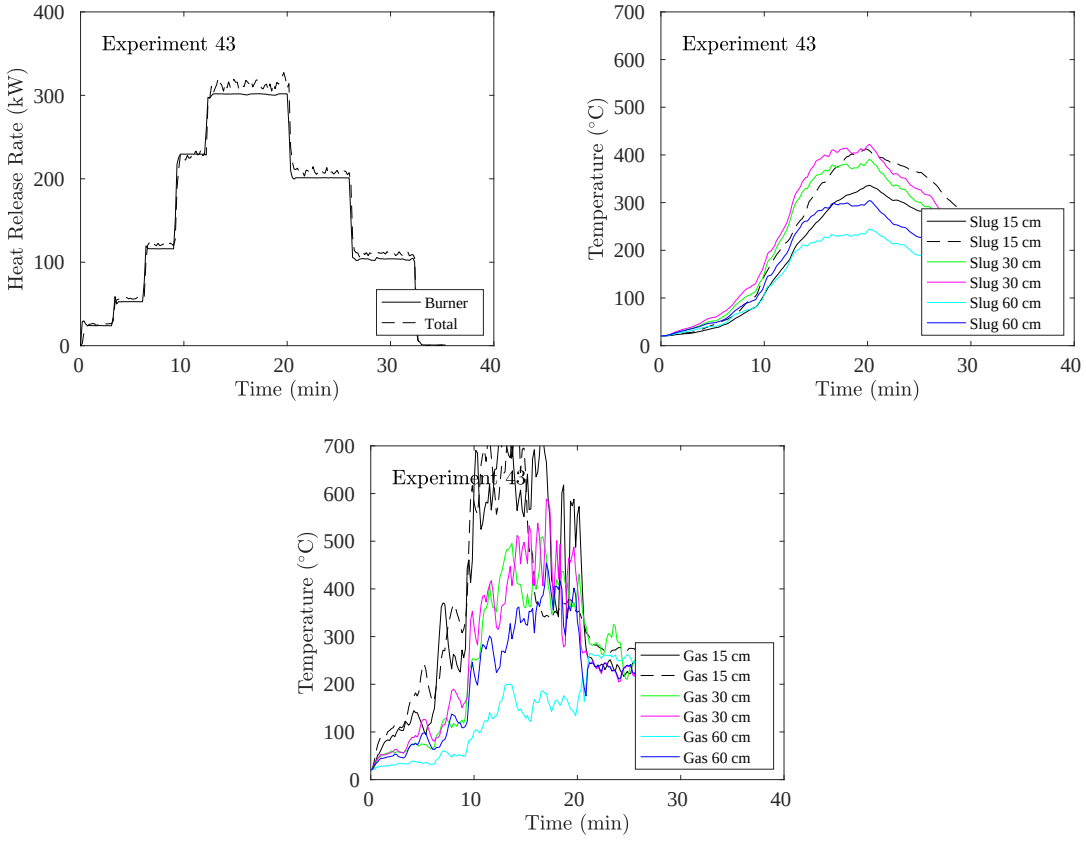


Fig. 35. Heat release rate (upper left) slug (upper right) and sheathed thermocouple (bottom) temperatures above a burning breaker enclosure. The HRR measurement is based on natural gas consumption ("Burner") and oxygen-consumption calorimetry ("Total").

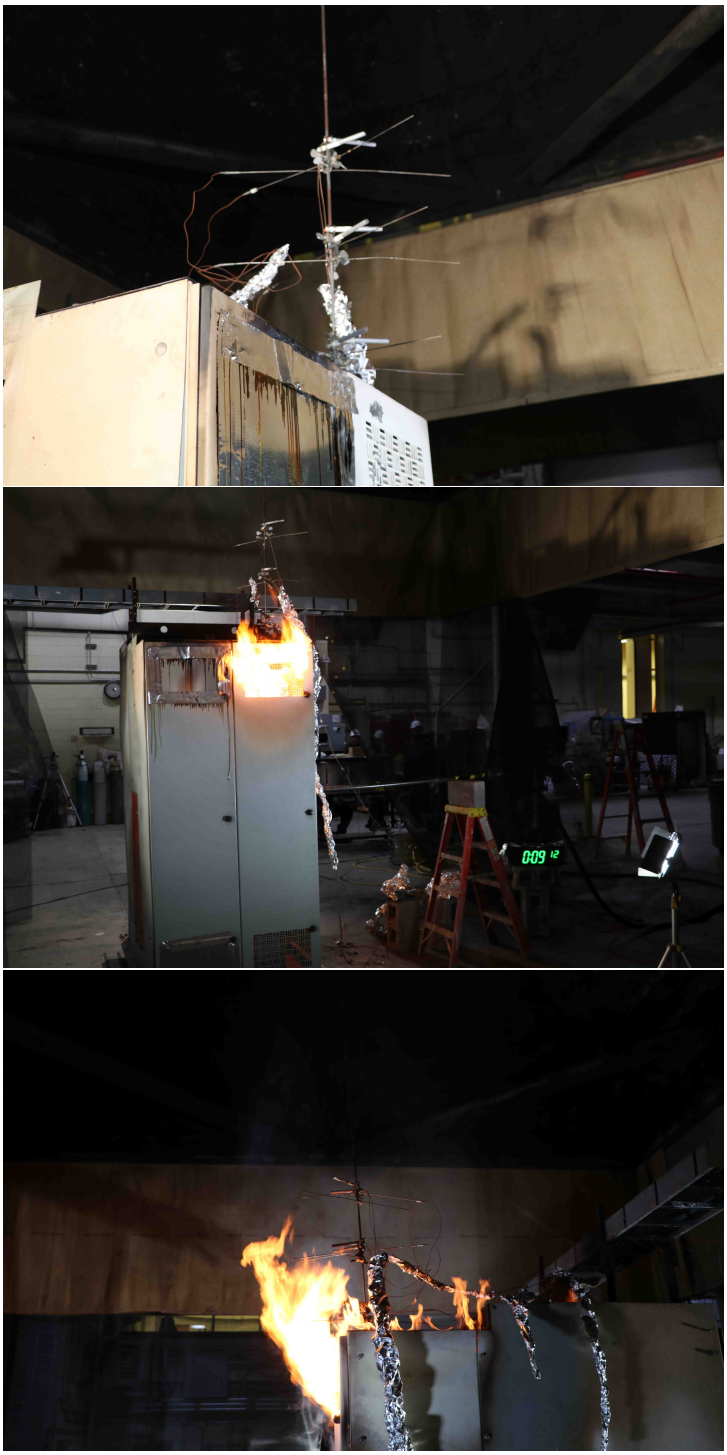


Fig. 36. Photographs of Experiment 43. The upper photograph shows that vertical array of sheathed thermocouples and aluminum slugs, positioned in such a way as to capture the peak plume temperatures at the various heights, based on observations of the previous experiment. The middle photograph shows the fire at 9 min, 12 s at which time its HRR is 125 kW. The lower photograph shows the fire at 300 kW.

4.2.3. Experiment 44

Experiment 44 was similar to Experiment 43 except that two vents in the left rear door of the enclosure were closed off with a metal barrier. The closing of these other vents led to a higher velocity and higher flame heights at the vent above the burner.

The figures below show the HRR of the gas burner, along with the temperatures measured by the sheathed thermocouples and aluminum rods above the enclosure.

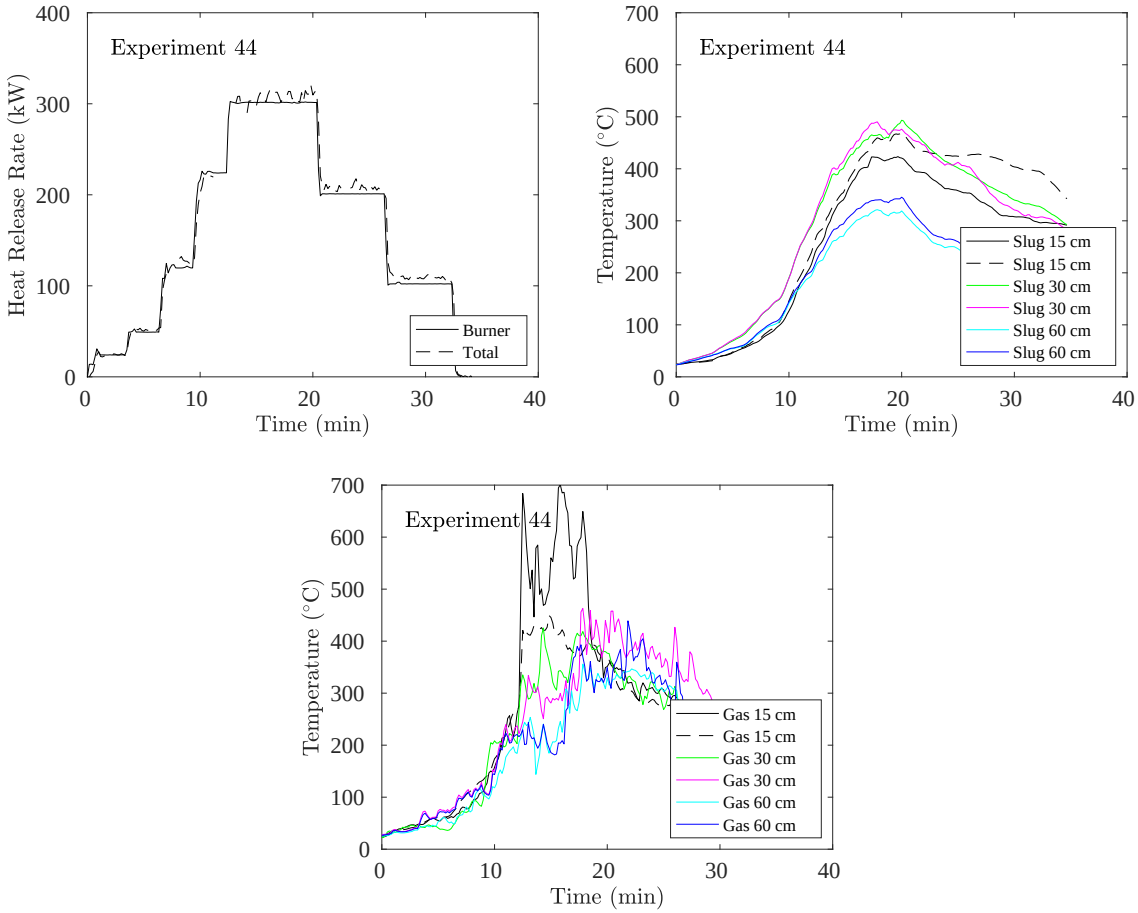


Fig. 37. Heat release rate (upper left) and slug (upper right) and sheathed thermocouple (bottom) temperatures above a burning breaker enclosure. The HRR measurement is based on natural gas consumption (“Burner”) and oxygen-consumption calorimetry (“Total”).

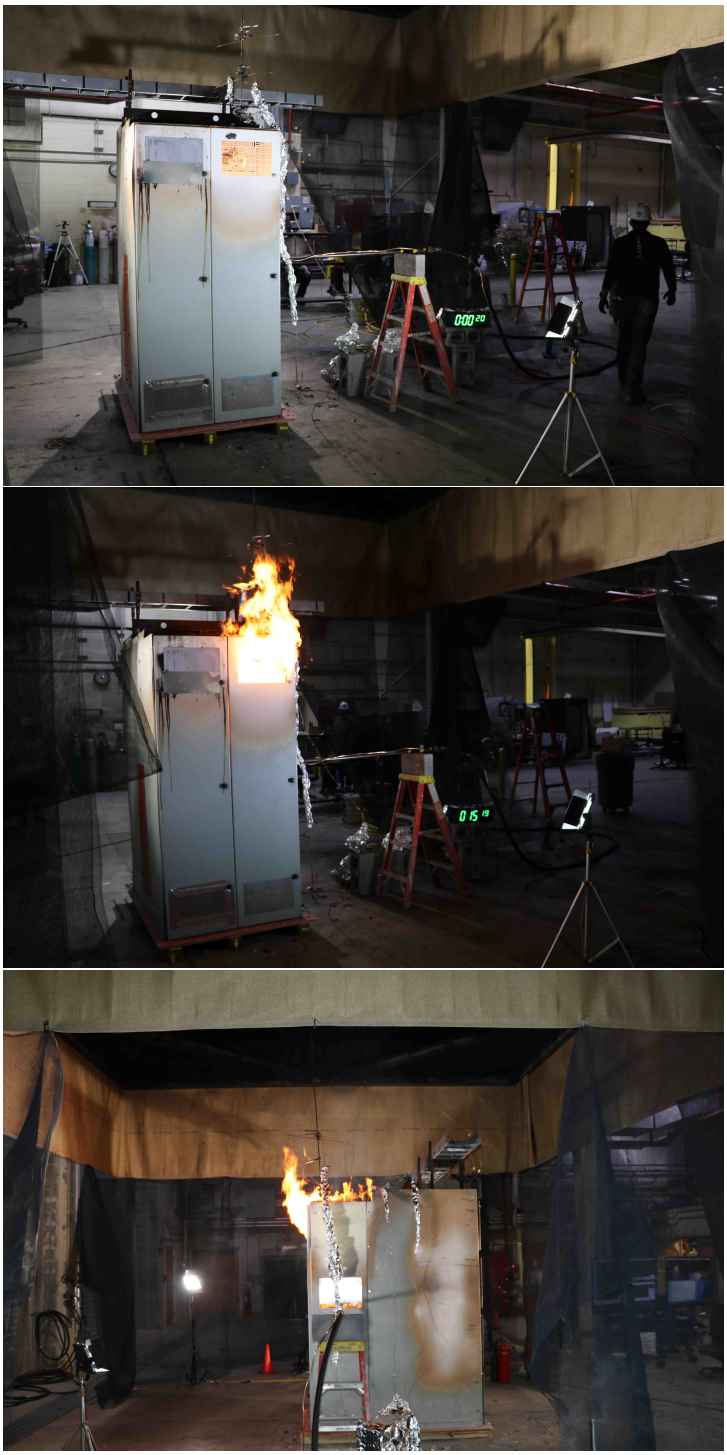


Fig. 38. Photographs of Experiment 44. The top photograph shows the fire within the enclosure 20 s following ignition of the burner. Note that the vents on the left side of the enclosure have been sealed. The middle photograph shows the fire 15 min, 19 s following ignition, at which time the HRR is 300 kW. The bottom photograph shows the enclosure from the side at about this same time. The flames can be seen emerging from the side panel, which has opened due to the extreme heat of this and previous experiments.

4.3. Measuring Cable Temperatures above an Enclosure Fire

Experiments 49 through 64, conducted in March 2024, made use of two empty electrical enclosures used in a previous set of experiments [4]. Drawings are shown in Figs. 39 through 42. One or two 30 cm (12 in) wide cable trays were positioned on top of the enclosures. The trays contained (usually) ten thermoplastic or thermoset cables, some of which were instrumented with a thermocouple embedded in its center amongst the conductors. Aluminum rods ("slugs") were also placed on top of the cables in the vicinity of the embedded thermocouples. The aluminum rods have a similar thermal mass to the cables, but are more convenient for modeling. Sheathed thermocouples were also positioned above the

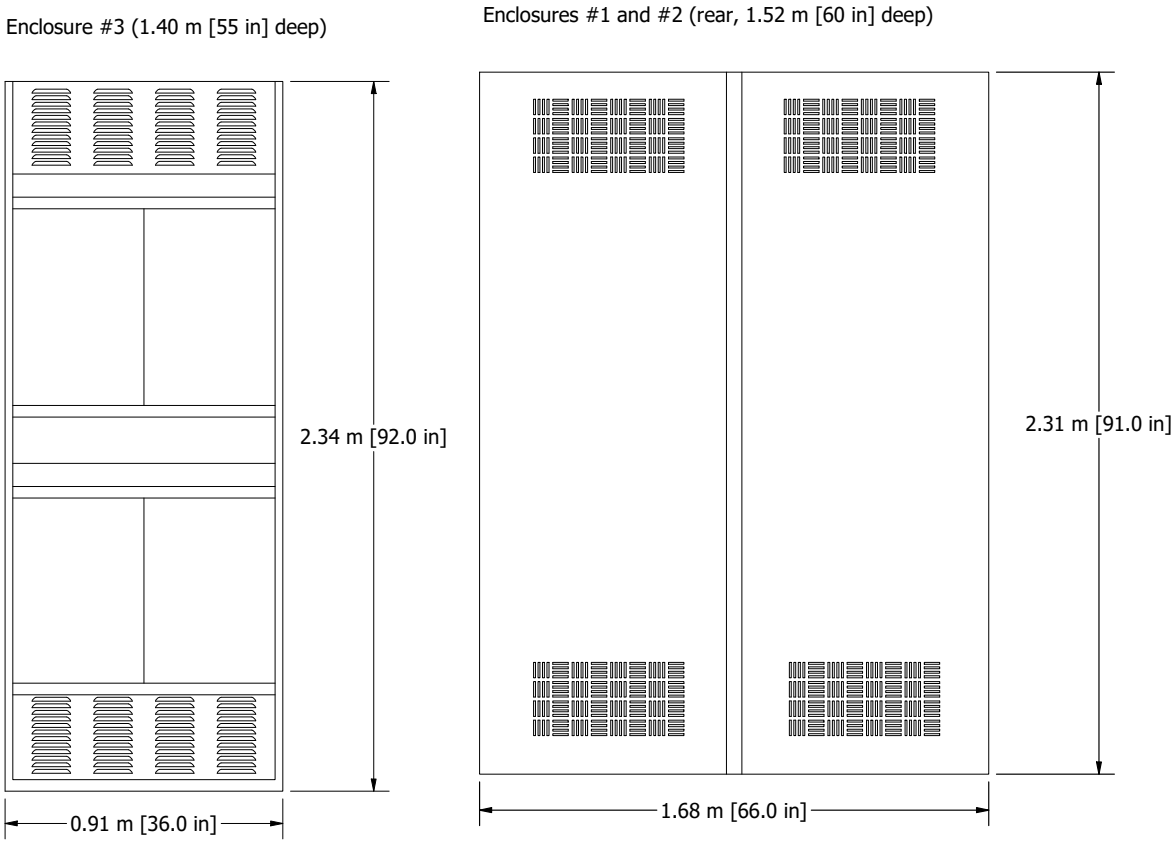


Fig. 39. Drawings of Enclosure #3 (left) and #2 (right).

trays to measure the plume (gas) temperature, but these measurements are of little value because they rarely capture the peak plume temperature or the actual exposing temperature of the cables. The reason is that the plume centerline does not follow a vertical path, but rather jets out of the vent and then turns back towards the enclosure face. The path changes as the fire grows. Initially the fairly weak plume is drawn inwards towards the top of the enclosure, but then extends outwards as the fire grows and the plume temperature increases.

The same 30 cm (12 in) natural gas burner used in previous experiments was positioned in the center of Enclosure #3, approximately 1.5 m (60 in) below the ceiling, or below the left vent in Enclosure #2, approximately 56 cm (22 in) below the ceiling. The HRR profile was varied, but in all cases it was designed to ignite the cables.

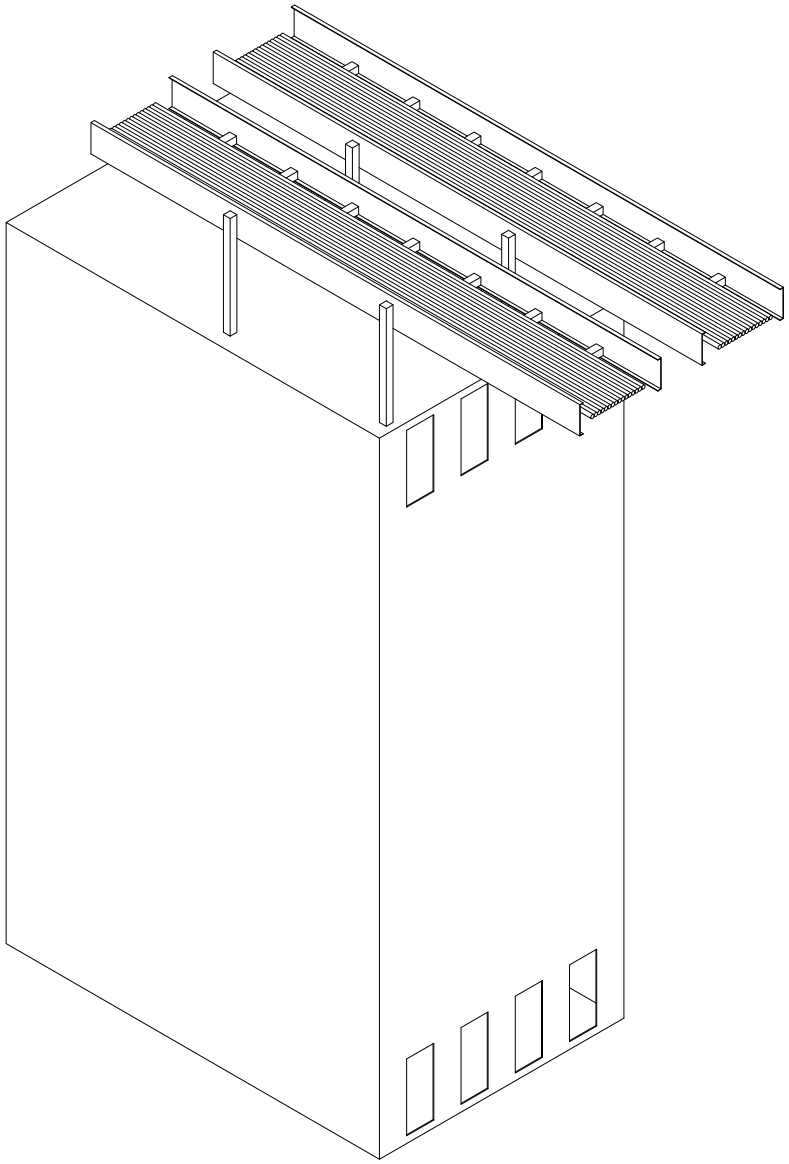


Fig. 40. Schematic diagram of Enclosure #3 used in Experiments 48-51.

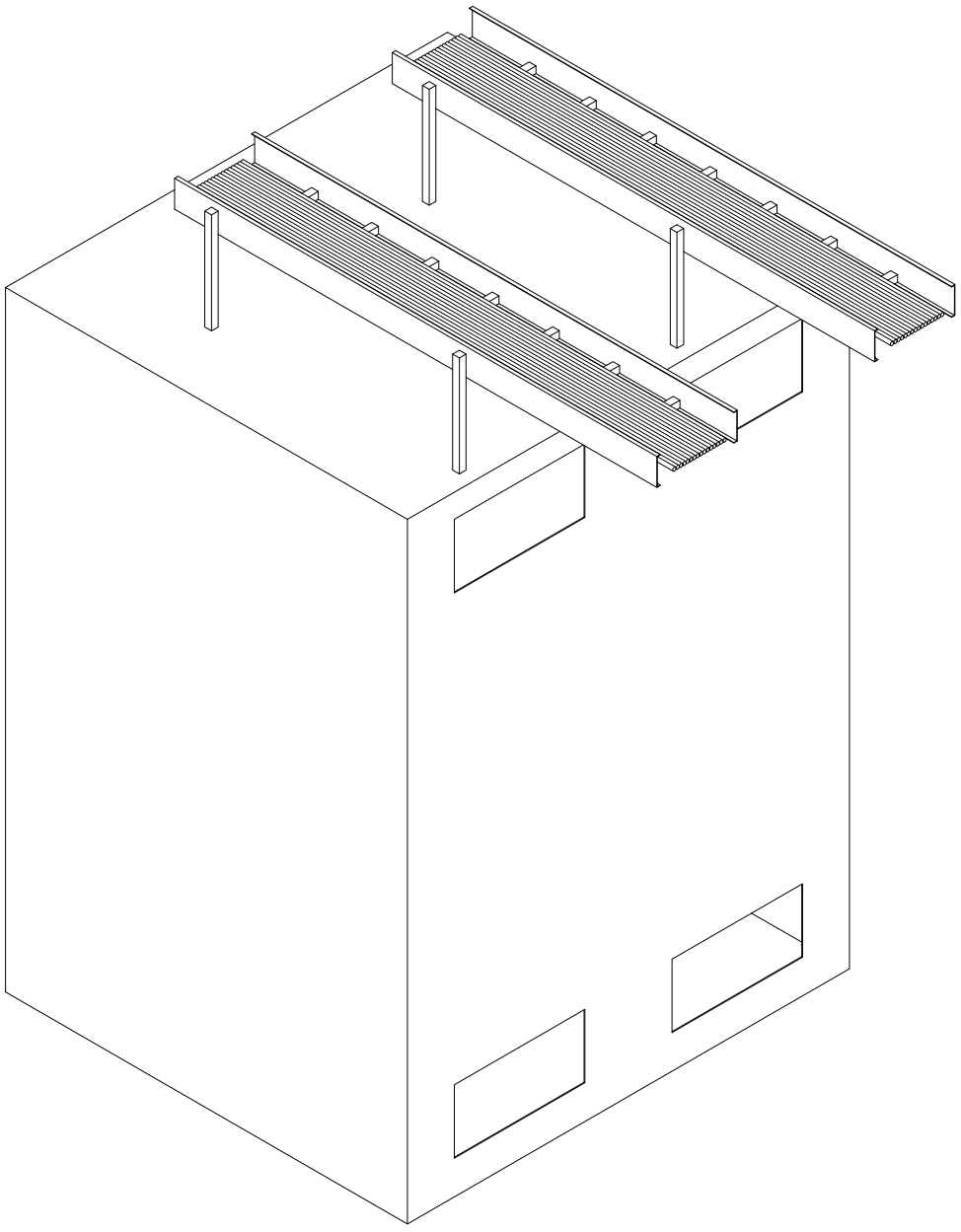


Fig. 41. Schematic diagram of Enclosure #2 used in Experiments 52-60.

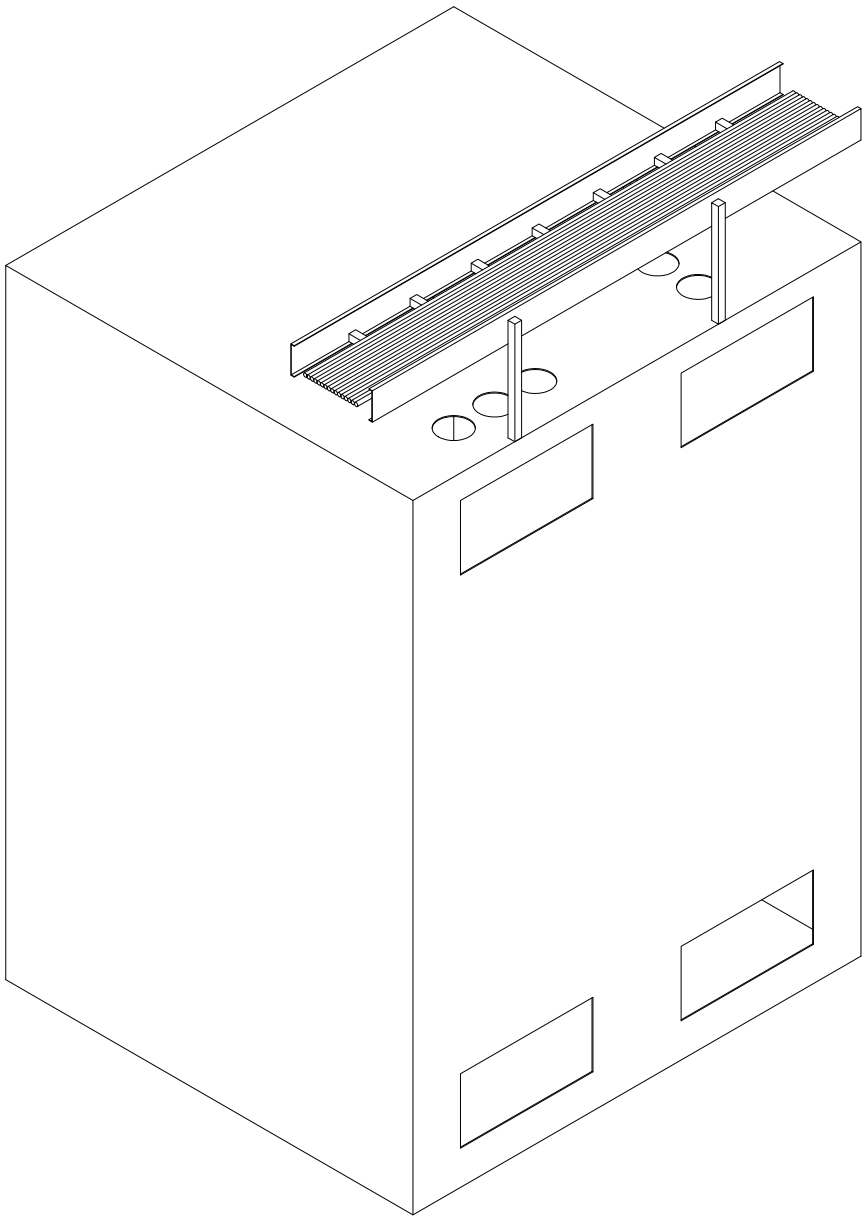


Fig. 42. Schematic diagram of Enclosure #2 used in Experiments 61-64.

4.3.1. Experiment 49

Two nominally 30 cm (12 in) wide cable trays were set approximately 30 cm (12 in) above Enclosure #3. The dimensions of this enclosure are approximately 0.91 m (36 in) wide and 1.40 m (55 in) deep. Each tray overhung a louvered vent whose top edge was approximately 8 cm (3 in) below the top of the enclosure. The burner was positioned approximately 1.5 m (60 in) below the ceiling of the enclosure in the position shown in Fig. 43. The fire was set to approximately 100 kW for 10 minutes and then increased to 200 kW for an additional 5 min. No flames were observed exiting the upper vent, and the natural gas flow was increased again to sustain a 300 kW and then 400 kW fire. However, due to ventilation limitations, the actual HRR of the fire did not surpass 200 kW, and the natural gas flow was decreased to that level. Flames were not observed exiting the vent at any time during the experiment and the target temperatures did not surpass 200 °C.

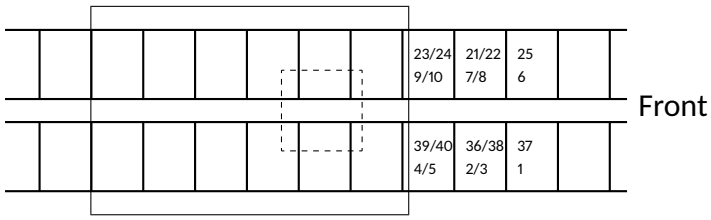


Fig. 43. Plan view of the Enclosure #3 with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray in the lower part of the figure held 10 thermoset cables; the other held 10 thermoplastic cables.

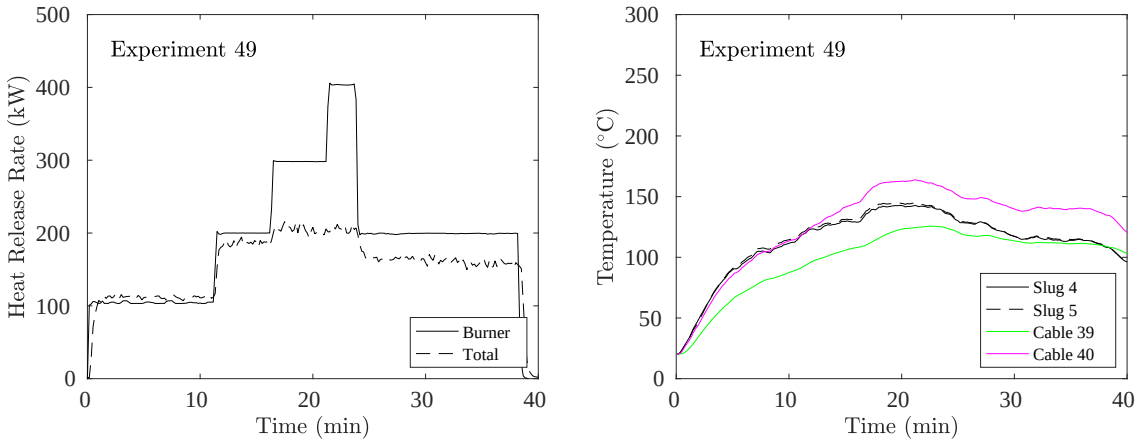


Fig. 44. Heat release rate (left) and peak target temperatures (right) for Exp. 49. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.

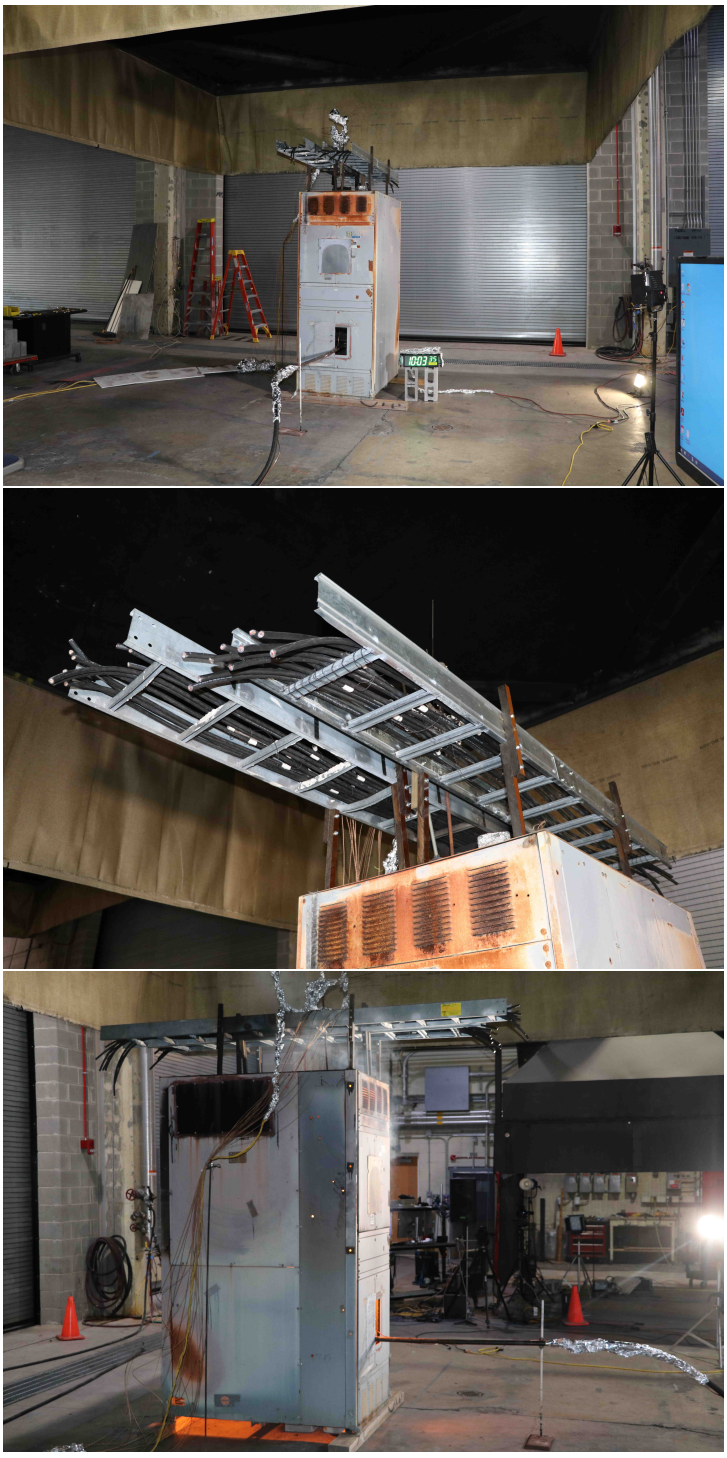


Fig. 45. Photographs of Experiment 49. The top photograph shows the initial set up. The middle photograph indicates the locations of the thermocouples that are embedded in the cable and secured with white, noncombustible tape. The bottom photograph shows the enclosure during the experiment. Flames did not emerge from the louvered vents during the experiment.

4.3.2. Experiment 50

This experiment retained the same basic setup as Exp. 49 except that the louvered vent was removed leaving an approximately 20 cm (8 in) tall vent across the width of the enclosure, 8 cm (3 in) below the top. In addition, the trays were shifted so that the leftmost cable and slug targets shown in Fig. 46 would fall within the smoke plume observed in Exp. 49. However, because the vent louvers were removed, the flames and plume were thrust further to the right, and no targets were directly impacted. As a result, this experiment did not yield a meaningful target temperature at the time of ignition. It was decided after this experiment to perform the remaining experiments using a different enclosure.

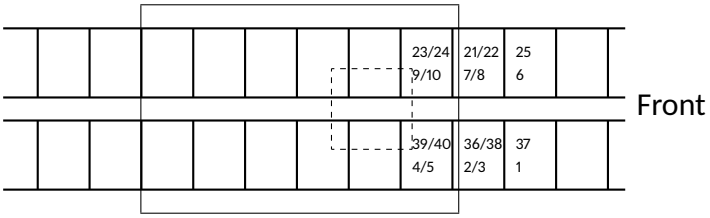


Fig. 46. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray in the lower part of the figure held 10 thermoset cables; the other held 10 thermoplastic cables.

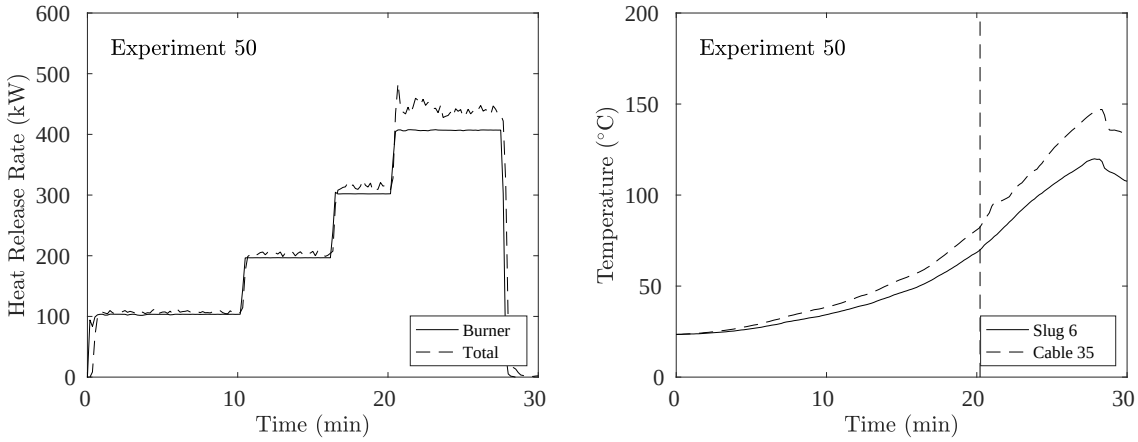


Fig. 47. Heat release rate (left) and peak target temperatures (right) for Exp. 50. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry. The increase in "Total" over "Burner" HRR after 20 min represents the HRR of the burning cables.

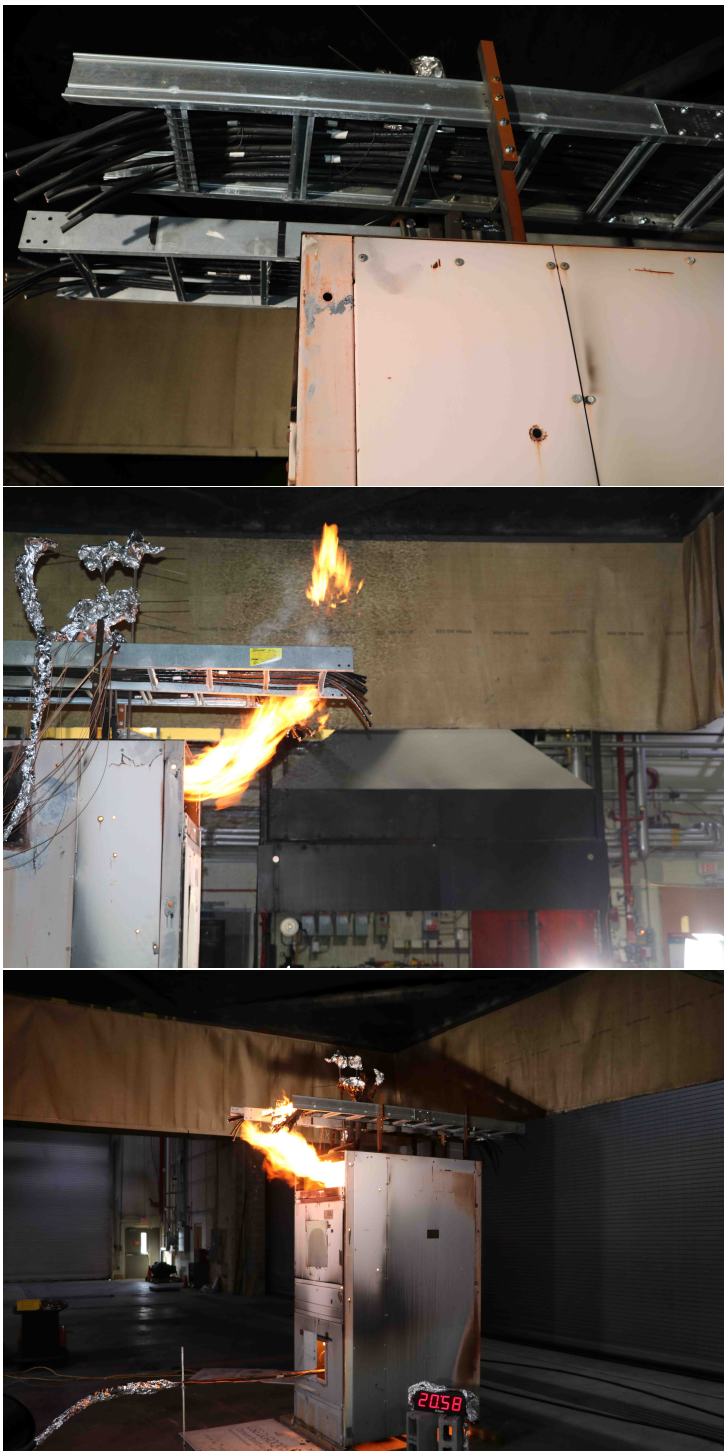


Fig. 48. Photographs of Experiment 50. The upper photograph shows the position of the instrumented cables and aluminum rods. Because the louvered vents were removed, the flames jetted outward such that the peak target temperatures occurred beyond the extent of the instrumented target cables and aluminum rods, as seen in the middle photograph. The bottom photograph was taken 21 minutes after ignition and shows ignition of the cables near the end of the tray.

4.3.3. Experiment 51

Two cable trays were set approximately 30 cm (12 in) above Enclosure #2 which measured approximately 1.68 m (66 in) wide and 1.52 m (60 in) deep. Each tray overhung a grilled vent whose top edge was approximately 10 cm (4 in) below the top of the enclosure. The burner was positioned approximately 56 cm (22 in) below the ceiling of the enclosure in the position shown in Fig. 49. The thermoset cables in the tray directly above the left upper vent ignited after approximately 18 min. The thermoplastic cables in the second tray did not ignite.

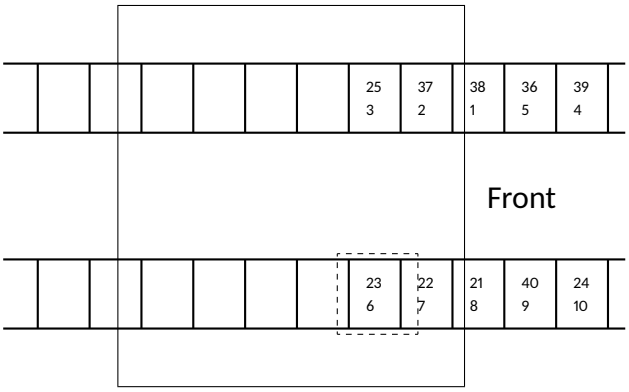


Fig. 49. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray directly above the burner held 10 thermoset cables; the other held 10 thermoplastic cables.

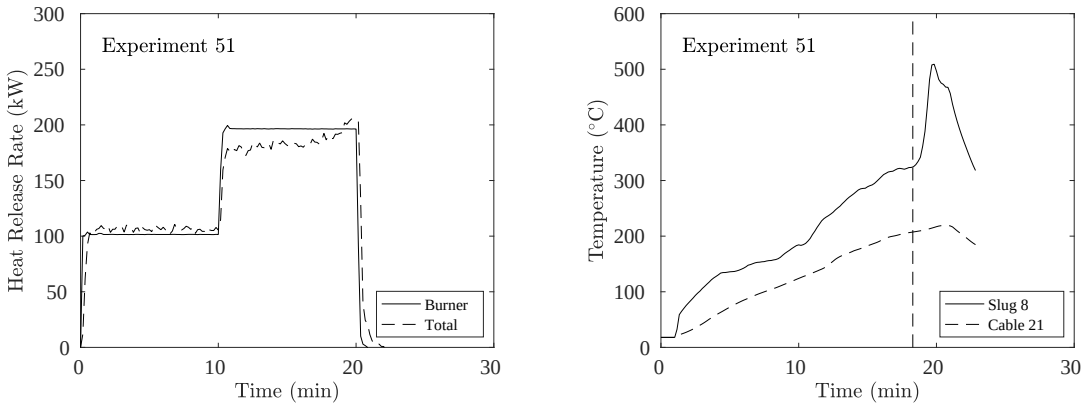


Fig. 50. Heat release rate and target temperatures for Exp. 51. The curve labeled “Burner” in the left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry. The ignition time of the thermoset cables directly above the burner is indicated by the vertical dashed line. The cables in the other tray did not ignite.

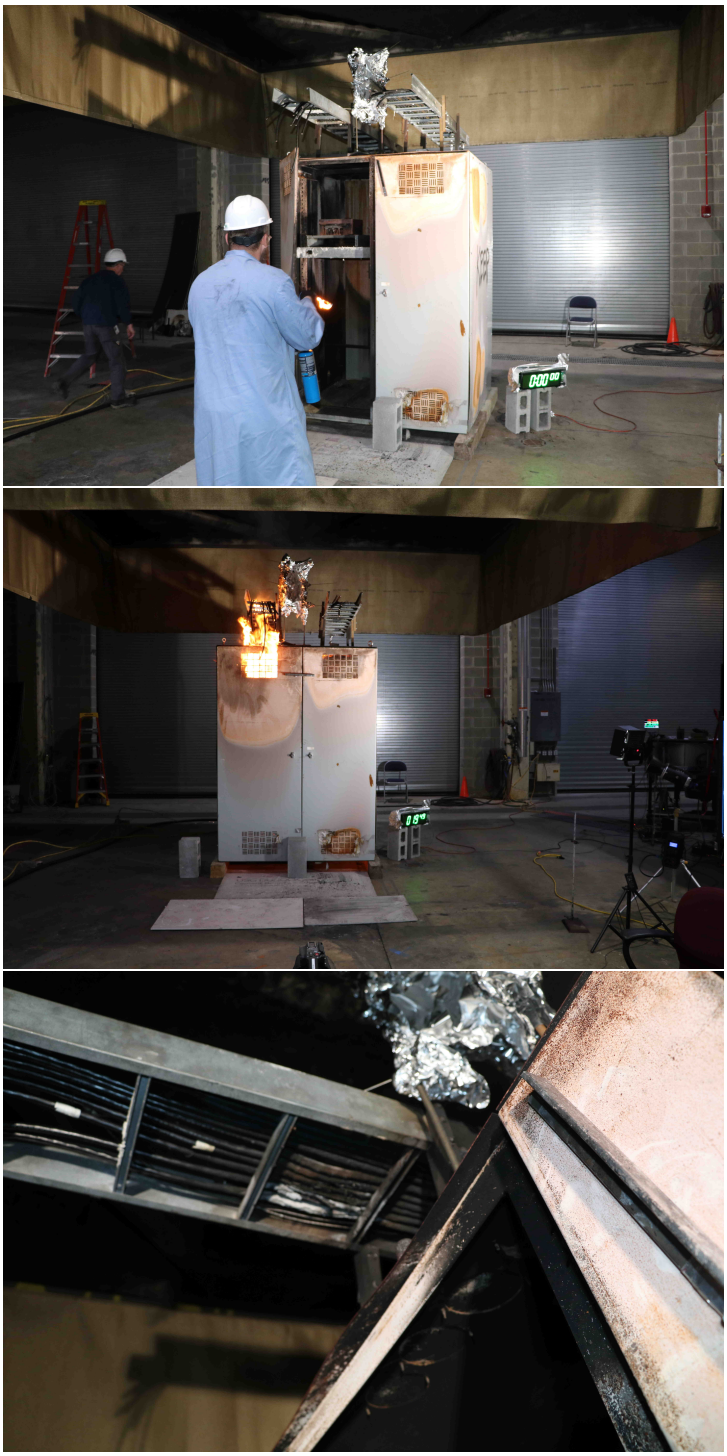


Fig. 51. Photographs of Experiment 51. The upper photograph shows the position of the burner on the left side of the enclosure. The middle photograph shows the burning cables approximately two minutes after they ignited and approximately 20 minutes after ignition of the burner. The bottom photograph shows the damaged cables after the fire has been extinguished.

4.3.4. Experiment 52

This experiment is similar to Exp. 51 except that a single cable tray of thermoplastic cables was set approximately 30 cm (12 in) above the enclosure, directly in line with the fire plume exiting the left upper vent. The cables ignited after approximately 11 min.

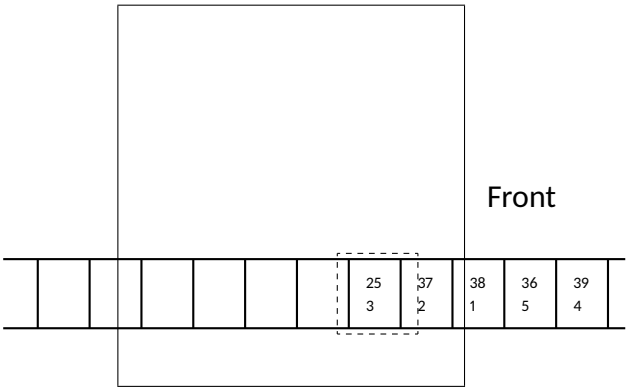


Fig. 52. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoset cables.

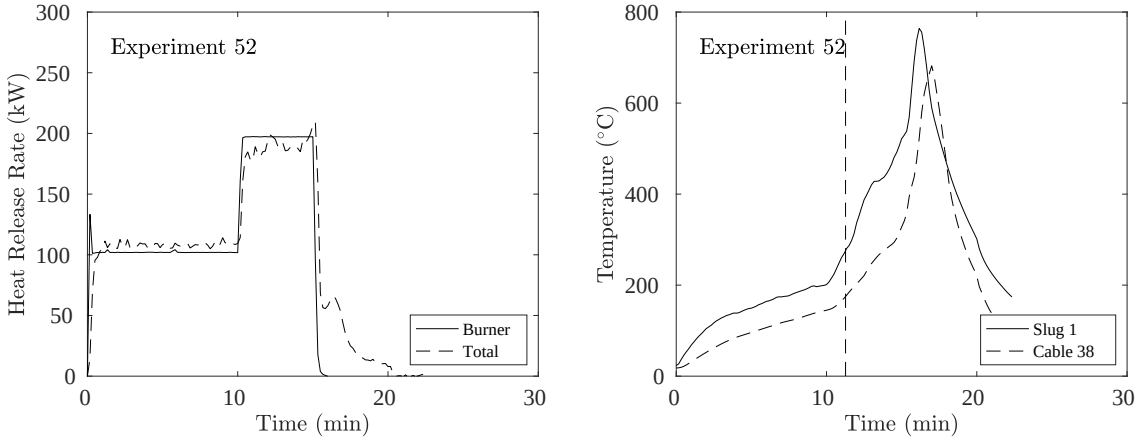


Fig. 53. Heat release rate (left) and peak target temperatures (right) for Exp. 52. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.

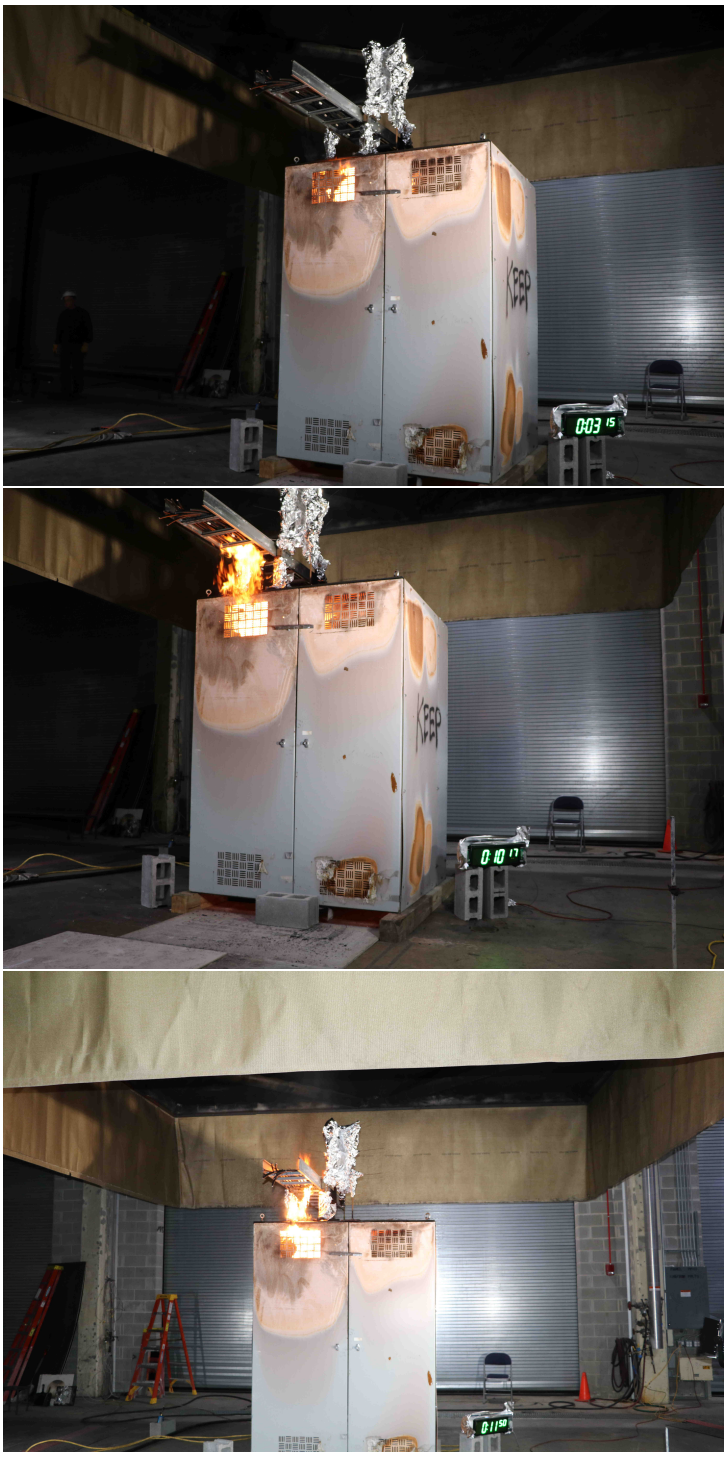


Fig. 54. Photographs of Experiment 52. The upper photograph shows the fire within the enclosure 3 min, 15 s following the ignition of the burner. The middle photograph shows the flames impinging on the cables just 40 s prior to cable ignition at 11 min. The bottom photograph shows the burning cables just after ignition.

4.3.5. Experiment 53

This experiment is similar to Exp. 52 except that a different HRR ramp was implemented to better mimic a so-called “t-squared” fire, where the HRR ramps up to 200 kW in 12 min following a quadratic time function. The thermoplastic cables ignited after approximately 11 min.

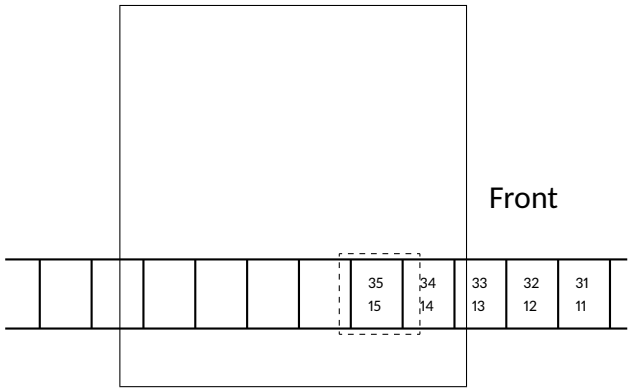


Fig. 55. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoplastic cables.

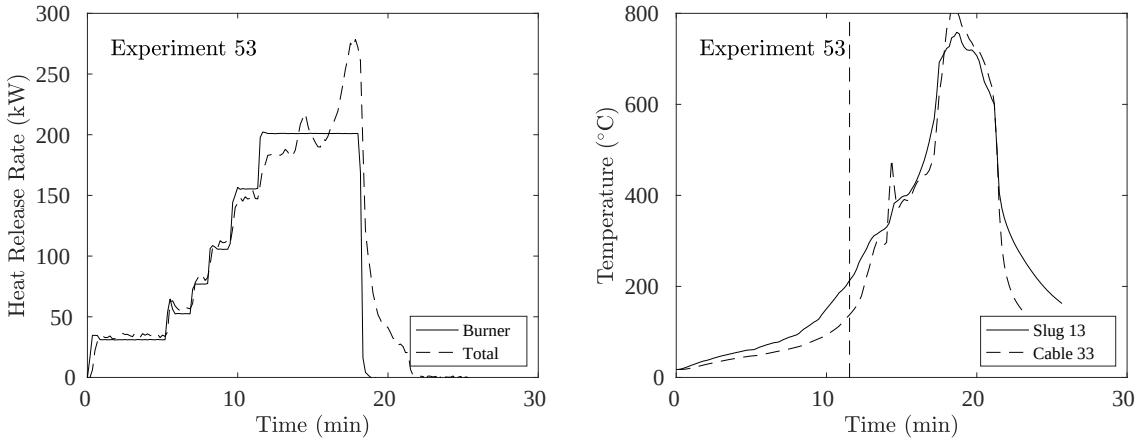


Fig. 56. Heat release rate (left) and peak target temperatures (right) for Exp. 53. The curve labeled “Burner” in the left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry.

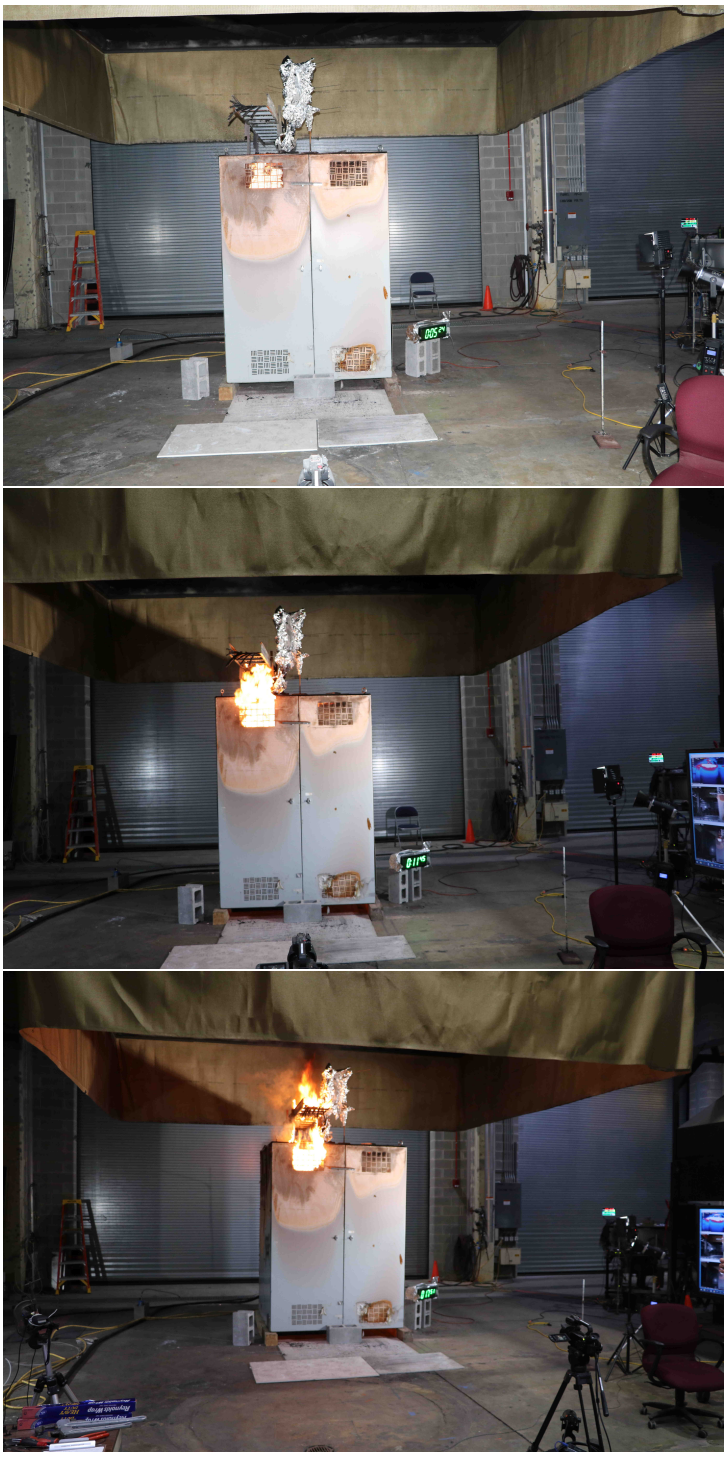


Fig. 57. Photographs of Experiment 53. The upper photograph shows the fire within the enclosure 5 min, 24 s following the ignition of the burner. The middle photograph shows the flames impinging on the cables just 15 s prior to cable ignition at 12 min. The bottom photograph shows the burning cables just after ignition.

4.3.6. Experiment 54

This experiment is the same as Exp. 53 except that 10 thermoset cables were laid into the tray. They ignited after approximately 20 min.

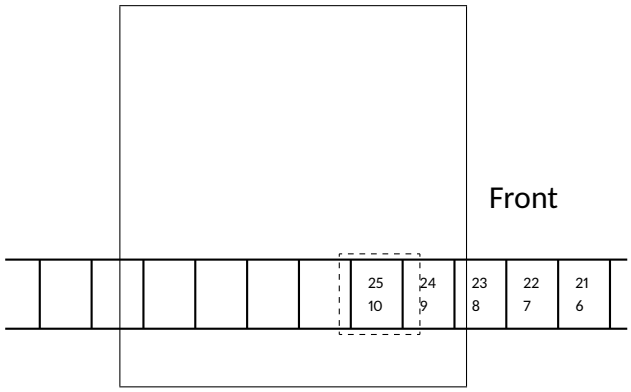


Fig. 58. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoset cables.

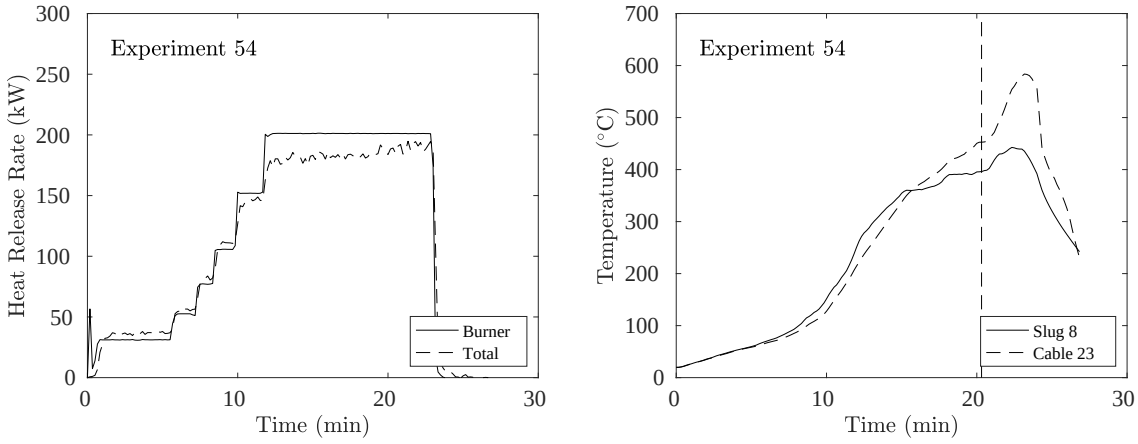


Fig. 59. Heat release rate (left) and peak target temperatures (right) for Exp. 54. The curve labeled “Burner” in the left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry.

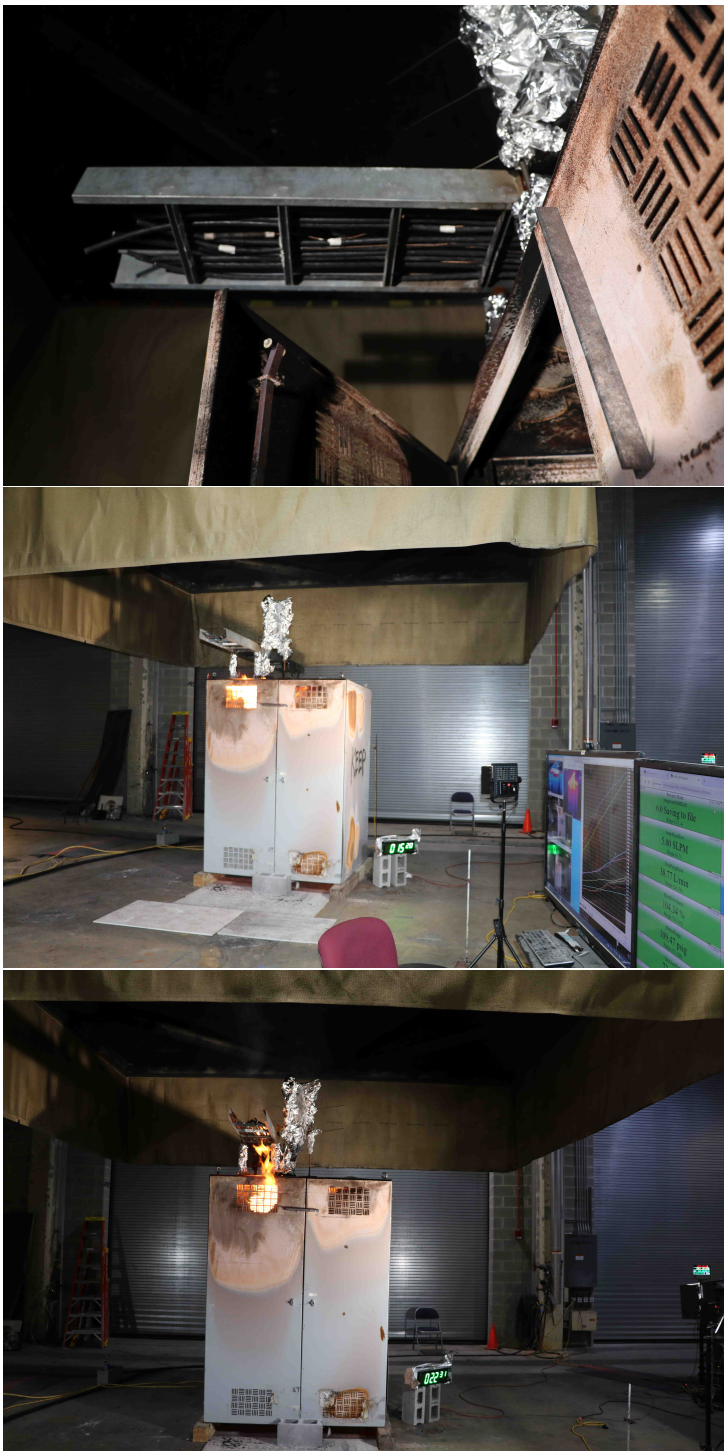


Fig. 60. Photographs of Experiment 54. The upper photograph shows the location of the instrumented cables that extend beyond the front edge of the enclosure. The middle photograph shows the fire within the enclosure approximately 15 min after ignition of the burner. The bottom photograph shows the cables burning at 22 min, 30 s, approximately 2 min after the cables first ignited.

4.3.7. Experiment 55

This is a replicate of Exp. 53, but with the cable and slug targets moved closer together to provide additional measurements of the plume centerline temperature. The thermoplastic cables ignited after approximately 12 min.

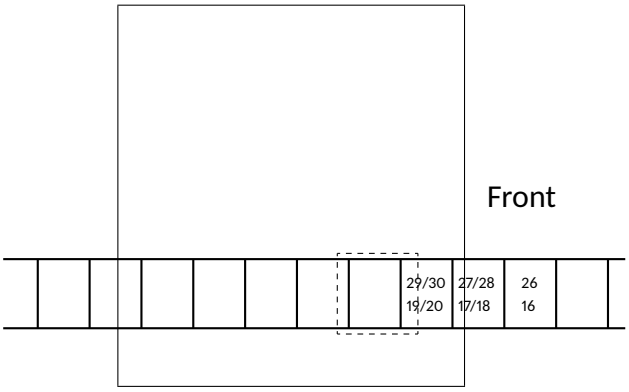


Fig. 61. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoplastic cables.

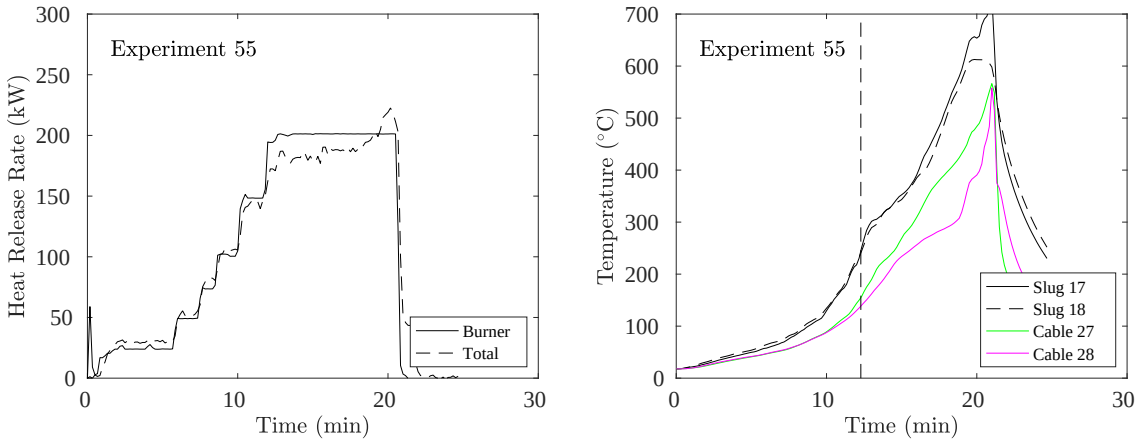


Fig. 62. Heat release rate (left) and peak target temperatures (right) for Exp. 55. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.



Fig. 63. Photographs of Experiment 55. The upper photograph shows the position of the instrumented cables. The lower photograph was taken 15 min after the burner was ignited and 3 min after cable ignition.

4.3.8. Experiment 56

This is a replicate of Exp. 54, but with the cable and slug targets moved closer together to provide additional measurements of the plume centerline temperature. The thermoset cables ignited after approximately 22 min.

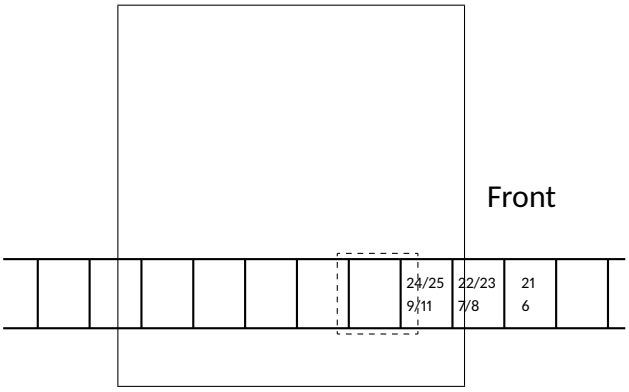


Fig. 64. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoset cables.

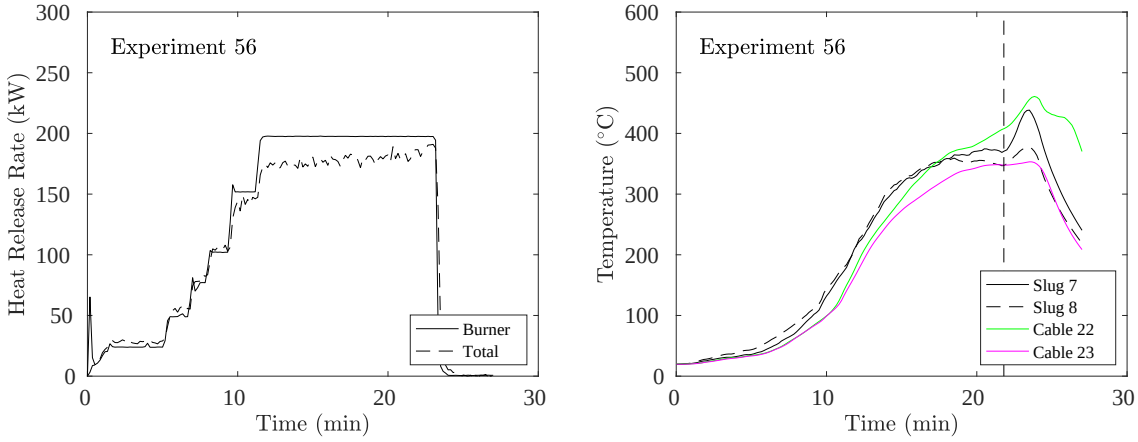


Fig. 65. Heat release rate (left) and peak target temperatures (right) for Exp. 56. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.



Fig. 66. Photographs of Experiment 56. The top photograph shows the fire within the enclosure 10 min after burner ignition. The middle photograph shows the flame emanating from the vent and impinging on the cable at 17 min, 30 s. The bottom photograph shows the cables igniting at 22 min.

4.3.9. Experiment 57

This experiment was similar to Exp. 56, except that the tray of thermoset cables was raised an additional 20 cm (8 in) above the top of the enclosure for a total of 50 cm (20 in). The 200 kW fire used in previous experiments was not large enough to ignite the cables, and the HRR was increased to approximately 250 kW and then 300 kW, at which point the cables ignited at approximately 46 min.

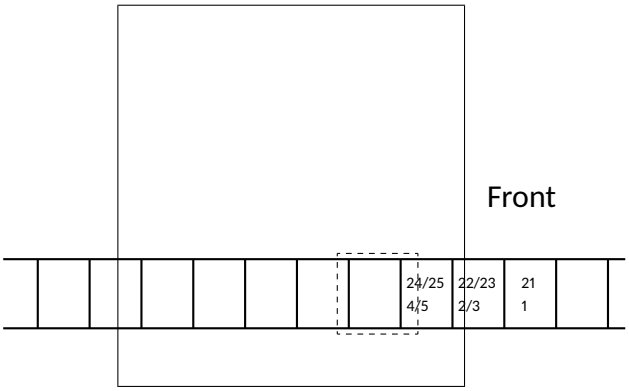


Fig. 67. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoset cables.

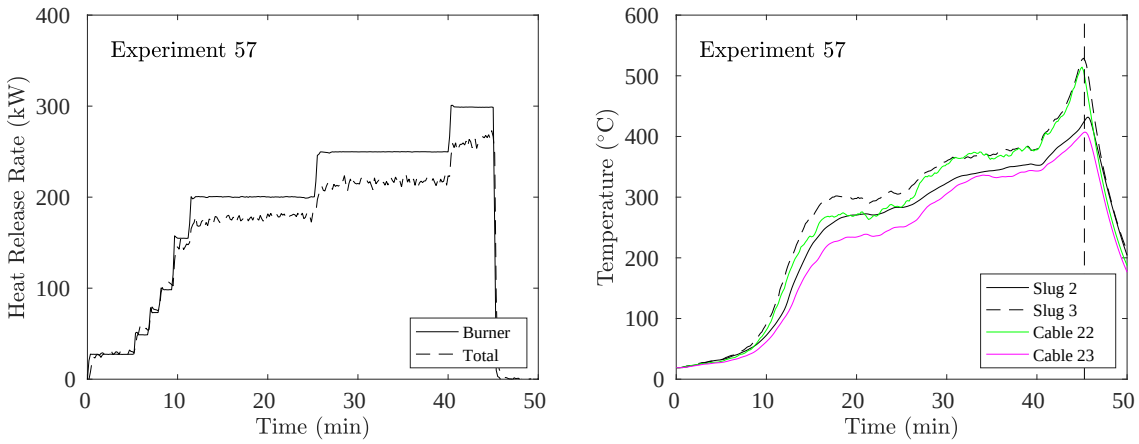


Fig. 68. Heat release rate (left) and peak target temperatures (right) for Exp. 57. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.



Fig. 69. Photographs of Experiment 57. The top photograph shows the cable trays sitting atop concrete blocks, raising them approximately 20 cm (8 in). The middle photograph shows the flames extending outside of the enclosure, approximately 25 min after burner ignition. The lower photograph shows the extent of the damage.

4.3.10. Experiment 58

This experiment was similar to Exp. 55, except that the tray of thermoplastic cables was raised an additional 20 cm (8 in) above the top of the enclosure for a total of 50 cm (20 in). The 200 kW fire used in previous experiments was not large enough to ignite the cables, and the HRR was increased to approximately 250 kW and then 300 kW, at which point the cables ignited at approximately 36 min.

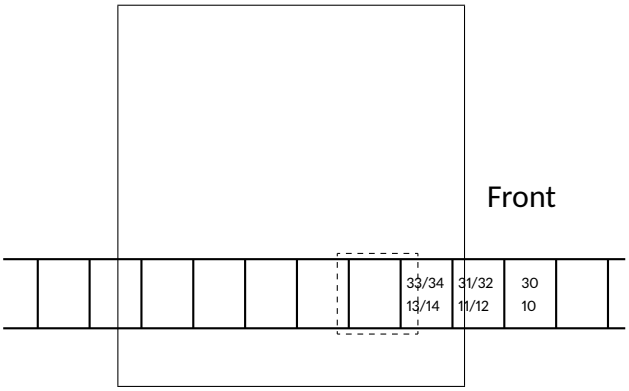


Fig. 70. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoplastic cables.

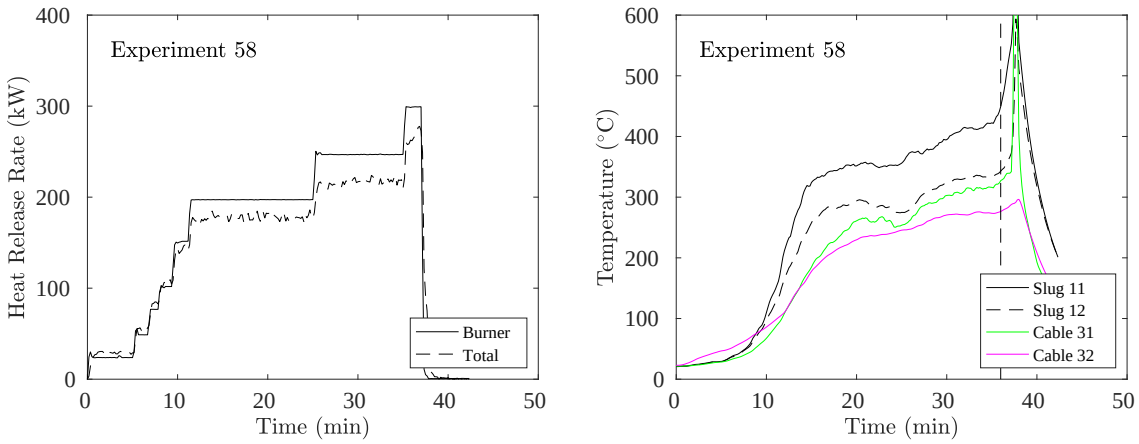


Fig. 71. Heat release rate (left) and peak target temperatures (right) for Exp. 58. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.



Fig. 72. Photographs of Experiment 58. The upper left photograph shows flames extending outside of the enclosure at 12 min, 29 s. The upper right photograph shows the flickering onset of cable ignition at 34 min, 44 s. Sustained ignition occurred approximately 1 min later. The lower photograph shows the damage.

4.3.11. Experiment 59

The experiment was a replicate of Exp. 57. The thermoset cables ignited after approximately 34 min.

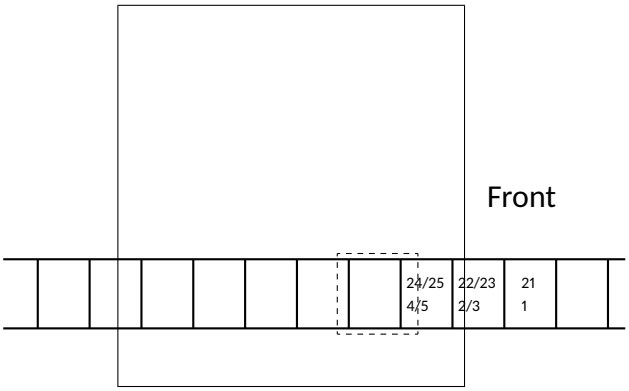


Fig. 73. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoset cables.

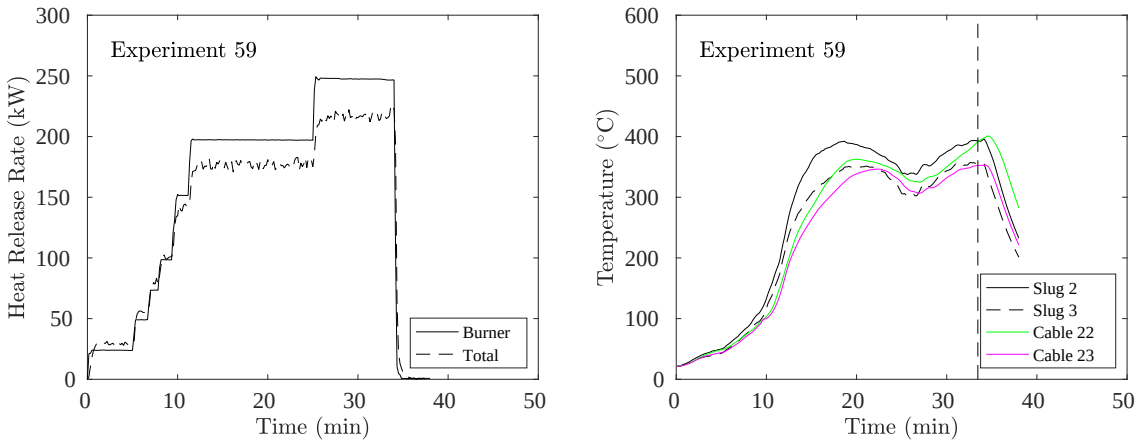


Fig. 74. Heat release rate (left) and peak target temperatures (right) for Exp. 59. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.



Fig. 75. Photographs of Experiment 59. The upper left photograph shows flames extending outside of the enclosure at 25 min, 55 s. The upper right photograph shows flame impingement just prior to cable ignition at 34 min. The lower photograph shows the damage.

4.3.12. Experiment 60

The experiment was a replicate of Exp. 58. The thermoplastic cables ignited after approximately 36 min.

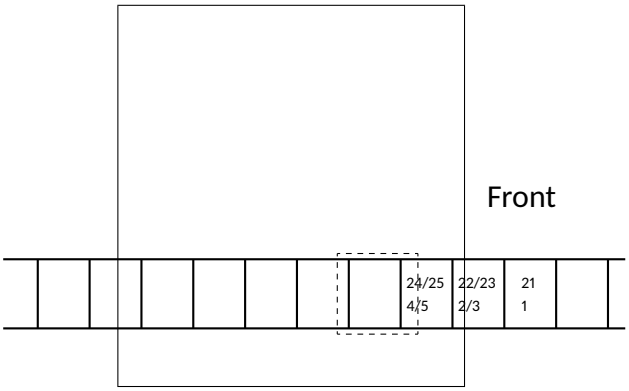


Fig. 76. Plan view of the enclosure with cable trays set on top. The dashed box indicates the location of the burner within the enclosure. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40). The tray held 10 thermoplastic cables.

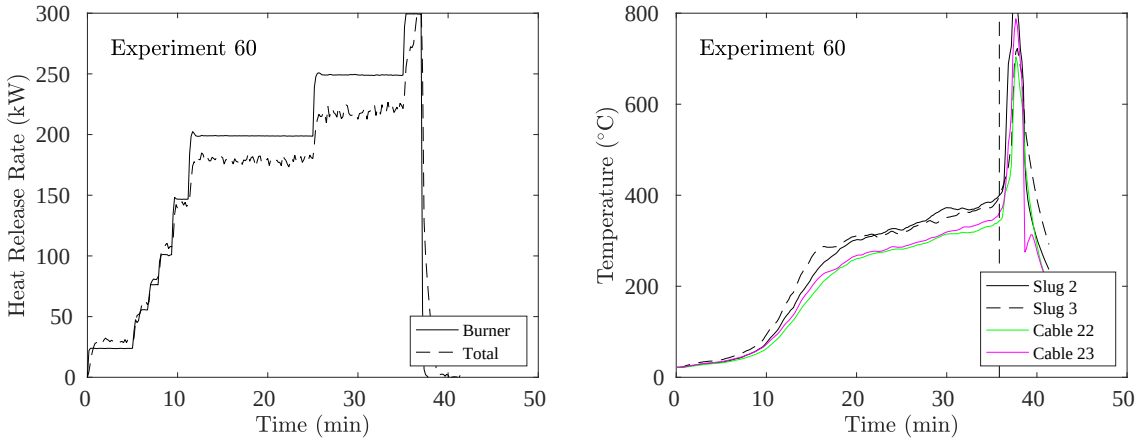


Fig. 77. Heat release rate (left) and peak target temperatures (right) for Exp. 60. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.



Fig. 78. Photographs of Experiment 60. The upper left photograph shows flame extension at 26 min, 23 s. The upper right photograph shows flame impingement at 35 min, 18 s, just prior to sustained ignition at 36 min. The lower photograph shows the damaged cables.

4.3.13. Experiment 61

This experiment used the same Enclosure #2 as in previous experiments, but now five approximately 11.4 cm (4.5 in) diameter holes were opened on the top of the enclosure, as shown in Fig. 79. The same "t-squared" fire growth curve was used. Because three of the holes were located over the burner, and the cable tray was located above the holes, the thermoset cables ignited after approximately 10 min.

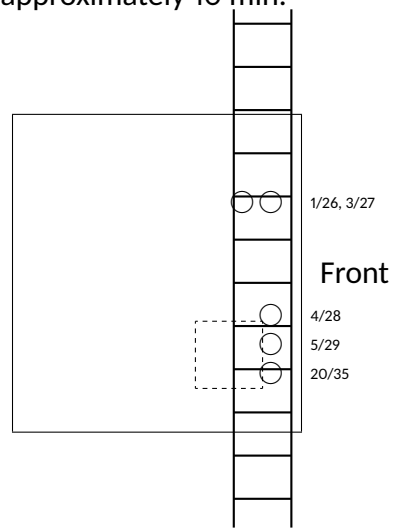


Fig. 79. Plan view of the enclosure with a single cable tray set on top. The dashed box indicates the location of the burner within the enclosure. The circles indicate the location of the 11 cm (4.5 in) diameter holes cut into the enclosure ceiling. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40) which were positioned over each hole. The tray held 10 thermoset cables.

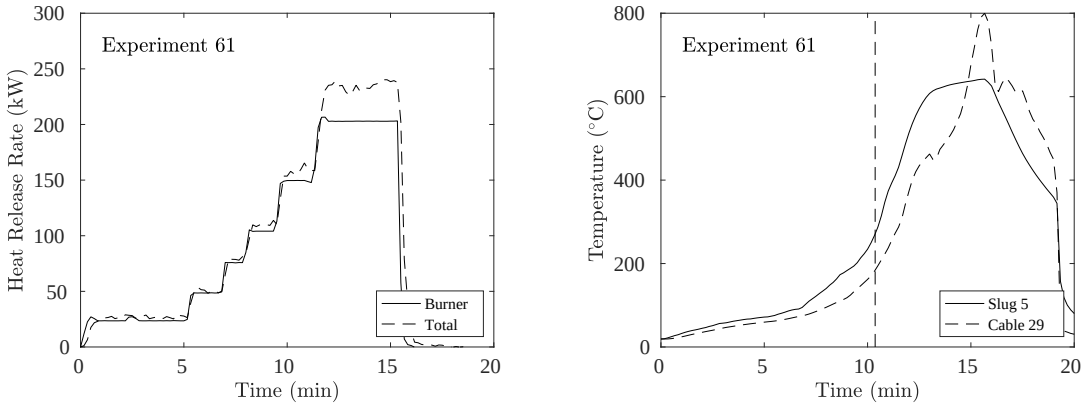


Fig. 80. Heat release rate (left) and peak target temperatures (right) for Exp. 61. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.

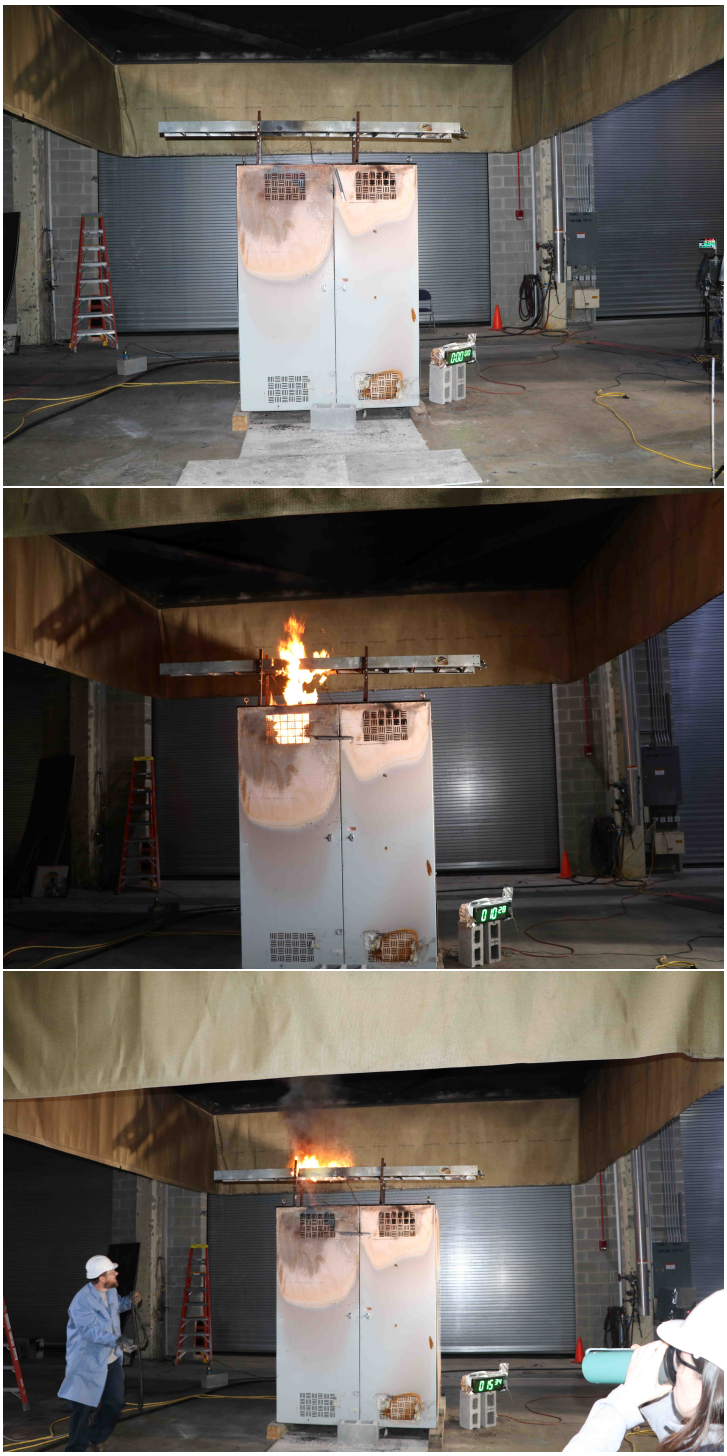


Fig. 81. Photographs of Experiment 61. The upper photograph shows the overall set up of the experiment. The middle photograph shows the burning cables just after ignition. The lower photograph shows the cables continuing to burn after the burner is turned off at approximately 15 min. The cable fire was extinguished shortly after the photograph was taken.

4.3.14. Experiment 62

This experiment was similar to Exp. 60 except that thermoplastic cables were laid in the tray. Ignition occurred just before 10 min.

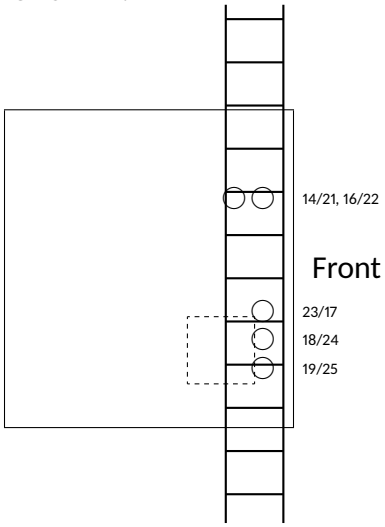


Fig. 82. Plan view of the enclosure with a single cable tray set on top. The dashed box indicates the location of the burner within the enclosure. The circles indicate the location of the 11 cm (4.5 in) diameter holes cut into the enclosure ceiling. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40) which were positioned over each hole. The tray held 10 thermoplastic cables.

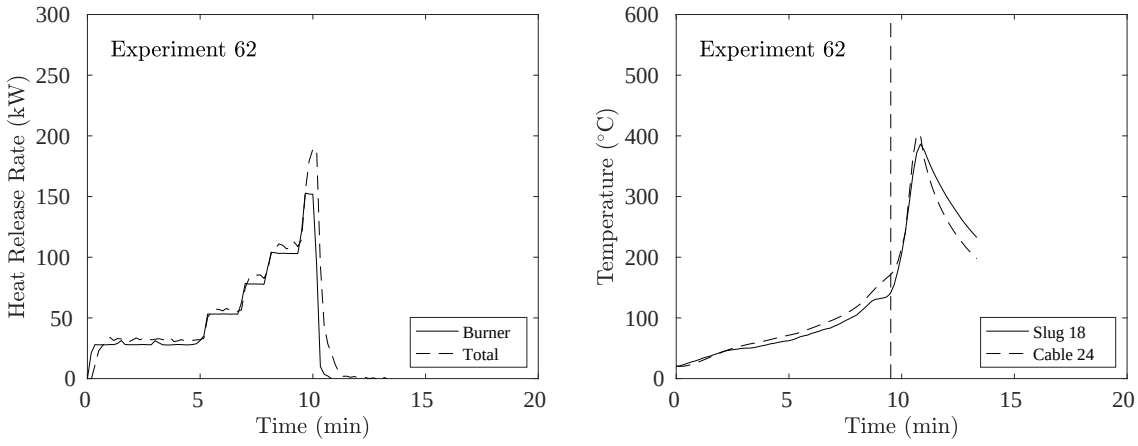


Fig. 83. Heat release rate (left) and peak target temperatures (right) for Exp. 62. The curve labeled “Burner” in the left plot represents the ideal HRR based on natural gas flow, and “Total” is the HRR measured via oxygen-consumption calorimetry.

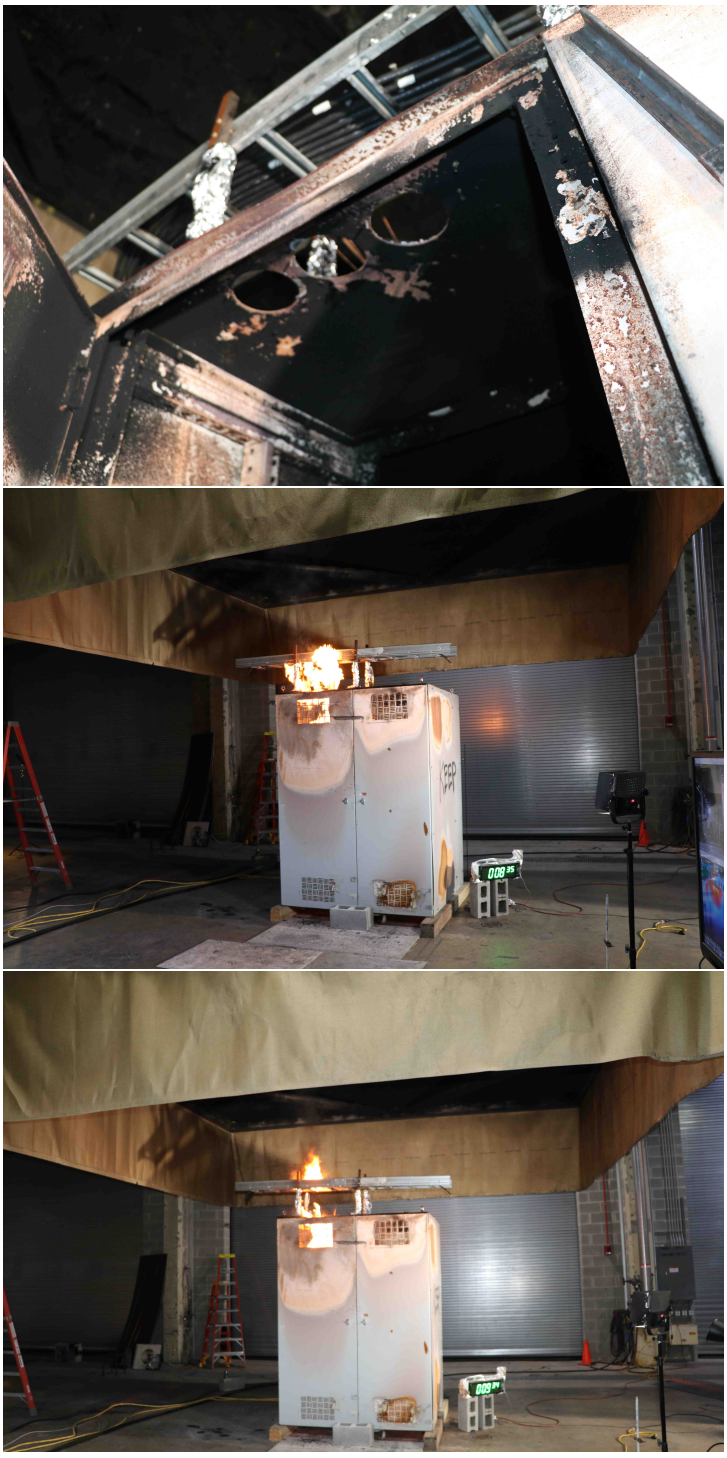


Fig. 84. Photographs of Experiment 62. The upper photograph shows the three holes in the enclosure top just above the location of the burner. The middle photograph shows the fire at 8 min, 35 s, just prior to cable ignition. The bottom photograph shows the cables igniting at 9 min, 34 s.

4.3.15. Experiment 63

This experiment was similar to Exp. 61 except that the three holes above the burner were covered with a thin sheet of steel. This sheet did not completely seal the holes, and some flames were able to pass through the gaps. Nevertheless, the shielding delayed ignition of the thermoset cables until approximately 44 min.

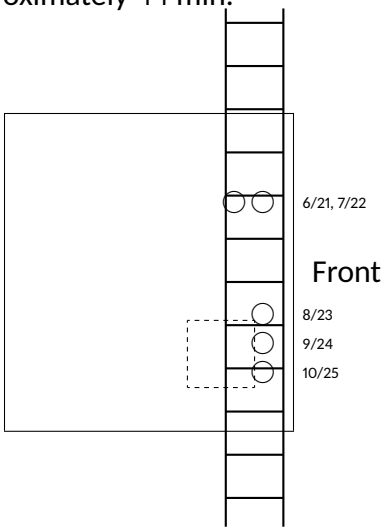


Fig. 85. Plan view of the enclosure with a single cable tray set on top. The dashed box indicates the location of the burner within the enclosure. The circles indicate the location of the 11 cm (4.5 in) diameter holes cut into the enclosure ceiling. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40) which were positioned over each hole. The tray held 10 thermoset cables.

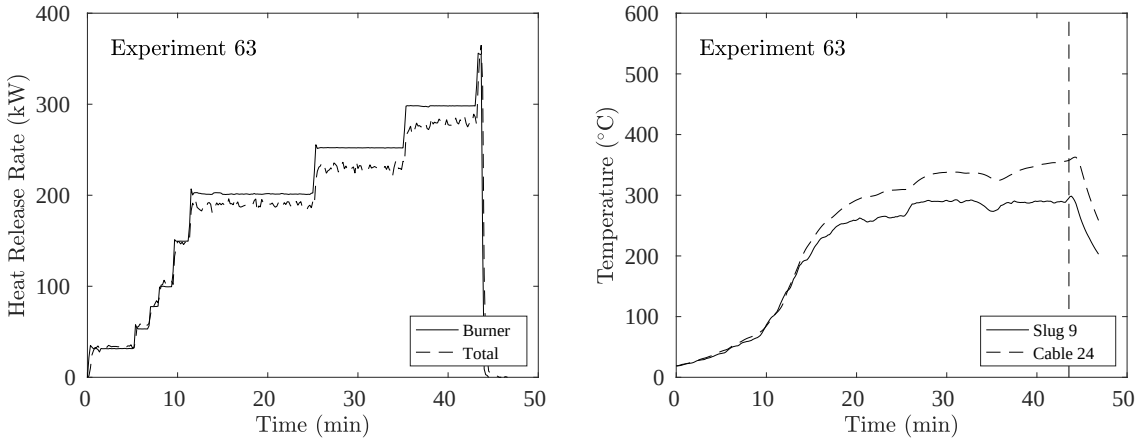


Fig. 86. Heat release rate (left) and peak target temperatures (right) for Exp. 63. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.

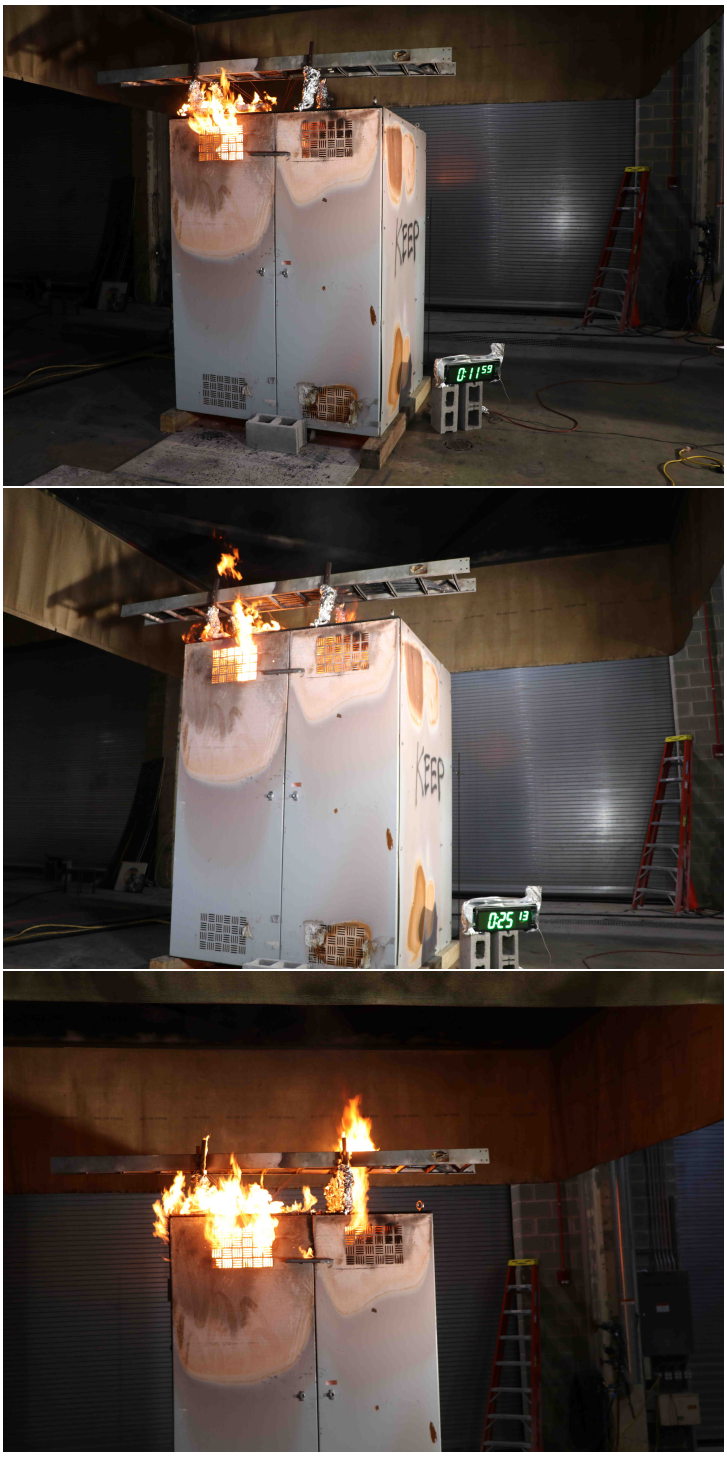


Fig. 87. Photographs of Experiment 63. The upper photograph shows the fire 12 min after the ignition of the burner. The middle photograph shows the fire at 25 min, 13 s. The lower photograph shows ignition of the cables above the two holes in the enclosure top that were not covered at approximately 44 min.

4.3.16. Experiment 64

This experiment was similar to Exp. 63 except that thermoplastic cables were used, and they ignited after approximately 14 min.

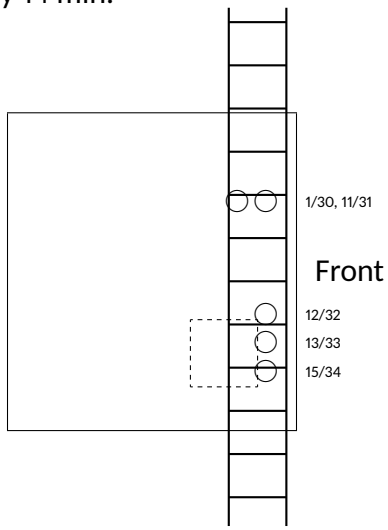


Fig. 88. Plan view of the enclosure with a single cable tray set on top. The dashed box indicates the location of the burner within the enclosure. The circles indicate the location of the 11 cm (4.5 in) diameter holes cut into the enclosure ceiling. The numbers refer to either the aluminum slugs (1-20) or instrumented cables (21-40) which were positioned over each hole. The tray held 10 thermoplastic cables.

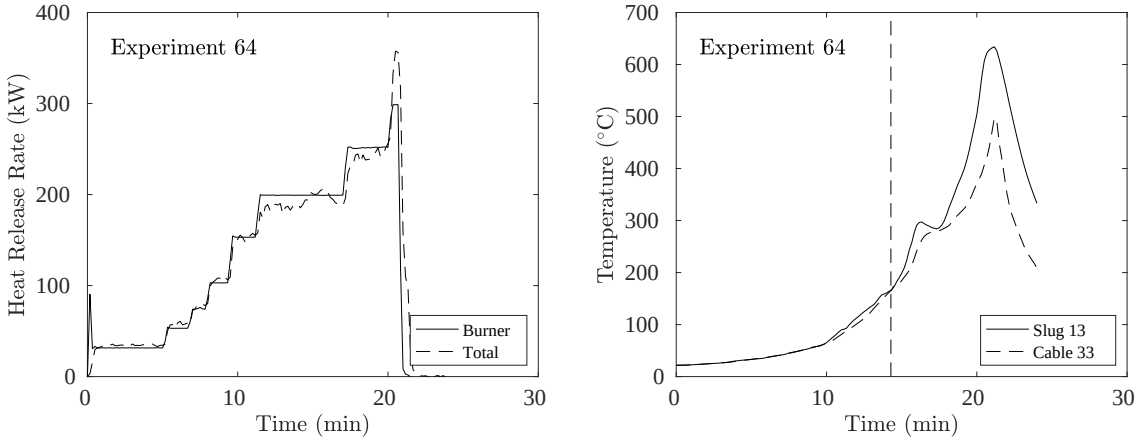


Fig. 89. Heat release rate (left) and peak target temperatures (right) for Exp. 64. The curve labeled "Burner" in the left plot represents the ideal HRR based on natural gas flow, and "Total" is the HRR measured via oxygen-consumption calorimetry.

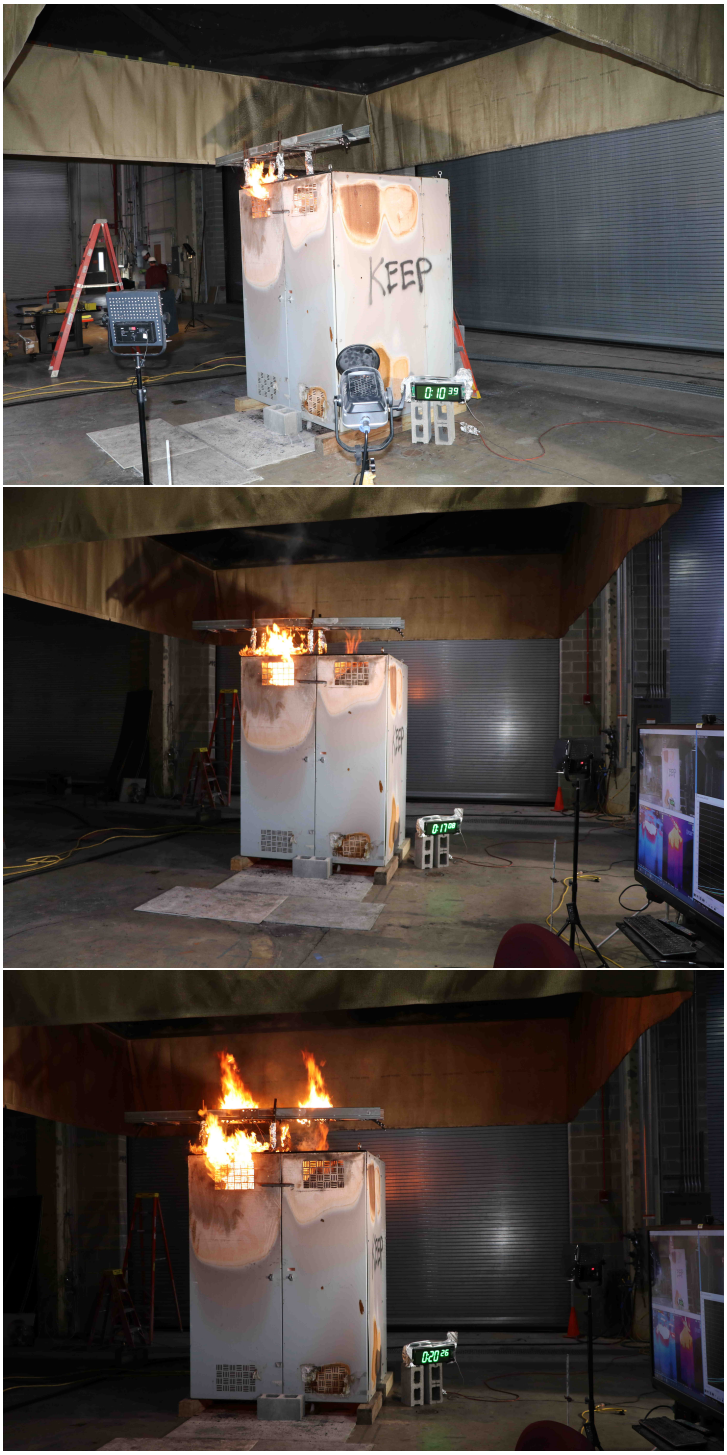


Fig. 90. Photographs of Experiment 64. The upper photograph shows the fire at 10 min, 39 s. The middle photograph shows the fire at 17 min, 8 s. The lower photograph shows the cables burning above each set of holes at 20 min, 26 s.

5. Conclusion

Experiments were conducted to measure the heat release rate (HRR) and burning behavior of circuit breaker fires within closed steel enclosures. Of note:

- Fires within compartments of the enclosure exhibited typical “flashover” behavior; that is, flames emerging from the opening of an under-ventilated compartment. The measured temperatures within these compartments (both gas and solid) ranged between 600 °C and 800 °C, typical of an uninsulated steel enclosure.
- In the first experiment (Exp. 33) conducted in the ABB enclosure, the fire spread through double-walled steel partitions in approximately 10 min. Vigorous burning of combustibles was noted when the compartment gas temperature reached approximately 400 °C.
- Referring to Exp. 33 in the ABB enclosure, the combustible load within the upper compartments was sufficient to maintain a fire long enough for the neighboring compartment to heat up and burn.
- The aluminum “slug calorimeters” and the interior of the instrumented cable segments exhibited similar temperatures, suggesting that the slugs might be a suitable surrogate to assess the vulnerability of electrical cables near or within a fire.
- Using the measured mass loss of one of the breakers and estimates of the total mass consumed, a least squares regression was used to estimate the combustible mass of the ABB breaker (3.7 kg), lower compartment (3.5 kg), and upper compartment (2.7 kg). The uncertainty of these estimates is approximately 20 %.
- The peak HRR of a fire burning within a single compartment of the ABB enclosure is approximately 100 kW.

Experiments were also conducted to characterize the thermal environment of cables in trays above a burning electrical enclosure. For the two types of cables considered in this study, cable ignition does not occur unless they are substantially bathed within the flames of the exposing fire. The thermoplastic cable used in the experiment tends to ignite more readily than the thermoset cable, but it still requires contact with flames rather than just the hot plume.

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