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# Effects of Quantity and Arrangement of a Flame-Retardant Cable on Burning Characteristics in Open and Compartment Environments

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**Abstract:** The results of cable burning experiments conducted in a well-controlled or open environment may differ from fire phenomena in an actual installation environment of cables where the effects of ventilation conditions and thermal feedback exist. In order to prevent the misunderstanding of fire phenomena due to these differences, the changes in burning characteristics in open and compartment environments were investigated for a flame-retardant (TFR-8) cable and general PVC (VCTF) cable arranged on three-layer trays. As a result, it was confirmed that the fire scale, fire spread area, and cable damage varied greatly depending on the cable arrangement under the same cable quantity condition. Furthermore, the maximum heat release rate (HRR) and fire growth rate of TFR-8 in the compartment environment increased more than 3-times compared to the open environment, and showed a similar level of fire risk to VCTF even though it is a flame-retardant cable. Additional experiments using vertical and horizontal openings of various shapes were conducted to evaluate the individual contributions of thermal feedbacks from the wall and smoke layer to the changes in burning characteristics within the compartment. The results of this study can be used as basic data to reduce fire damage while providing an essential understanding of cable fire phenomena.

**Keywords:** burning characteristics; compartment fire; flame-retardant cable; maximum heat release rate; fire growth rate



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## 1. Introduction

Technological developments have led to a significant increase in electricity-based equipment and power transmission, which has led to electric cables being widely used in large-scale facilities such as factories, petrochemical complexes, and power plants as well as in typical buildings such as residential spaces. For example, hundreds of kilometers of cables are used in a nuclear power plant for power supply, signal transmission, and equipment control [1]. However, cables can turn into ignition sources due to various causes such as poor jacket life, short circuits, and poor grounding. The fires that occurred in Greifswald unit 1 (1975) and Armenia unit 1 (1982) can be considered as representative cases, where the fires were caused by defects in cables and involved severe damage [2]. Cables can act as ignition sources and become secondary combustibles that cause the spread of fire attributed to the heat applied from the nearby fire. In the Browns Ferry nuclear power plant in 1975, a fire that occurred in polyurethane foam used for sealing the walls through which the cables pass spread to the cable spreading and main control rooms. Thus, in such large facilities, cables represent the majority of all combustible materials; for this reason, recently, flame-retardant cables capable of suppressing or reducing ignition and fire spread have been widely used.

Flame-retardant cables have a higher flame resistance than the standard, and they are evaluated by international standard test methods [3–6]; the flame-retardant performance is evaluated through various test methods and standards based on the application. Flame-retardant cables with certified performance are used widely to control fire extinguishing systems in typical buildings, which include nuclear power plants. However, for standard test methods, the flame-retardant performance of cables is evaluated under specific experimental conditions that are different from the actual installation environment of the cable. Furthermore, the evaluation criteria for quantifying the flame-retardant performance are significantly different based on the test methods. Riese [7] quantitatively compared the fire characteristics of the cables used in nuclear power plants based on test methods used at various scales (small, intermediate, and real-scale) and reported that there were significant differences in the heat release rate (HRR), smoke development, damaged area, and time required for combustion depending on the test method. Hull et al. [8] compared the yields of CO, HCl, $CO_2$, and smoke for five types of cables through bench and large-scale experiments and reported that the fractional effective dose (FED) of occupants for toxic substances varied significantly based on the ambient temperature, ventilation conditions, and the scale of the experiment. Therefore, standard test methods can be used to evaluate the flame-retardant performance of cables in a specific fire environment, but there are clear limitations in evaluating intrinsic fire hazards such as the ignition, flame, and smoke spread of cables in actual fire environments. To address this problem, various studies have been recently conducted to identify and predict actual cable fires through lab-scale and full-scale fire experiments [9–18].

In laboratory-scale studies, to understand the burning characteristics of cables [9–15], the fire characteristics are investigated using a cone heater [19] and a microscale combustion calorimeter [20]. For example, Luche et al. [9] examined the mass loss rate of polyethylene cables and the concentrations of chemical species included in combustion products based on the incident heat flux. Yang et al. [10] compared the pyrolysis characteristics and flammability of eight types of cables with different configurations and materials using a pyrolysis combustion flow calorimeter. Mun and Hwang [14,15] conducted an experimental study on cables composed of various materials to secure the input parameters of the cable fire simulation; they presented reference temperatures and reference rates for predicting the CO and soot yields as well as the pyrolysis performances of each cable based on the incident heat flux.

Lab-scale experimental studies provide useful information to understand the characteristics of cables such as pyrolysis, burning, and toxic substance generation under controlled fire environments despite the quantitative differences from actual fires. The HRR per unit area, ignition temperature, combustion heat, and yields of chemical species are measured for various cables; the results are then used as input parameters for qualitative fire risk assessment and fire simulation for cable fire spread. Zavaleta et al. [21] evaluated the prediction performance of the FLASHCAT model [1,16,22] for predicting cable fires using a Fire Dynamics Simulator [23] and found that it was significantly different from the experimental results. In addition, a modified FLASHCAT model was proposed to reflect the changes in fire phenomena attributed to the interaction between the walls and the cable tray in the prediction results. The modified FLASHCAT model provided appropriate prediction results when optimized input variables were applied to the experiment to be verified. However, the simulation results may have significantly different errors from the actual phenomena when the arrangement of cable trays, quantity and arrangement of cables, and ventilation conditions are changed. Therefore, experimental study under various fire conditions is necessary for understanding cable fires and strengthening the reliability of the fire risk assessment.

Full-scale fire experiments on cable trays are actively conducted to understand the actual fire phenomena under various conditions and to overcome qualitative and quantitative differences between the lab-scale experimental results and actual phenomena [1,16–18]. The U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) conducted horizontal and vertical fire spread experiments on various cables arranged in trays and examined differences in HRR and fire spread patterns [1,16]. Zavaleta et al. [18] examined the effect of the tray angle on fire spread for nuclear power plant cables and measured various physical quantities such as the mass loss rate, HRR, and gas temperature. Since these experimental studies were conducted in an open environment, they had clear limitations in understanding the burning characteristics of cables that can be changed by the thermal feedback applied from the walls and the smoke layer inside the cable installation compartment.

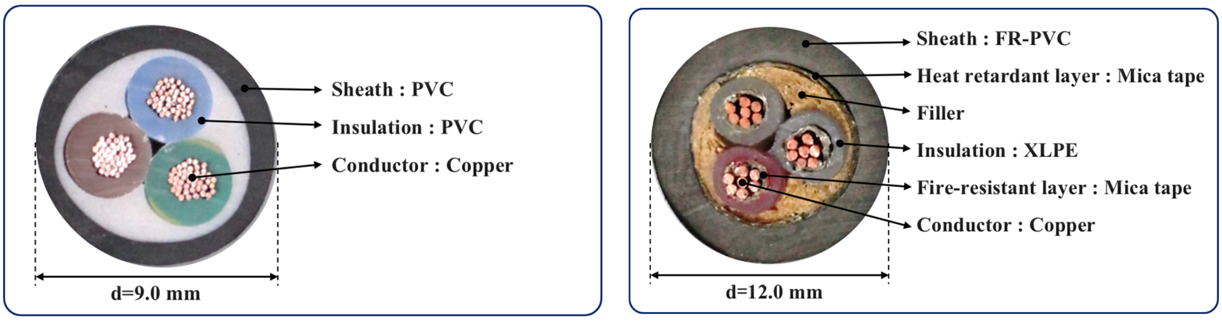
As a study on the cable fire spread inside a compartment, a corridor fire was reproduced in a tunnel-shaped structure under some conditions in a study conducted by NRC and EPRI [16]. However, a tunnel-shaped compartment with only side walls and a ceiling may have significantly different fire behaviors from typical compartments with openings. Recently, in the PRISME door test, an international joint research project of OECD/NEA—an experimental study on cable fire spread inside multiple components—was conducted [24]. This study examined the fire behavior based on the forced ventilation rate in a closed compartment; the fire growth was reported to be significantly different based on the quantity and arrangement of cables on the tray [25–27]. Although the results of these previous studies can be utilized, it can be limited to special fire environments in nuclear power plants where forced ventilation is applied in closed compartments. Therefore, it is necessary to examine fire phenomena based on the quantity, arrangement, and type of cables in compartments for a more general cable fire risk assessment, where the natural ventilation is performed through vertical openings. This is highly valuable from the perspective of fire safety design.

Given this context, the burning characteristics of the cables arranged on three trays were examined experimentally in open and compartment environments in this study. The tray flame-retardant power cable (TFR-8), which passed the IEEE-383 standard [6] and has been used for the control of firefighting equipment in buildings, was selected as the flame-retardant cable for this study. Furthermore, the vinyl cabtire (VCTF) cable is made of polyvinyl chloride (PVC) and is vulnerable to heat; it is considered as a comparison target to clarify the difference in burning characteristics depending on the flame-retardant performance of the cable. For these two cables, the HRR, fire growth rate, and thermally damaged area were compared in open and compartment fire environments. The changes in cable burning characteristics attributed to the combustion environment are discussed. Meanwhile, the change in the burning characteristics based on the quantity of the cable, which is defined as the ratio of the area occupied by the cable to the projected area of the tray, and the arrangement of the cable were also examined. Finally, the change in the height of the vertical opening and the application of the horizontal opening located on the ceiling of the compartment were additionally considered to identify the effect of the thickness of the high-temperature smoke layer inside the compartment on the fire spread. Through this, the thermal feedback effects of the walls and smoke layer, which are considered the main causes of differences in the fire characteristics in open and compartment environments, were examined individually.

## 2. Experimental Details

### 2.1. Target Cables

A flame-retardant cable (TFR-8) and a conventional PVC (VCTF) cable were selected as experimental targets to examine changes in the burning characteristics based on the quantity and arrangement of cables in open and compartment fires. TFR-8 cables are used in firefighting equipment such as in fire alarm devices, emergency lights, and sprinklers, wherein the performance needs to be maintained consistently in the event of a fire. The VCTF cable is used as an electrical cord for power supply to everyday electronic devices. Figure 1 shows the cross-sectional geometry of the two types of cables with multiple layers and multiple components. As shown in Figure 1a, the VCTF cable is significantly vulnerable to heat because both the insulation and sheath excluding the conductor are made of PVC. As shown in Figure 1b, the flame-retardant performance of the TFR-8 cable is strengthened because the outer sheath and insulation are made of flame-retardant PVC and cross-linked polyethylene, respectively. Moreover, mica tapes located inside the sheath and insulation form heat-retardant and fire-resistant layers, respectively. The TFR-8 cable can maintain its flame-retardant performance for 3 h in an environment of 750 °C. Conductors inside these selected cables have the same specification of 1.5 mm$^2$ $\times$ 3C.




(**a**) VCTF (diameter = 9.0 mm) (**b**) TFR-8 (diameter = 12.0 mm)

**Figure 1.** Cross-section photos of target cables and their constituent materials.

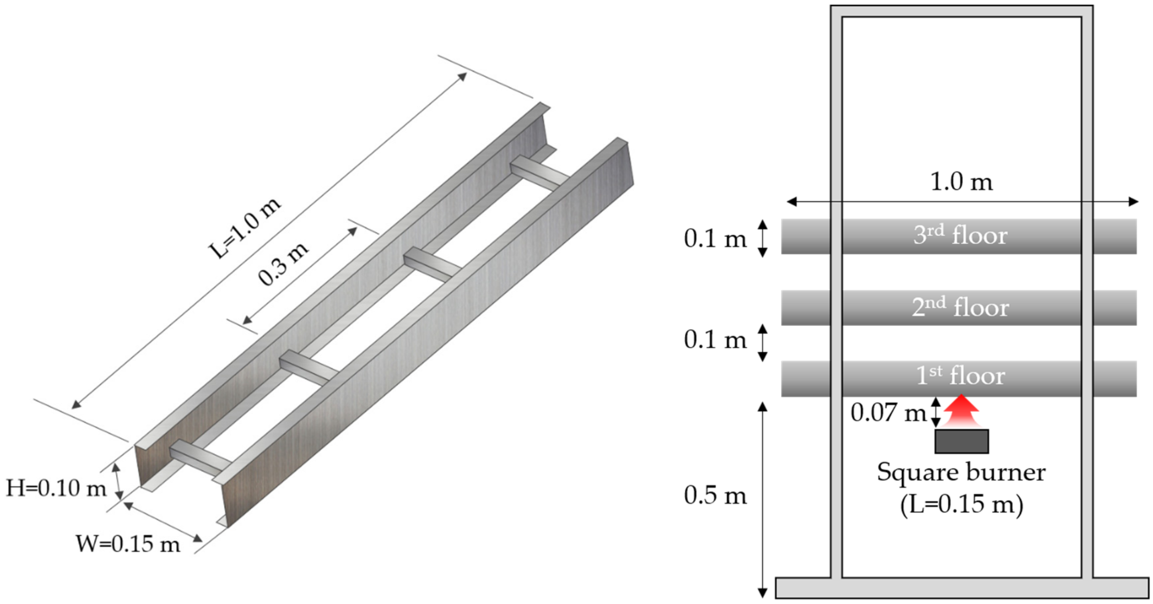
*2.2. Experimental Setup in Open and Compartment Fire Environments*

Figure 2 shows the schematic of the cable tray and experimental setup for the arrangement of the VCTF or TFR-8 cables in an open environment. The experimental setup was geometrically reduced to a 1/3 scale based on the experimental setup geometry used in a study conducted by the U.S. NRC and EPRI [1]. Since a 3.0 m long and 0.45 m wide cable tray was used in the referenced study [1], a 1.0 m long and 0.15 m wide cable tray was employed in this study, as shown in Figure 2a. Figure 2b shows the schematic of the cable trays in the three layers. The spacing between the trays and the relative position of the square burner installed for cable ignition (distance between the bottom surface of the 1st floor tray and burner rim) were 0.1 and 0.07 m, respectively; these were determined by reducing the scale applied in the previous study [1] to a 1/3 level.

The most important experimental conditions considered in the scale model for the ignition of solid combustibles and fire spread include the area of the ignition source (burner) and the HRR of the burner. The correlation between the prototype and the model can be derived through the dynamic similarity of the flow using the Froude number in a fire experiment where the scale model is applied [28]. For example, for the HRR (40 $\pm$ 5 kW) of the prototype applied in the previous study [1], the HRR that can be applied to the surface of the burner with a side length reduced to a 1/3 level is approximately 2.57 kW. However, in this study, geometrical similarity is not applied to the cables unlike that in the cable tray. Furthermore, it is impossible to identify the physicochemical correlation between the prototype and the model through the similarity law of the Froude number for the complex pyrolysis and gas-phase reactions of the cables. Flame length based on the surface of the burner installed under the cable tray significantly affects the ignition and fire spread through interaction with the cable. Unfortunately, the ignition and fire spread of the cable placed on the first floor cannot be observed because of the short flame length and low HRR when the HRR calculated through the similarity law based on the Froude number is applied. Therefore, in this study, the flame length in the scale model was determined considering the experimental condition of the prototype wherein the flame length from the burner reaches the cable tray on the second floor.

The correlation of the mean flame height proposed by Heskestad was applied to reproduce the determined flame length [29]; then, the final burner size and HRR were determined. Consequently, a square burner with an area of 0.15 m $\times$ 0.15 m was installed under the tray on the first floor, as shown in Figure 2b. Propane was used as fuel, and an HRR of 7.07 kW was supplied. Propane gas was supplied at a controlled flow rate through a mass flow controller (MFC), and the burner was filled with glass beads to form uniform flow. The HRR from the burner was supplied continuously until the end of the experiment.

The experiment was terminated when the flame ignited on the cable was extinguished without further spread or when the cable was completely burnt.




(**a**) Cable tray (**b**) Experimental setup

**Figure 2.** Schematic diagrams of the experimental setup to examine the burning characteristics of cables in an open environment.

Figure 3 shows the schematic of the experimental setup used to investigate the burning characteristics of cables in a compartment environment and under various vertical openings. The 1/3 reduced model of the ISO 9705 room is shown in Figure 3a [30]; the inner dimensions of this compartment were 0.8 m × 1.2 m × 0.8 m. Two layers of 12.5-mm-thick fire-resistant gypsum boards were installed as the walls of the compartment, and the interior was finished with a 25-mm thick blanket-type (Cerakwool) insulation material. Inside the compartment, the cable trays in the three layers with the same size and spacing as in the open environment were installed. Furthermore, the position, size, and HRR of the applied burner were identical to the experimental conditions in the open environment. The standard vertical opening shown in Figure 3b was applied in the compartment fire experiment conducted for comparison with the cable-burning characteristics in the open environment. In addition, the height of the smoke layer was changed by adjusting the height of the vertical opening (h) to examine the effect of the high-temperature smoke layer on the burning characteristics of the cables. Thus, the reduced and expanded vertical openings as well as the standard vertical openings were considered. The height of the opening was reduced by half for the reduced vertical opening condition to induce an increase in the thickness of the smoke layer compared to that for the standard case. In the expanded vertical opening condition, the height of the opening was increased to 0.8 m, the same as the compartment, to minimize the smoke layer formation. However, under the expanded vertical opening condition, a certain thickness of the smoke layer is inevitably formed while the combustion products generated from the burner and combustibles are discharged to the outside of the compartment through the vertical opening. Thus, a horizontal opening was additionally applied to the compartment ceiling under the condition where the expanded vertical opening is applied to exclude the effect of the smoke layer on the burning characteristics of the cables. The horizontal opening is located directly above the cable trays, and smoke is immediately discharged outside the compartment.

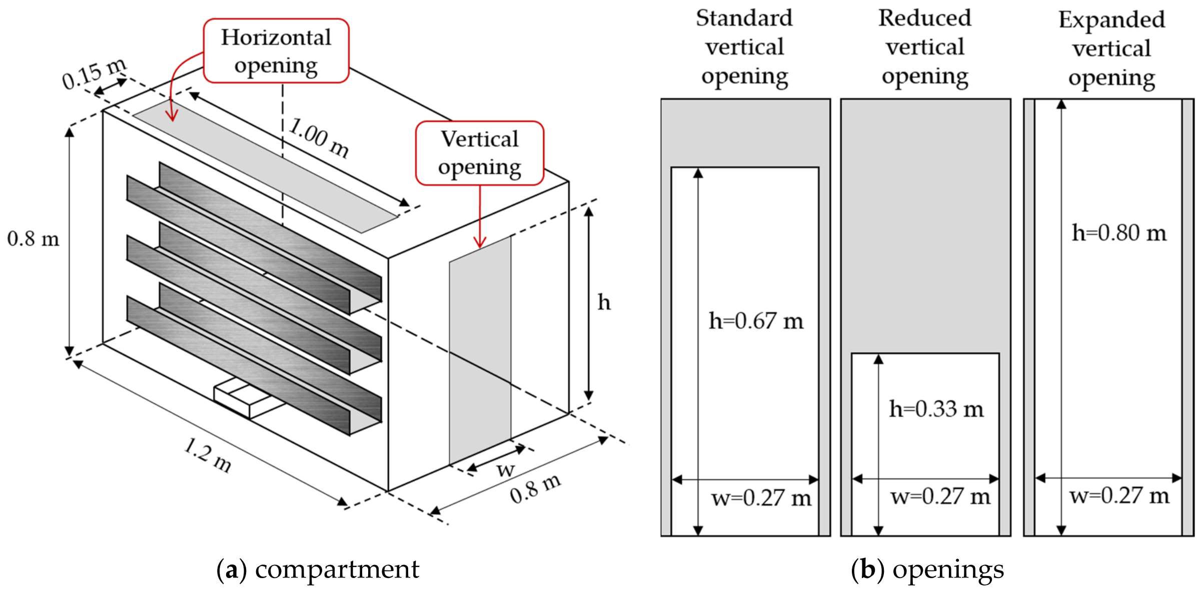


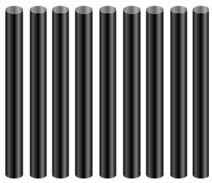

**Figure 3.** Schematic diagrams of the experimental setup to examine the burning characteristics of the cables in a compartment fire environment.

The change in the geometry of the vertical opening affects the air inflow rate into the compartment directly. Consequently, it can have a direct impact on the fire growth. Based on the ventilation factor concept [31], the maximum air inflow rate (kg/s) into the compartment through the vertical opening in the flashover or fully developed fire growth stage was calculated using 0.52 $A\sqrt{h}$, where $A$ and $h$ represent the area of the vertical opening (m$^2$) and vertical height of the opening (m), respectively. For the standard, reduced, and expanded vertical openings considered in the study, the maximum mass flow rates of the introduced air were 0.077, 0.027, and 0.100 kg/s, respectively. The changes in the amount of air introduced caused by the change in the geometry of the vertical opening led to a change in the global equivalence ratio ($\phi_g$) inside the compartment [32]. The global equivalence ratio is defined as the ratio of the fuel mass loss rate within the compartment to the air inflow rate into the compartment, and is normalized by the stoichiometric ratio for the fuel. Thus, under the condition $\phi_g < 1$ (over-ventilated fire condition), most chemical reactions occur inside the compartment because the air is sufficient compared to that in the supplied fuel. However, under the condition $\phi_g > 1$ (under-ventilated fire condition), incomplete combustion occurs because of insufficient air, and an ejected flame is created through the opening because of the increased flame length. In order to calculate the global equivalence ratio according to the experimental conditions, the mass flow rate of fuel (mass loss rate) must be measured. However, it was impossible to measure the mass loss rate using the load cell in this study because the cables were placed on the trays. Consequently, the global equivalence ratio based on the change in the geometry of the vertical opening was also not calculated. Considering that most of the burning was completed inside the compartment, except for the intermittent flame ejection through the vertical opening under some experimental conditions, it can be sufficiently expected that all experimental conditions considered in this study correspond to the over-ventilated fire condition. Thus, the effect of the change in the ventilation conditions on the burning characteristics is insignificant under the experimental conditions considered in this study; furthermore, changing the height of the vertical opening to control the smoke layer height inside the compartment can be evaluated as an appropriate approach.

*2.3. Conditions for the Quantity and Arrangement of Cables Placed on Trays*

Table 1 summarizes the experimental conditions for the quantity and arrangement of the VCTF and TFR-8 cables placed on trays in open and compartment environments. The quantity of cables is changed by $R_A$, which is defined as the ratio of the projected area of cables to the floor ($A_{cable}$) to the area of the tray ($A_{tray}$). The dense arrangement of cables in contact with each other, arrangement at equal intervals, and a cable bundle with two or three layers were considered as the cable arrangement conditions. These conditions were referred to as types 1, 2, and 3, respectively. For types 1 and 2, $R_A$ = 0.50, 0.75, and 1.00 conditions were considered. For type 1, the cables were placed in the center of the tray when the number of cables decreased. Furthermore, the spacing between the cables was determined by equally dividing the width of the empty space not occupied by the cables placed on the tray when the number of cables changed under the condition of type 2. Moreover, the condition $R_A$ = 1.00 was not considered for type 2 because it was the same as $R_A$ = 1.00 of type 1.

**Table 1.** Experimental conditions regarding the quantity and arrangement of the VCTF and TFR-8 cables placed on trays.

| | | **Type 1** | | | **Type 2** | | | **Type 3** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $R_A$ $(A_{cable}/A_{tray})$ | | 0.50 | 0.75 | 1.00 | 0.50 | 0.75 | - | 0.25 | | |
| Arrangement of cable (examples of 9 TFR-8) | |  | | |  | | |  | | |
| Number of cable | VCTF (d = 9.0 mm) | 8 | 12 | 16 | 8 | 12 | - | 8 (4 × 2) | 12 (4 × 3) | 16 (4 × 4) |
| | TFR-8 (d = 12.0 mm) | 6 | 9 | 12 | 6 | 9 | - | 6 (3 × 2) | 9 (3 × 3) | 12 (3 × 4) |

All experimental conditions of type 3 had the same projected area of cables with $R_A$ = 0.25; however, the number of cables was changed through an arrangement in multiple layers. In this instance, the change in the number of cables under the condition of type 3 was the same as that for the conditions of $R_A$ = 0.50, 0.75, and 1.00 for types 1 and 2. Therefore, $R_A$ = 0.50, 0.75, and 1.00 were indicated based on the number of cables for convenience during the analysis process. The number of cables according to $R_A$ is presented for types 1 and 2, respectively, in Table 1. For type 3, the number of cables placed on the floor and the number of layers in the vertical direction when the number of cables changed are included in parentheses. For example, the schematic presented in Table 1 shows an example of the arrangement method for nine TFR-8 cables. All experimental conditions presented in Table 1 were applied in the cable fire spread experiment performed in the open environment. However, in the compartment environment, only the selected experimental conditions were considered for examining the fire spread phenomenon based on the quantity and arrangement of cables. For type 1, the experiment was performed under all $R_A$ conditions, and the effect of the quantity of cables on fire spread was also examined. The experiments for types 2 and 3 were conducted under the condition ($R_A$ = 0.75), where 12 VCTF cables and nine TFR-8 cables were arranged.

### 2.4. Measurement and Analysis of Heat Release Rate (HRR)

In order to investigate the difference in fire spread according to the quantity and arrangement of cables in open and compartment environments, a number of thermocouples were installed inside (insulation) cables, on their surface, and on trays. However, the positions of the thermocouples were significantly changed because of the change in the geometry of cables during the pyrolysis process. The non-negligible measurement error caused by the radiant heat inside the compartment and the damage to thermocouples caused by high temperature were also confirmed. Because of this, there were significant limitations in identifying the quantitative difference in fire spread based on the quantity and arrangement of cables when performing the temperature measurements. Therefore, HRR [33], which is the most important physical quantity representing the global parameter of fire phenomena, was measured in this study to examine the change in the burning characteristics based on the quantity and arrangement of cables in the open and compartment environments. A medium-scale calorimeter with a measurement range of 300 kW based on the oxygen consumption method [34,35] was employed to measure HRR.

HRR is perceived as a measure that represents the scale of fire, and therefore, it is appropriate to consider the maximum HRR as the main physical quantity for the quantitative analysis on the burning characteristics of cables. In addition, the fire growth rate can be used as the main physical quantity for fire risk assessment. Thus, cable fires can be analyzed through the maximum HRR, fire growth rate, and thermally damaged area in this study. The maximum HRR and thermally damaged area can be evaluated through measurement and visual inspection, respectively, and the fire growth rate ($\alpha$) is quantified by the time square law [36], defined as

$$\dot{Q}\ (\mathrm{kW}) = \alpha t^2 \tag{1}$$

where $\dot{Q}$ and $t$ represent the change in the HRR from the start point of fire growth to its peak point and the time required between the two points, respectively. In this instance, the evaluation of the fire growth rate by the time square law shows a different result based on the judgment of the researcher on the start and peak points of fire growth. Thus, it is necessary to examine the quantification method for the fire growth rate prior to analyzing the experimental results. Figure 4 illustrates the fire growth rate calculation method in the present study; the total HRR measured in the open environment under the conditions of the TFR-8 cable, type 1, and $R_A = 0.50$ as well as the HRR of the square burner are shown in the figure. The $\alpha$ value has a significant error when the $\dot{Q}$ value is derived based on 0 kW at the starting point of the experiment because the total HRR includes the amount of heat supplied by propane gas. Therefore, the fire growth rate is calculated for the HRR change from the moment when the HRR for the burner reaches the set value to the moment when the maximum HRR caused by the fire spread of cables is reached. The increase in the HRR at approximately 100 to 350 s is attributed to the contact of cables with the flame generated by the burner, rather than the spontaneous fire spread. Thus, the change in the HRR in the burning section caused by flame contact is not reflected in the calculation of the fire growth rate. The maximum HRR mentioned hereafter represents the total HRR measured through the calorimeter; the HRR measured using the square burner was plotted simultaneously in all figures to confirm the net HRR caused by the burning of cables.

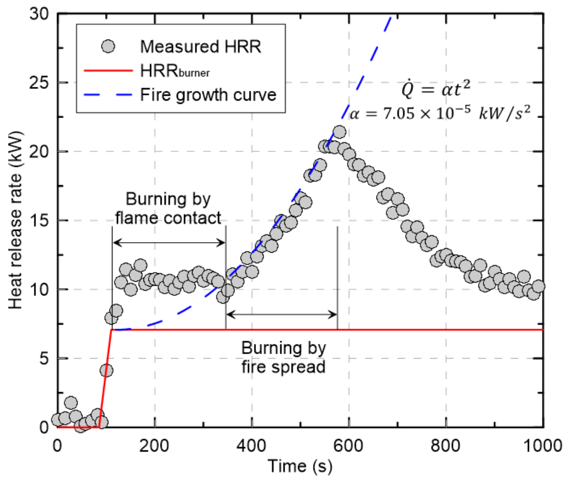



**Figure 4.** A fire growth curve to evaluate the fire growth rate using the measurement results of the TFR-8 cable (Type 1, $R_A = 0.5$) in an open environment as an example.

## 3. Results and Discussion

### 3.1. Burning Characteristics in the Open Environment

The global burning characteristics of the VCTF and TFR-8 cables based on the quantity and arrangement of cables were investigated in the open environment using the cable trays in three layers. Figure 5 shows the photographs of the flames at the moment of reaching the maximum HRR after ignition for the VCTF cables. The time required to reach the maximum HRR according to the quantity and arrangement of cables is indicated in the photographs. The results of $R_A$ = 0.50, 0.75, and 1.00 for type 1 were compared to examine the flame behavior according to the quantity of cables. Furthermore, in order to analyze the effect of cable arrangement, flame photographs according to arrangement type under the same conditions ($R_A$ = 0.75) were compared. For type 1, where cables were arranged in the center of the tray, the time required to reach the maximum HRR increased with an increase in the quantity of cables (i.e., the increase in $R_A$); the flame spread in the longitudinal direction of the tray. Thus, the spontaneous flame spread increased when the quantity of cables on the tray increased under the condition of type 1 because of the sufficient thermal energy. For type 2, where cables were arranged on the tray at equal intervals, the longest flame lengths among all types were obtained when the difference depending on the arrangement of cables was examined under the same condition ($R_A$ = 0.75). This can be attributed to the separated cables increasing the contact area with the flame, which accelerates pyrolysis and burning; type 3, where the same amount of cables was placed as a bundle, showed the shortest flame length among all types; and the fire spread in the longitudinal direction of the tray was hardly observed.

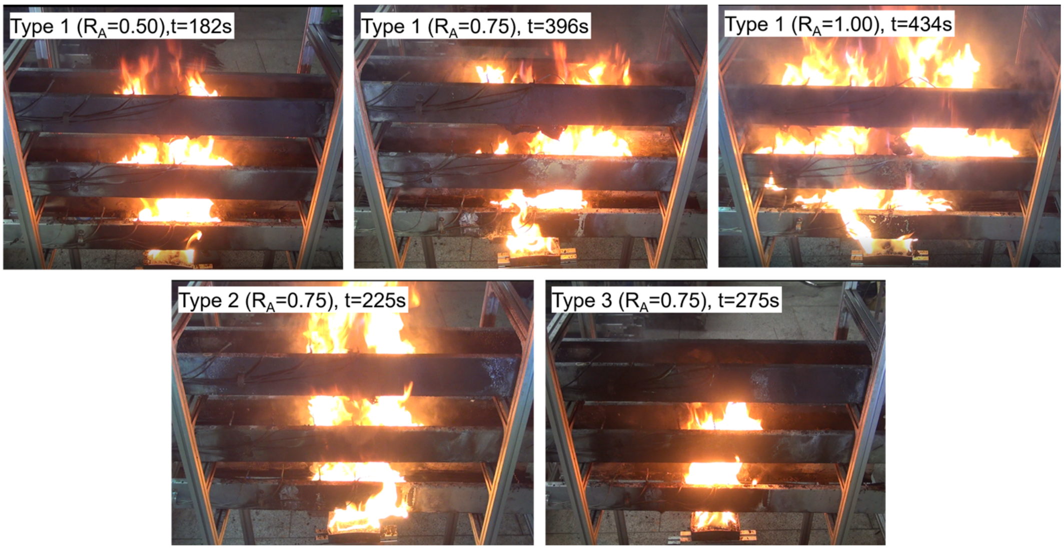
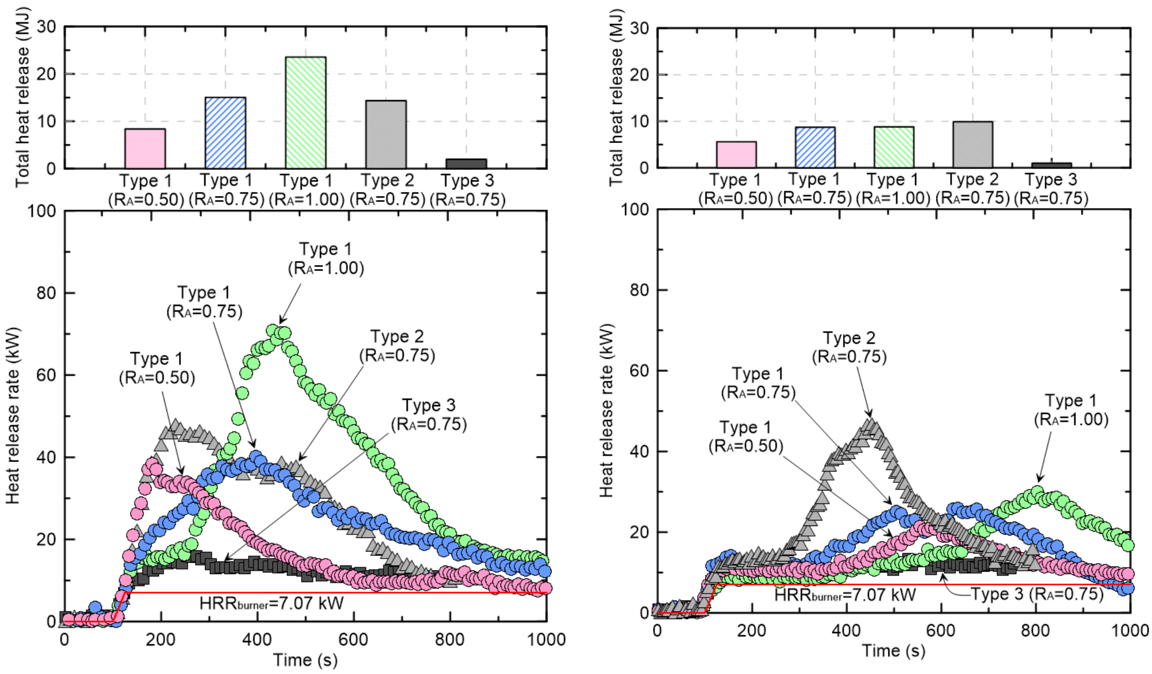



**Figure 5.** Photos of the flame at the moment of the maximum HRR according to the quantity and arrangement of the VCTF cable in an open environment.

Figure 6 shows the fire growth curve (lower figure) and total heat release (upper figure) based on the quantity and arrangement of the VCTF and TFR-8 cables. The HRR over time was measured using the calorimeter, and the HRR for the propane flame generated from the square burner was indicated using a solid line. Furthermore, the total heat release was obtained by integrating the HRR curve until the end of the experiment; this indicates the total thermal energy (MJ) generated after ignition. The results of the VCTF cables shown in Figure 6a indicate the different fire growth curves over time from the perspectives of the maximum HRR and fire growth rate depending on the increase in $R_A$ for type 1. For $R_A$ = 0.50, a sharp increase in HRR was observed at the beginning and decreased gradually; this implies that active fire spread in the longitudinal direction of the tray did not occur, as confirmed in Figure 5. Considering that the sufficient thermal energy caused by an increase in the quantity of cables is used as energy for further fire spread, the increase in the maximum HRR and total heat release caused by an increase in the quantity of cables can be understood clearly. Furthermore, the area on the first floor tray through which the flame from the square burner can penetrate decreases with an increase in the $R_A$ for type 1. Thus, the time required to reach the maximum HRR can be expected to increase gradually. When the fire phenomena was examined considering the arrangement of cables under the same condition ($R_A$ = 0.75), type 2 exhibited a faster fire growth and higher maximum HRR than type 1. However, types 1 and 2 exhibited similar total heat release values. Type 3 showed the lowest HRR and total heat release, as confirmed in Figure 5. The total heat release had the same value under the same type and quantity of cables, if the cables were completely burnt under all experimental conditions. However, the total heat release was different depending on the quantity and arrangement of cables, which indicates that the area of fire spread was different. In other words, it can be interpreted that the fire spreading area in types 1 and 2 was similar, but the fire spreading in type 3 hardly occurred.




(**a**) VCTF (**b**) TFR-8

**Figure 6.** Comparison of the fire growth curve and total heat release according to the quantity and arrangement method of cables in an open environment.

Figure 6b shows the results of the TFR-8 cables, which is a flame-retardant cable. The time required to reach the maximum HRR, the maximum HRR, and the total heat release increased with an increase in the $R_A$ for type 1. However, unlike the VCTF cable, even if the amount of cable is increased, the change in maximum HRR and the total heat release is not quantitatively large due to the flame-retardant performance. Type 2 exhibited the highest maximum HRR under the same condition ($R_A$ = 0.75) among the cable arrangement methods considered in this study. This result provides an important physical insight that even a flame-retardant cable can exhibit similar results to the fire growth of the general PVC cable (VCTF) based on the arrangement of the cables on the tray. Finally, type 3 exhibited the lowest maximum HRR and total heat release, similar to the results of the VCTF cables.

Figure 7 compares the maximum HRR results measured in the experiments performed using the trays in the three layers in the open environment. Figure 7a shows that the maximum HRR of the VCTF cables increased as $R_A$ (or the number of cables) increased for type 1, as indicated in Figure 6. For type 2, the maximum HRR increased with an increase in $R_A$, which was similar to that for type 1. When the difference between types 1 and 2 was examined under the same $R_A$ condition, no significant difference was observed in the maximum HRR depending on the arrangement method at $R_A$ = 0.50 because the absolute quantity of the combustibles was small. However, at $R_A$ = 0.75, the maximum HRR of type 2 (approximately 48 kW) was approximately 20% higher than that of type 1 (40.4 kW). For type 3, no significant change in the maximum HRR (approximately 16 kW) was observed despite the increase in $R_A$ (i.e., the number of cables). This implies that the contact area with the flame, which changes depending on the arrangement method, can significantly change the maximum HRR of a cable fire. Figure 7b shows the results for the TFR-8 cables. For type 1, the maximum HRR increased alongside the increase in $R_A$, which was similar to the results of the VCTF cables. However, the maximum HRR of the TFR-8 cables was significantly lower than that of the VCTF cables; this difference can be attributed to the flame-retardant performance of the cable. For type 2, the maximum HRR of the TFR-8 cables according to $R_A$ also increased. Under the condition $R_A$ = 0.75 for type 2, the maximum HRR of the TFR-8 cables (approximately 45 kW) was similar to that of the VCTF cables (48.1 kW), despite the flame-retardant performance. Thus, even for the flame-retardant cable, the maximum HRR increased significantly when the contact area with the flame increased. For type 3, the maximum HRR of the TFR-8 cables (approximately 10 kW) showed no significant change despite the increase in the quantity of cables as with the VCTF cables. This implies that the cable arrangement condition on the tray is a very important factor for the global burning characteristics of the cable.

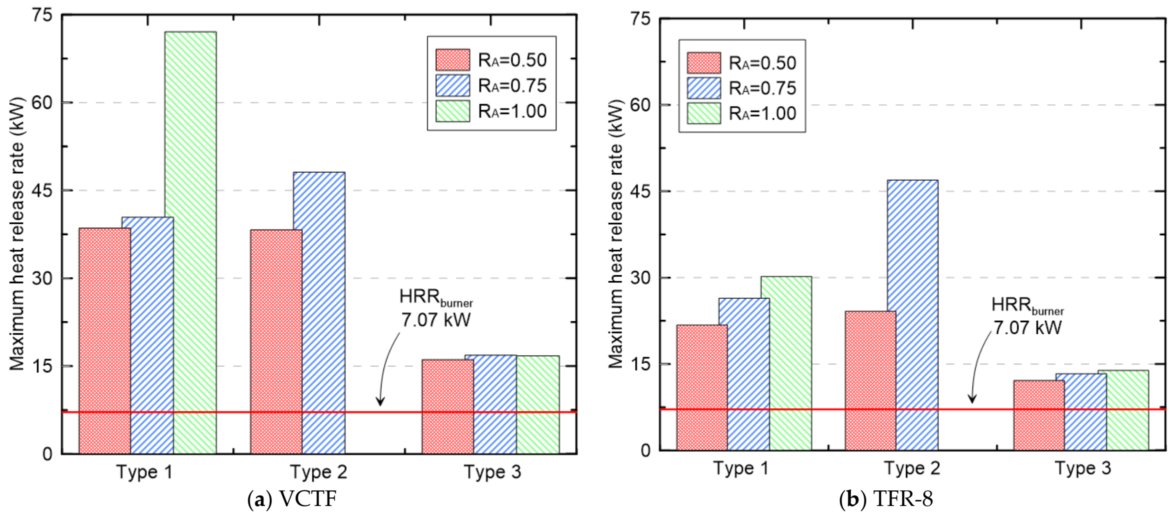



**Figure 7.** Comparison of the maximum HRR according to the quantity and arrangement method of cables in an open environment.

Figure 8 presents the comparison between the fire growth rates of the VCTF and TFR-8 cables in an open environment. Type 3 was excluded from the comparison because each cable showed negligible fire growth for type 3. Figure 8a shows the results of the VCTF cables. The fire growth rate decreased for type 1 with an increase in the quantity of cables; this was because the densely arranged cables showed the effect of blocking the flame propagation to higher layers, which is related to finding the time to reach the maximum HRR being delayed as more cables are arranged, as shown in Figures 5 and 6. However, for type 2, the fire growth rate increased with an increase in the quantity of cables; this was higher compared to that of type 1 under the same condition of $R_A = 0.75$. Figure 8b compares the fire growth rates of the TFR-8 cables. The overall trend was similar to that of VCTF, but when compared quantitatively, the fire growth rate of TFR-8 was less than 10% of that of VCTF under the same conditions. Under the $R_A = 0.75$ condition, the fire growth rate of the TFR-8 cables was several times higher for type 2 compared to that for type 1, which reconfirms that the cable arrangement method significantly changes the maximum HRR and fire growth rate.

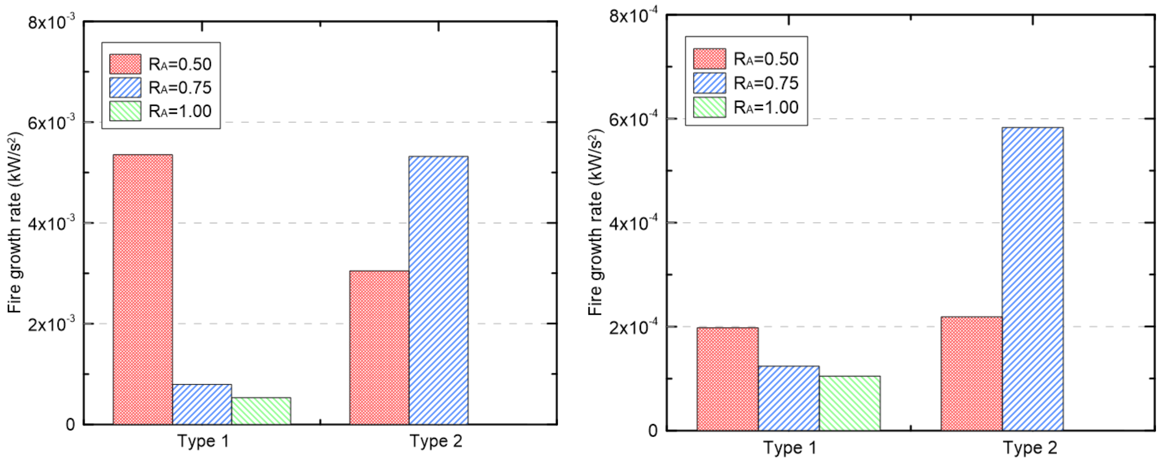
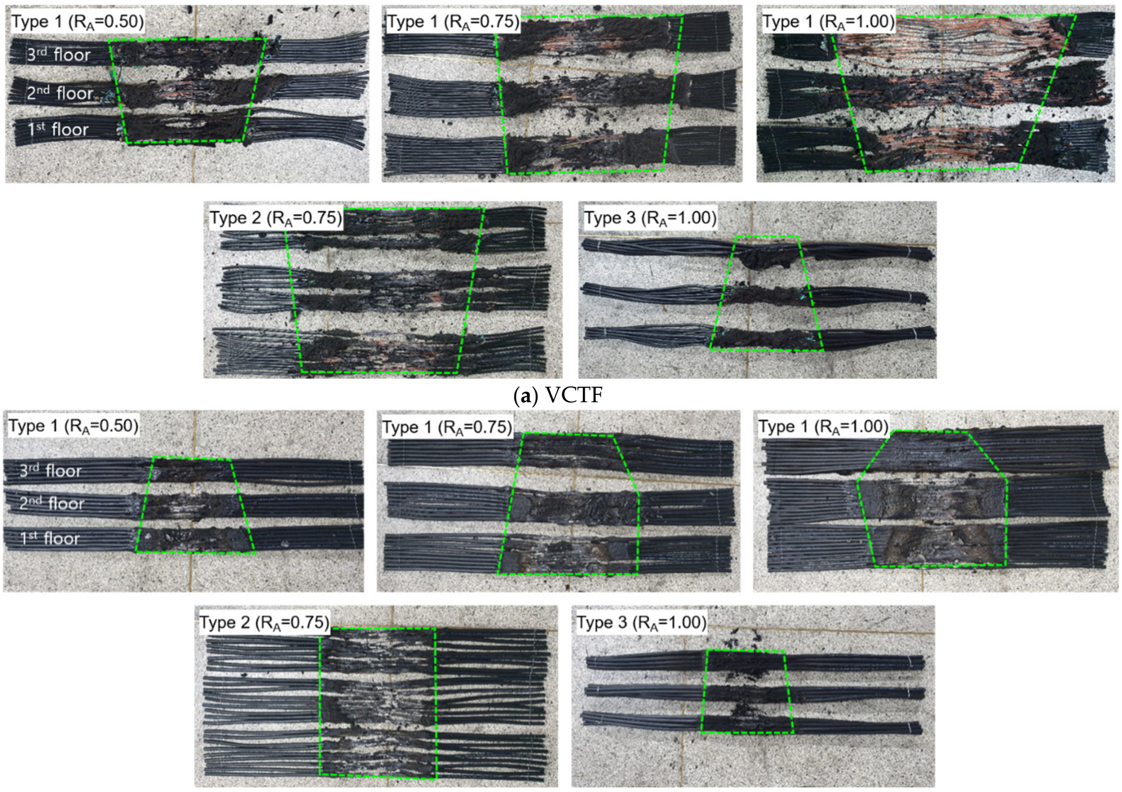



**Figure 8.** Comparison of the fire growth rate according to the quantity and arrangement method of cables in an open environment.

Figure 9 shows the photographs of cables captured after the experiment to compare the damaged area based on the experimental conditions (The green line represents the damaged area in each experiment). The photographs of all $R_A$ values can be seen for type 1, whereas those of $R_A$ with the largest number of cables under each condition can be seen for types 2 and 3. Figure 9a shows that the VCTF cables yielded a V-pattern fire spread tendency in which the damaged area increased on higher floors for type 1. Furthermore, the damaged area increased with an increase in the quantity of cables for the same arrangement method. Type 2 also showed a V-pattern fire spread behavior. Type 3 showed the opposite tendency, in which the damaged area decreased on higher floors. In terms of damage, types 1 and 2 exposed the conductors because of the combustion of the sheath and insulation; however, type 3 did not expose the conductors and only the sheath was damaged. Thus, type 3 indicates high safety. Figure 9b shows the damaged area of the TFR-8 cables. The TFR-8 cables with flame-retardant performance did not show a V-pattern fire spread tendency, unlike that of the VCTF cables. This implies that the combustion and fire spread of the cable were inhibited by the flame-retardant performance and that the fire risk was relatively low. Type 1 showed the largest damaged area under the same $R_A$ condition when the damaged area was examined based on the arrangement method. This result is contrary to the relatively high fire risks of type 2 in Figures 7 and 8. This is because the flame that collided with the cables is expanded in the horizontal direction for type 1, but the flame passes between the cables and the fire spreads because the combustion of the cables is inhibited by the flame-retardant performance for type 2. However, in terms of damage, type 2 showed the highest degree of damage among the three arrangement methods. Only the sheath surface was damaged under all conditions for type 1, but the sheath was burnt completely and the internal mica tapes and fillers were exposed for type 2. Nevertheless, the TFR-8 cables did not exhibit conductors under all conditions, unlike the VCTF cables. Table 2 summarizes the maximum HRR, fire growth rate, and damaged area for clearly identifying the burning characteristics according to the quantity and arrangement of cables in the open environment.




(**a**) VCTF

(**b**) TFR-8

**Figure 9.** Comparison of the damaged area according to the quantity and arrangement method in an open environment.

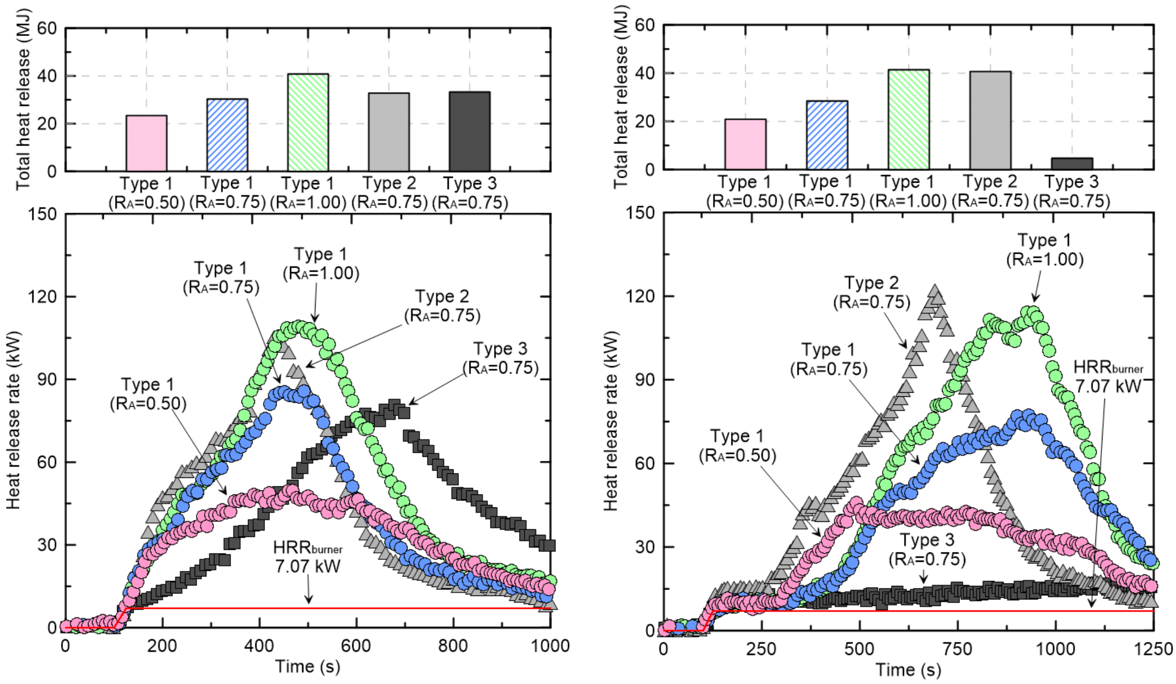
**Table 2.** Summary of the experimental results (maximum heat release rate, fire growth rate, and damaged area) according to the cable type, amount, and arrangement method in the open environment.

| Arrangement Method | $R_A$ | Max. HRR (kW) | | Fire Growth Rate (kW/s$^2$) | | Damaged Area (m$^2$) | |
|---|---|---|---|---|---|---|---|
| | | VCTF | TFR-8 | VCTF | TFR-8 | VCTF | TFR-8 |
| Type 1 | 0.50 | 38.6 | 21.8 | $5.4 \times 10^{-3}$ | $2.0 \times 10^{-4}$ | 0.092 | 0.059 |
| | 0.75 | 40.4 | 26.4 | $7.9 \times 10^{-4}$ | $1.2 \times 10^{-4}$ | 0.153 | 0.109 |
| | 1.00 | 72.1 | 30.2 | $5.3 \times 10^{-4}$ | $1.1 \times 10^{-4}$ | 0.245 | 0.152 |
| Type 2 | 0.50 | 38.3 | 24.2 | $3.1 \times 10^{-3}$ | $2.2 \times 10^{-4}$ | 0.086 | 0.043 |
| | 0.75 | 48.1 | 46.9 | $5.3 \times 10^{-3}$ | $5.8 \times 10^{-4}$ | 0.163 | 0.104 |
| Type 3 | 0.50 | 16.1 | 12.2 | - | - | 0.049 | 0.053 |
| | 0.75 | 16.9 | 13.3 | - | - | 0.080 | 0.079 |
| | 1.00 | 16.7 | 13.9 | - | - | 0.102 | 0.129 |

### *3.2. Burning Characteristics in the Compartment Environment*

Figure 10 shows the fire growth curve (lower figure) and total heat release (upper figure) based on the quantity and arrangement of the VCTF and TFR-8 cables in the compartment environment with the standard vertical opening. As shown in Figure 6, the HRR for the propane flame generated from the square burner is indicated using a solid line. Figure 10a shows the results of the VCTF cables. When the HRR according to $R_A$ was examined for type 1, significant changes in the maximum HRR and fire growth rate were observed compared to the experimental values in the open environment. For the VCTF cables arranged under the condition of type 1 in the open environment, the time required to reach the maximum HRR increased with an increase in the quantity of cables. However, the maximum HRR was reached at approximately 500 s regardless of the $R_A$

when combustion was performed in the compartment under the condition of the same quantity and arrangement of cables. This can be attributed to the thermal feedback applied from the high-temperature smoke layer formed in the upper layer in the compartment and the heated walls. In other words, despite the shielding effect provided by the cable arrangement in type 1, the pyrolysis of the second and third floor cables by the high-temperature smoke layer accelerates the fire growth rate. This acceleration of the fire growth rate causes the total heat release of type 1 to exhibit a significant increase compared to that for the open environment. When the burning characteristics were examined considering the cable arrangement method, type 2 exhibited a relatively faster growth and higher maximum HRR compared to that of type 1 with the same quantity ($R_A$ = 0.75). However, under the same condition of $R_A$, no significant difference was observed in the total heat release between types 1 and 2. Finally, the maximum HRR and total heat release of type 3 did not show a significant difference from types 1 and 2. In terms of the total heat release, the VCTF cables burnt in the compartment had a significant fire risk regardless of the arrangement method.

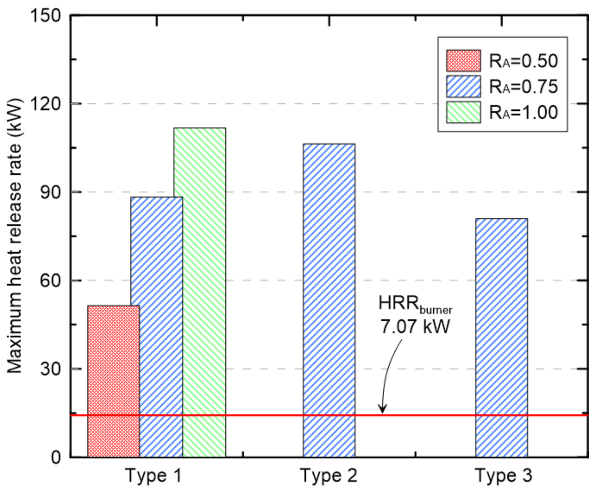



(**a**) VCTF (**b**) TFR-8

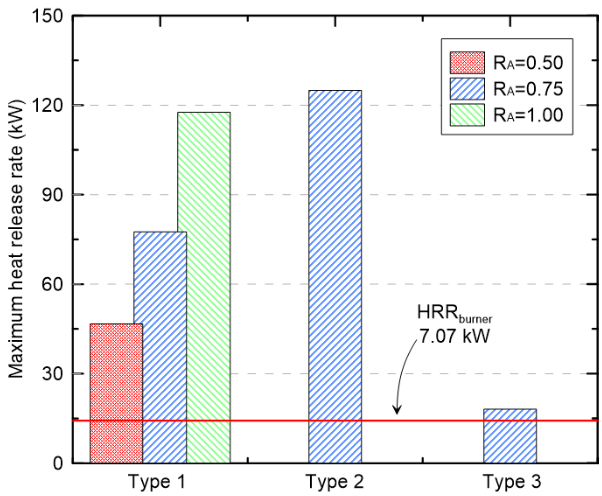
**Figure 10.** Comparison of the fire growth curve and total heat release according to the quantity and arrangement method of cables in a compartment environment.

Figure 10b shows the results of the TFR-8 cables. For type 1, the time required to reach the maximum HRR increased with an increase in $R_A$. This confirmed the delay of fire spread attributable to the flame-retardant performance; however, the maximum HRR and total heat release showed values similar to those of the VCTF cables. In addition, type 2 under the same condition ($R_A$ = 0.75) exhibited the highest maximum HRR among all experimental conditions, which includes the VCTF cables. This leads to an important fact that fire risk significantly increases in the compartment, even for a flame-retardant cable. However, type 3 showed very low maximum HRR and total heat release, similar to that in the open environment.

Figure 11 shows the comparison results of the maximum HRR according to the quantity and arrangement of cables within the compartment where the standard vertical opening is applied. The effect of the quantity of cables ($R_A$) in the compartment was examined only under the condition of type 1, and the effect of the arrangement method was examined under the condition $R_A$ = 0.75. Figure 11a shows the experimental results for the VCTF cables. The maximum HRR increased linearly with an increase in the quantity of cables. In the comparison of results based on the arrangement methods, type 2 exhibited the highest value, similar to that in the open environment. The VCTF cables burnt in the compartment environment showed a high maximum HRR of approximately 80 kW even for type 3, which confirms that the change in the fire risk depends on the combustion environment. Figure 11b shows the experimental results for the TFR-8 cables. In the experiment with the TFR-8 cables, the change in the fire phenomena based on the combustion environment was observed clearly. The maximum HRR according to $R_A$ for type 1 was similar to that of the VCTF cables and ranged from 45 to 120 kW; this is significantly higher compared to the results in the open environment. The TFR-8 cables arranged in type 2 showed the highest maximum HRR among all of the experimental conditions including that of the VCTF cables, when the effect of the arrangement method was examined under the condition $R_A$ = 0.75. This implies that even a flame-retardant cable has a high fire risk in the compartment environment. On the other hand, the maximum HRR of the TFR-8 cables arranged in type 3 was approximately 15 kW, which showed no significant change even in the compartment environment.




(**a**) VCTF




(**b**) TFR-8

**Figure 11.** Comparison of the maximum heat release rate according to the quantity and arrangement method of cables in a compartment environment.

Figure 12 compares the fire growth rates according to the quantity and arrangement of cables in the compartment environment with the standard vertical opening. Figure 12a shows the results for the VCTF cables. The fire growth rate for VCTF deployed as type 1 increased with the amount of cable, in contrast to that in the open environment. This can be attributed to the effect of combustion acceleration caused by the thermal feedback from the high-temperature smoke layer and walls in the compartment being more dominant than the shielding effect of cables. Under the same condition ($R_A$ = 0.75), type 3 showed the lowest fire growth rate. Thus, the arrangement method of type 3 can be considered as the safest in terms of the fire growth rate even though it showed no significant difference from types 1 and 2 for the total heat release and maximum HRR. Figure 12b shows the experimental results for the TFR-8 cables. For type 1, the fire growth rate decreased with an increase in the quantity of cables. This can be attributed to the effect of the flame-retardant performance. However, the fire growth rate in the compartment environment was approximately 1.3- to 3.4-times higher compared to the experimental results obtained in the open environment. This indicates that the flame-retardant cable has a high fire risk when burnt inside the compartment. Type 3 exhibited a very low fire growth rate despite combustion in the compartment. In addition, although the pictures are not presented, the cables were completely burnt in all experiments except for the condition where TFR-8 was arranged in type 3. Nevertheless, considering that no current was supplied to cables in this study, it is difficult to interpret whether type 3 is the safest arrangement method. This is because additional fire spread due to temperature increase can be caused when cables to which current is applied are arranged in a bundle. The quantitative difference in fire spread based on the application of current will be examined in future studies. Table 3 summarizes the experimental results in the compartment (maximum HRR, fire growth rate, and damaged area).

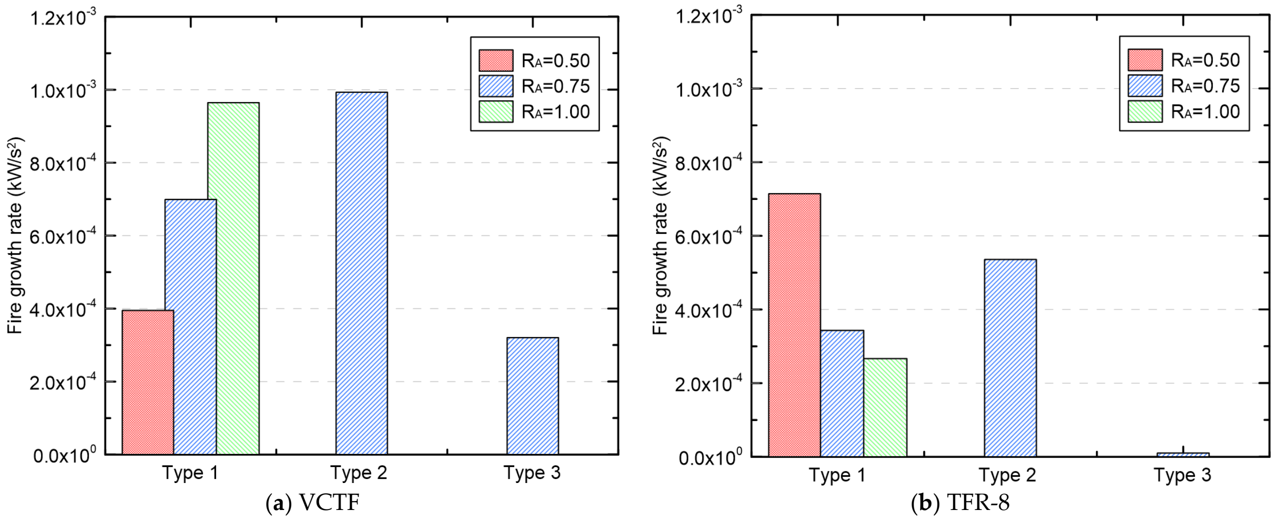


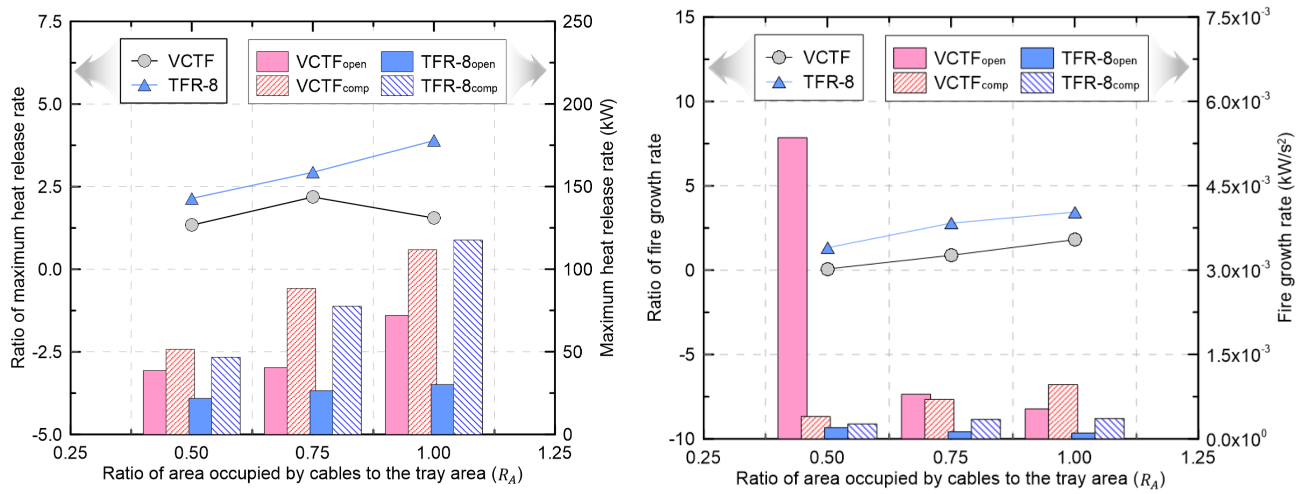

**Figure 12.** Comparison of the fire growth rate according to the quantity and arrangement method of cables in a compartment environment.

**Table 3.** Summary of the experimental results (maximum heat release rate, fire growth rate, and damaged area) according to the cable type, amount, and arrangement method in the compartment fire environment.

| Arrangement Method | $R_A$ | Max. HRR (kW) | | Fire Growth Rate (kW/s$^2$) | | Damaged Area (m$^2$) | |
|---|---|---|---|---|---|---|---|
| | | VCTF | TFR-8 | VCTF | TFR-8 | VCTF | TFR-8 |
| Type 1 | 0.50 | 51.4 | 46.7 | $4.9 \times 10^{-4}$ | $7.1 \times 10^{-4}$ | 0.204 | 0.198 |
| | 0.75 | 88.3 | 77.5 | $8.1 \times 10^{-4}$ | $3.4 \times 10^{-4}$ | 0.306 | 0.297 |
| | 1.00 | 111.7 | 117.6 | $9.7 \times 10^{-4}$ | $2.7 \times 10^{-4}$ | 0.408 | 0.396 |
| Type 2 | 0.75 | 106.4 | 124.9 | $9.9 \times 10^{-4}$ | $5.4 \times 10^{-4}$ | 0.306 | 0.297 |
| Type 3 | 0.75 | 81.0 | 18.1 | $3.2 \times 10^{-4}$ | $0.1 \times 10^{-4}$ | 0.306 | 0.114 |

### *3.3. Changes in the Fire Phenomena Based on the Combustion Environment*

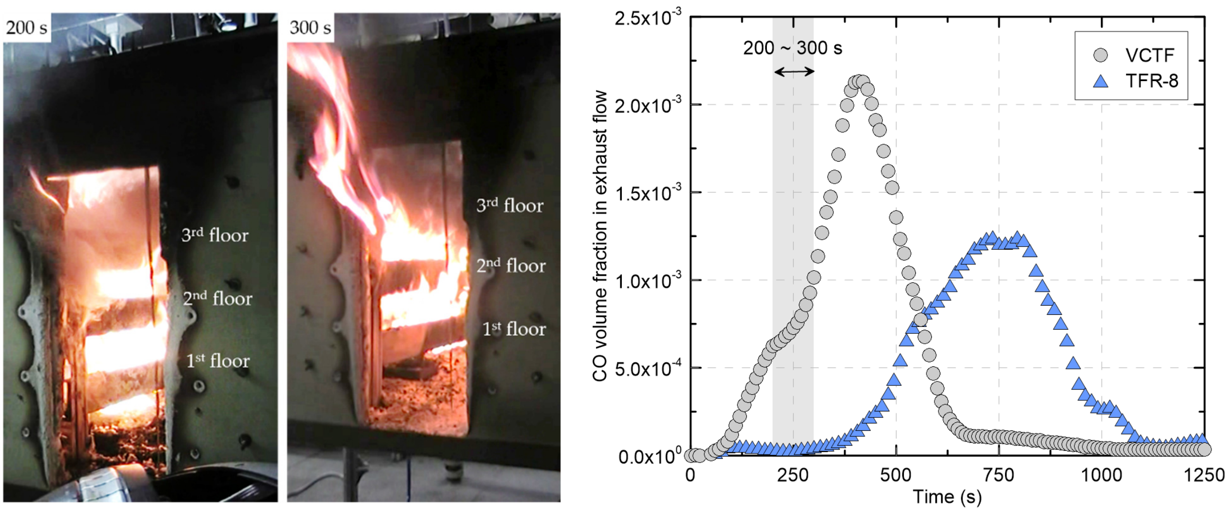
Figure 13 shows the ratios of the experimental results (maximum HRR and fire growth rate) in the compartment environment according to the values obtained in the open environment for analyzing the burning characteristics of the cables based on the combustion environment. In this comparison, only the experimental data for type 1 were considered. If the Y-axis value of the symbol is less than 1, it can be interpreted as showing a smaller value in the compartment fire. Figure 13a shows the ratio of the maximum HRR based on the combustion environment. The ratio of TFR-8 ranged from 2 to 4, and showed a greater change than VCTF, which ranged from 1.3 to 2.2. Considering that the maximum HRR in the compartment environment presented by the bar chart was similar regardless to the cable type, this difference can be attributed to the relatively low maximum HRR of the TFR-8 cables in the open environment. Furthermore, this difference indicates that the fire risk of the flame-retardant cable is significantly increased in the compartment environment. The TFR-8 cables showed a linear increase tendency when the maximum HRR ratio according to $R_A$ was examined; however, the maximum HRR ratio of the VCTF cables decreased under the condition $R_A$ = 1.00. Figure 13b shows the analysis results for the ratio of the fire growth rate based on the combustion environment. In terms of ratio, the TFR-8 cables with relatively slow fire growth in the open environment exhibited a larger increase, as indicated in Figure 13a. In terms of the fire growth rate ($\alpha$) value, the VCTF cables showed a faster fire growth under all conditions regardless of the combustion environment. However, the fact that the fire growth rate of the TFR-8 cables can increase by 1.3 to 3.4 times in the compartment must be considered during fire risk assessment for a site where the flame-retardant cable is applied. The ratio of the fire growth rate based on the quantity of VCTF cables increased by approximately 1 to 2 times under the conditions $R_A$ = 0.75 and 1.00. Under the condition $R_A$ = 0.50, the ratio of the fire growth rate was approximately 0.1, which indicates a lower fire growth rate in the compartment environment than that in an open environment; this is related to the characteristics of the materials that constitute the VCTF cables. The PVC that constitutes the insulation and sheath of the VCTF cables is thermoplastic, and therefore, the VCTF cables heated in the compartment are softened, and the ends of the cables arranged on the trays fall to the floor. Consequently, a downward fire spread occurs, and this phenomenon can be understood considering that downward fire spread is quite slower than the horizontal and upward fire spread. At $R_A$ = 0.75 and 1.00, where a relatively large amount of cables is arranged, the ends of the cables did not fall and thus a faster fire growth was observed compared to that in the open environment. Consequently, the fire growth rate is expected to be equal to or higher than that of the open environment if the cables do not fall under the condition $R_A$ = 0.50.




(**a**) Maximum heat release rate (**b**) Fire growth rate

**Figure 13.** Changes in fire characteristics of the VCTF and TFR-8 cables between the open and compartment environments.

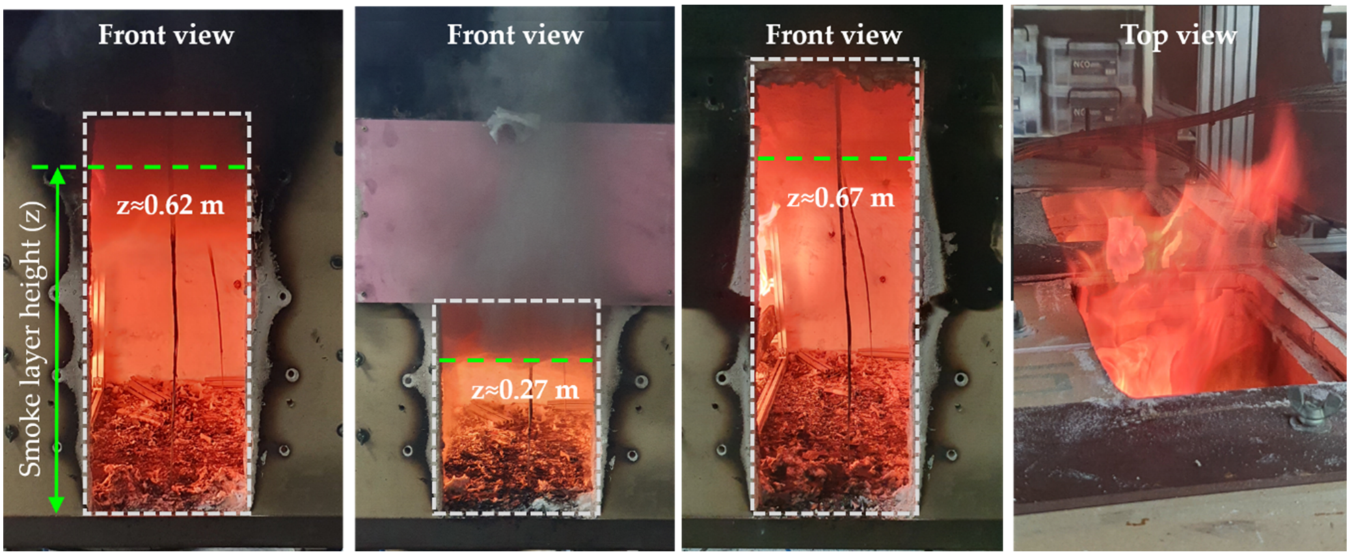
Figure 14 shows the results of analyzing the cause of the reduction in the maximum HRR ratio (VCTF) confirmed in Figure 13a. In the compartment environment, cables arranged on the second and third floor trays were subjected to pyrolysis even without direct contact with the flame because of the thermal feedback of the high-temperature smoke layer and walls. This thermal feedback supplies a large amount of fuel within a short period of time, and the compartment fire may exhibit temporary incomplete combustion even under the over-ventilated condition. Yamada et al. [37] reported that the combustion efficiency decreased rapidly when the global equivalence ratio of compartment fires ranged from 0.75 to 1.27. In a previous study [38], it was confirmed that the cause of this phenomenon was incomplete combustion occurring under conditions where the fuel concentration in the compartment rapidly increased locally. The photograph (Figure 14a) taken in the fire growth stage of VCTF (type 1 and $R_A$ = 1.00) showed that the ghosting flame caused by the fuel concentration increased near the ceiling at 200 s. The ghosting flame was observed only near the opening where contact with oxygen is easy. Afterward, intermittent flame ejection through the opening was observed at 300 s when the environment in the compartment became more severe. This indicates that a large amount of fuel components are included in the smoke layer in the corresponding experiment. However, this fuel component is not combusted, even outside the compartment, but is collected and discharged through the duct, and it was judged that the maximum HRR was reduced due to this. As evidence, the CO volume fractions included in the flows through the exhaust duct were compared as shown in Figure 14b. The maximum value of the VCTF cables was approximately twice as high as that of the TFR-8 cables under the same conditions (type 1 and $R_A$ = 1.00). This indicates that a large amount of incomplete combustion occurred in the experiment with the VCTF cables. In addition, the CO volume fraction of the VCTF cables increased sharply from 200 s when the ghosting flame was first observed. Consequently, it can be interpreted that the local incomplete combustion caused by the sharp increase in fuel supply decreased the maximum HRR of the VCTF cables (type 1 and $R_A$ = 1.00).




(**a**) Occurrence of ghosting flame (**b**) CO volume fraction in the exhaust flow

**Figure 14.** Fire phenomenon of the VCTF cables under the type 1 and $R_A$ = 1.00 condition.

Figure 14 indicates that the thermal feedback applied from the smoke layer and walls accelerates the combustion of combustibles. Thus, examining the effects of the thermal feedback applied from the smoke layer and walls on changes in fire phenomena separately can provide useful information for reducing the fire risk. Therefore, fire tests were conducted for the various opening conditions (vertical and horizontal) presented in Figure 3. Regarding the combustibles, TFR-8 ($R_A$ = 0.75) was considered as a type 1 arrangement. Figure 15 shows the photographs of the smoke layer captured at the peak period in each experiment. Under the standard opening condition, the height of the smoke layer was 0.62 m from the floor. Under the reduced opening condition, the thickness of the smoke layer increased, and the interface was formed at a height of 0.27 m. Under the expanded opening condition, the height of the smoke layer was not significantly different compared to that of the standard opening despite the increase in the height of the opening. Under the expanded and horizontal openings condition, no smoke layers were generated because the combustion products were discharged immediately through the horizontal opening above the trays. The photographs of the horizontal opening viewed from the outside is presented in Figure 15.




(**a**) Standard (**b**) Reduced (**c**) Expanded (**d**) Expanded & horizontal

**Figure 15.** Comparison of the smoke layer height at the peak period under various opening shape conditions.

Figure 16 shows the HRR measured in each experiment over time. The initial (up to 500 s) fire growth was similar regardless of the opening shape and combustion environment. In the open environment, the maximum HRR showed a value of approximately 28 kW, and then the fire was extinguished because of the limited fire spread. However, in all compartment fire experiments, continuous fire growth was observed because of the combustion of cables caused by the thermal feedback. The standard and expanded opening conditions exhibited very similar fire growth curves when the difference depending on the opening shape was observed because there was no significant difference in the smoke layer height in each experiment (Figure 15). The reduced opening condition was expected to promote combustion due to the thermal feedback of the smoke layer with increased thickness, but rather resulted in a decrease in the maximum HRR. This is because the combustion reaction of the cable is suppressed due to the reduced air inflow according to the limited ventilation area. The residence time of combustion products in the compartment was increased by the descent of the neutral plane, and the combustion products were re-introduced during the introduction of outdoor air, which made the internal environment richer. Under the expanded and horizontal conditions, the maximum HRR was lower compared to the standard and expanded conditions; this is because no smoke layer was formed, and thus, the thermal feedback applied to the cables was reduced. The above results indicate that there is a boundary at which the smoke layer accelerates or inhibits combustion, and this needs to be analyzed by setting more detailed conditions.

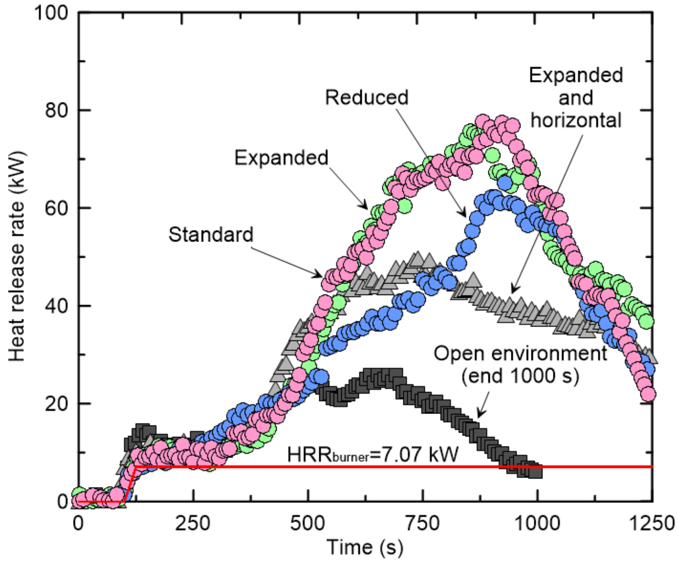
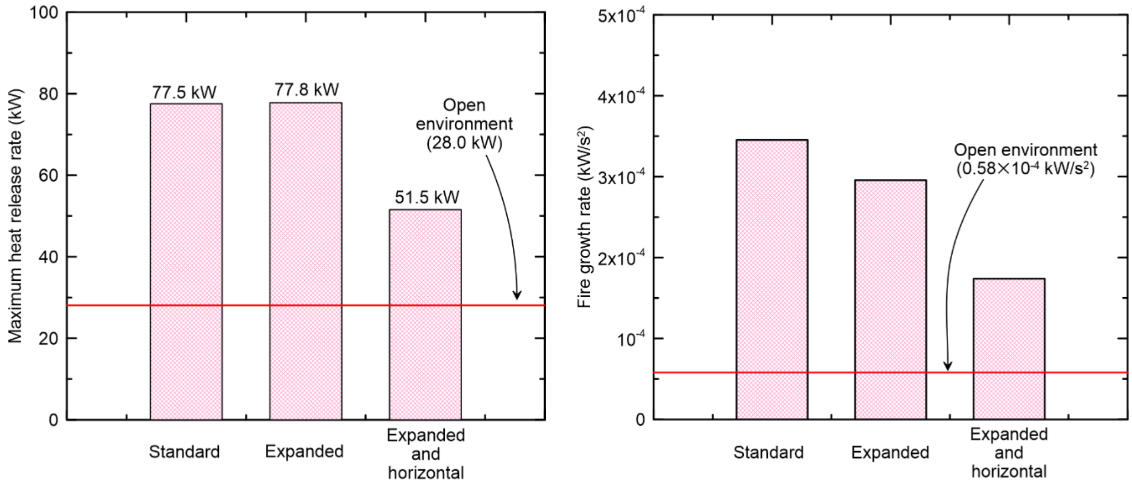



**Figure 16.** Comparison of the fire growth behavior for TFR-8 cables under various opening conditions.

Figure 17 shows a comparison of the maximum HRR and fire growth rate in order to analyze in more detail the effect of the smoke layer and wall thermal feedback that changes according to the opening shape. In the compartment environment, the maximum HRR is affected by various factors, which include minute changes in ventilation conditions, the rate of fire spread along combustibles, and the chemical composition inside the compartment. However, in this study, a more simplified one-dimensional analysis was conducted, and only the walls and smoke layer were considered as factors that affect the maximum HRR. The standard, expanded, and expanded and horizontal conditions in which transitions to under-ventilated fire did not occur were considered as analysis targets; the experimental results of the open environment were expressed as solid lines. Figure 17a compares the maximum HRR, and there was no difference between the maximum HRR of the standard condition (77.5 kW) and that of the expanded condition (77.8 kW). The maximum HRR of the expanded and horizontal conditions (51.5 kW) was approximately 22 kW lower compared to the other two conditions. Considering that no smoke layer formed in the compartment under the expanded and horizontal conditions, the difference of 22 kW can be attributed to the smoke layer. The influence of the walls can be examined by comparing the experiment in the open environment with the expanded and horizontal conditions that form no smoke layer. The maximum HRR of the open environment (28 kW) was different from that of the expanded and horizontal conditions by 23.5 kW; this difference was similar to the contribution of the smoke layer thermal feedback examined above. Furthermore, this tendency could also be observed in the comparison of the fire growth rate presented in Figure 17b. The standard and expanded conditions showed similar fire growth rates, while the expanded and horizontal conditions exhibited a relatively low fire growth rate. These results suggest that the thermal feedback of the smoke layer and walls has a similar dominance over the growth of cable fires under sufficient ventilation conditions. However, when ventilation is limited as in the reduced opening condition, the fire phenomena exhibited different changes. Thus, it is necessary to conduct further research on various ventilation conditions for a clear understanding of the fire phenomena of cables burnt in a compartment. However, the results of this study on the burning characteristics of a flame-retardant cable in open and compartment environments can be expected to be useful in assessing the risk of cable fires.




(**a**) Maximum heat release rate (**b**) Fire growth rate

**Figure 17.** Comparison of the fire characteristics according to the opening shape to analyze the effect of thermal feedback from the smoke layer and walls.

## 4. Conclusions

An experimental study was conducted to evaluate changes in the fire phenomena of a flame-retardant cable based on the combustion environment. Changes in the maximum HRR and fire growth rate in the open and compartment environments were analyzed considering the quantity and arrangement of cables. Furthermore, the fire phenomena of the flame-retardant cable based on the combustion environment were examined in more detail through comparison with the VCTF cables without the flame-retardant performance. The detailed results are as follows.

(1) Under the conditions of the same arrangement method, the amount of cable showed a close correlation with the maximum heat release rate and total heat release. In addition, it was confirmed that the contact area with the flame according to the cable arrangement method brought about a large change in the damage area of the cable as well as the fire growth rate and maximum heat release rate. In particular, when the cables were bundled, the risk of fire was greatly reduced.

(2) The flame-retardant cable showed sufficient performance in an open environment. However, the maximum heat release rate of the flame-retardant cable in the compartment environment increased to a level similar to the general PVC cable. Changes in these fire phenomena should be considered when evaluating the fire risk of the space where the flame-retardant cable is actually installed.

(3) Under the condition that sufficient ventilation is provided, the thermal feedback from the smoke layer and the walls has a similar effect on the increase in the maximum heat release rate and the fire growth rate. However, it was confirmed that there exists a boundary where the fire scale decreases when the thickness of the smoke layer is continuously increased. In order to confirm this boundary, more detailed opening shapes will be considered in future studies.

In this study, no current was supplied to the cable, and considering that the experiment was conducted with a limited type of cable, additional research is required for a clear understanding of the fire characteristics of flame-retardant cables.

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