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A Numerical Study of the Heat Release Rate of Exhibition Kiosks in a Fire

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In Taiwan, the current fire safety code is a prescriptive code. For some exhibition centers, it is very difficult to comply with the standard fire safety code. To solve this difficulty, it is necessary to apply the "performance-based" fire safety design method to ensure the goal of occupant safety. Thus, a fire dynamics simulator (FDS) developed by the National Institute of Standards and Technology (NIST) was used in this study to simulate fire incidents ignited in an exhibition kiosk and to analyze changes in temperature distribution and heat release rate under various conditions. The parameters studied include the types of partition board material and the numbers and layout of kiosks. Simulation results indicated that incombustible material of partition boards and furniture can inhibit fire efficiently. However, having a main aisle around the exhibition, which causes the fire to spread in different directions and has a "multiplication effect", may lead to a faster expansion of fire.

1. Introduction

With the rapid development of industry and commerce at home and abroad, various large global cities need a place to show their strengths to expand intercommunication and attract funds or talent and drive related industries; thus, all-purpose exhibition centers are built accordingly. This type of building usually has a wide area, complete functions, and advanced equipment, as well as a special shape, becoming a landmark in various places. In terms of current exhibition centers completed or under construction, to meet the operational requirements of spaciousness, flexibility, and comfort, new types of exhibition centers built by various major designers often have unique styles, which repeatedly derive from the traditional norm. In addition to a large space, they sometimes have the functions of a hotel, with meeting rooms, restaurants, shopping centers, areas of relaxation, and gymnasiums. While many enterprises or local governments like this type of exhibition center, owing to the particularity of the buildings, general building or fire safety codes and standards are unlikely to be applied to them. As performance-based design gradually emerges, as required by the times, and to follow the international architectural design trends for the applicability of special buildings, such as high-rise apartment buildings or large-scale combined meeting places, on January 1, 2004, Taiwan officially declared that carrying out fire prevention and evacuation safety

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design for buildings according to performance-based codes was permitted to meet the requirements of special buildings and conform to the necessary safety standards.[1] According to the fire control characteristics of exhibition centers, this type of building contains numerous combustible materials and many people; thus, it is difficult to confine the flames and dense smoke to a limited space. When a fire occurs, especially during an exhibition, if the building does not have corresponding fire safety or escape equipment, the fire can quickly spread and evolve into a conflagration, and heavy property loss and casualties are inevitable.[2,3] However, according to the authors' experience in long-term fire control research and practice, the fire prevention and evacuation safety design of buildings is certainly important, and booth material, location, and aisle design in the exhibition space are some of the factors addressed for disaster prevention. Therefore, how to protect people at an exhibition and how to use the performance-based fire control design concept to judge whether the design of a booth meets fire safety requirements to guarantee personal safety is the focus of this study.

Performance-based fire safety design is a new building fire protection design method based on fire safety engineering which uses the method and principle of fire safety engineering according to various physical circumstances, such as the use and structure of the building and the combustibles stored inside, where the designer freely chooses fire precaution measures for fire safety according to different functions, space, and other related conditions of the building, and the measures are combined to design the overall fire safety design scheme of the building.[4] Afterwards, the developed engineering method is used for simulated evaluation and prediction of the building fire hazard level and the extent of harm to obtain the optimized fire protection design scheme and provide the most reasonable fire protection for the building. Performance-based fire control design aims to analyze hazards and fires, which are very significant to solve the complex building fire control designs of the current code or those issues that technical standards cannot solve.

The concept of performance-based design (PBD) uses engineering evaluations to remedy the deficiencies in the code, while the spirit of the design allows the use of any system or method with the same or higher quality level, fire resistance, efficiency, durability, and safety as an alternative scheme for enhancing fire safety.[5] Performance-based fire control design comprises 7 procedures: Identify Site or Project Information, Identify Fire Safety Goals, Develop Performance Criteria and Design Criteria (Design Objective), Develop Fire Scenarios, Perform a Fire Safety Calculation, Develop and Evaluate Design Alternatives, and Perform Documentation and Specifications. The limitations of the code can be remedied and loss prevention capability can be enhanced to conform to constantly changing evolutionary industrial processes and equipment and to achieve the win–win goal of economic benefit and safety.[6]

At present, 3D computer simulation programs have been extensively used in the international fire safety domain. Many fire protection engineers have used 3D computer simulation programs for the quantitative evaluation of the fire control effects of refuge facilities and fire safety equipment in buildings, thus implementing PBD for fire safety. The fire resistance of exhibition booth building materials directly affects the safety of the people at an exhibition, and when a fire occurs, the fire and toxic smoke cause both direct and secondary damage. Therefore, before the PBD of fire safety, fire load in the building and burning duration must be analyzed, and the thermal parameters of booth building materials must be fully examined. Therefore, this research places emphasis on spacious exhibitions and establishes design criteria applicable to actual large spaces for simulation. The heat release rate is calculated using a 3D computer simulation program to determine the first influential factor that initiates the fire behavior. The fundamental purpose of this study is to provide prevention and control methods in the performance-based fire protection design concept.

2. Methodology

The fire dynamics simulator (FDS) software used in this study was developed by the Building and Fire Research Laboratory, National Institute of Standards and Fire Research Laboratory. Version 1 of FDS was released in February 2000, Version 2 was released in December 2001, Version 3 was released in November 2002, and Version 3.1 was released in September 2003; this study uses Version 6.[7]

The FDS simulation program is widely adopted in the fire safety industry and its results are widely accepted.[8] Currently, about half of published studies have used the FDS software to design smoke control systems and automatic fire sprinklers/detectors, while the other half simulated residential and industrial fire protection engineering design. FDS Version 6.0[9] can set the building size according to the user's requirements, and it calculates the cells, object size and heat attributes, relative position of fire source, different fire equipment (smoke exhaust system, sprinkler head, smoke detector, etc.), measuring point settings, and other boundary conditions to simulate the variations of various fire parameters (e.g., temperature, velocity, pressure, CO concentration) at fire scenes for different fire scenarios. The result of the calculation is processed by post processing software (Smokeview), where the obtained plume, gas temperature distribution, and flow field distribution at the fire scene are displayed in animation; thus, the fire scenario can be rapidly built and the fire scene information can be collected. The calculation processes of FDS and Smokeview are shown in Fig. 1.

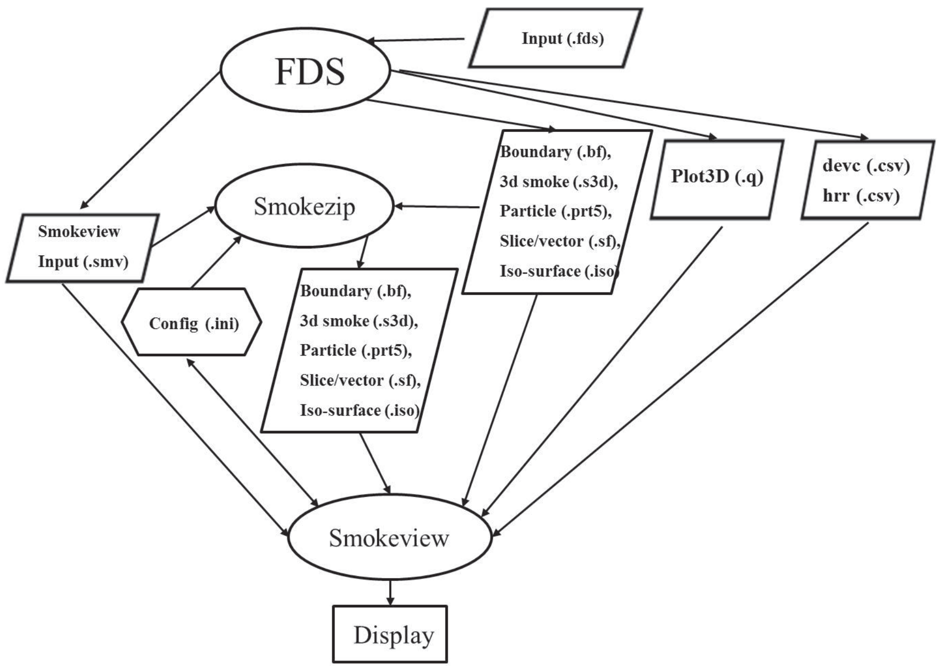
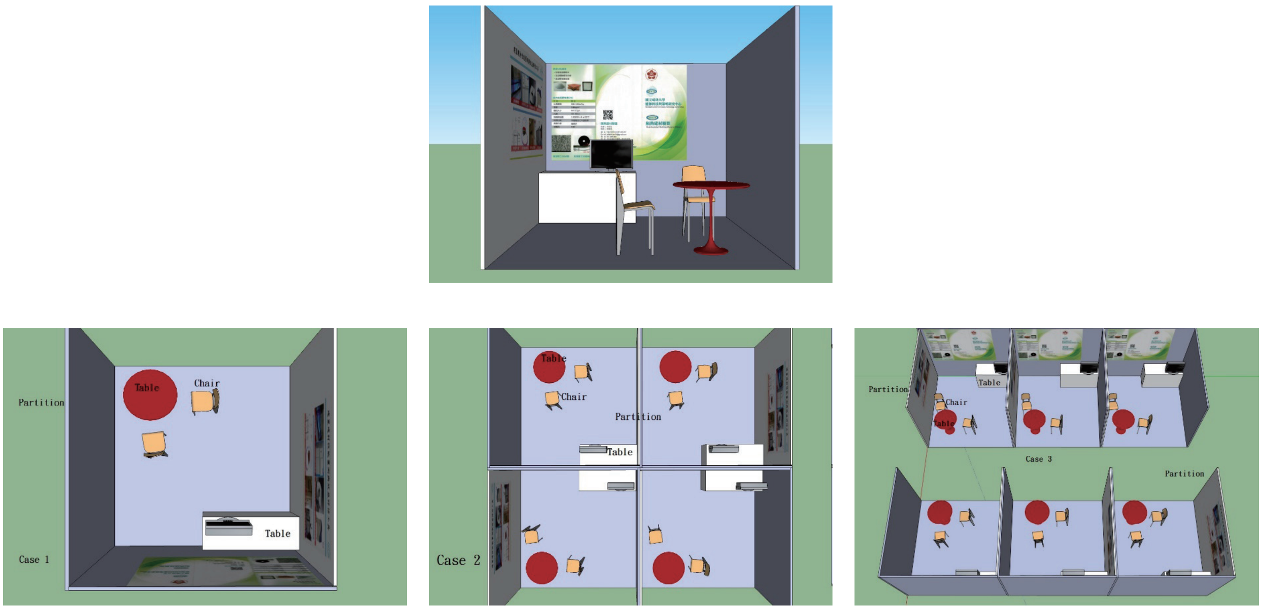


Fig. 1. Organizational structure and computing processes of FDS and Smokeview.

First, an input file (*.fds) is created for the simulation target and the result is exported; after the calculation using the FDS program, multiple result files (e.g., *.smv, *.bf, *.ini, *.s3d, *.prt5, *.sf, *.iso, *.q, and *.csv) are generated according to different conditions. These result files are processed by post processing software (Smokeview) to view the overall results of the analysis, the fire scene is displayed in 2D or 3D animation, and the results are drawn with multiple colors in 3D and continuous animation. The observable content includes the smoke layer flow direction in the simulated fire scene; smoke layer temperature; smoke layer descending rate; fire scene visibility; fire scene temperature distribution; magnitude of pressure; oxygen, CO, and CO_2 concentrations; combustion heat release rate (HRR); combustible burning rate; sprinkling actuation and water distribution of automatic sprinkler head; heat-sensitive detector actuation; and fume extractor actuation.[10]

3. Problem Settings of Case Studies

The inner area of an exhibition hall is limited; thus, how to maximize the operational benefit of a limited exhibition space while conforming to site planning for fire safety is the key point of the exhibition center's operating unit. In this study, we take common exhibition booths as the research subject, use FDS to simulate the combustion phenomenon of compartments in the exhibition, and analyze the combustion conditions of different compartment arrangement modes and compartment materials. In this study, we compile the common booth compartment modes in current exhibitions and design three booth compartment configuration modes; single compartment, four compartments, and six compartments; the schematic plan layout is shown in Fig. 2. The opening directions of booths are different: the openings of four booth compartments are outward, while the openings



(a) (b) (c)

Fig. 2. (Color online) Schematic layout of three cases. (a) case 1, (b) case 2, and (c) case 3.

of six booth compartments are inward. The internal dimensions of each booth are 3 m long, 3 m wide, and 3 m high, and there are two tables and two chairs in each booth. The origin of a fire is set as the top of the first table facing the exit. The minimum computing grid point is set as 0.1 m, the maximum grid size is 0.16 m. We focus on investigating the heat release rate at the early fire growth stage after the fire is ignited. Thus, the simulation time in all cases was set as 200 s. The compartment and furniture materials are divided into inflammable materials (foam) and flame resistant materials (calcium silicate board). The set conditions of all simulations are shown in Table 1.

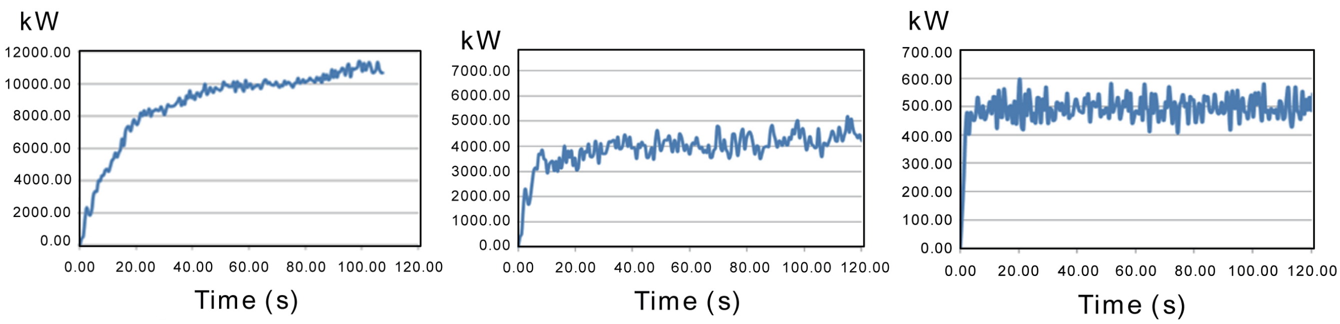
4. Results and Discussion

4.1 Case 1: single booth

Figure 3 shows the simulation results of the HRR of different materials. The results show that the HRR exceeds 10000 kW after 50 s when the partition board and decorative materials are inflammable. At 60 s of combustion, the steady-state combustion travels up, as the partition board, table, and chair materials are flammable, and combustion cannot be suppressed. If no effective fire protection measures are adopted, there will be heavy casualties or property loss.

Table 1
Simulation case settings.

No.	Number of compartments	Tables and chairs (ornaments) material	Partition board material
R1-1	1	Inflammable material	Inflammable material
R1-2	1	Inflammable material	Flame-resistant material
R1-3	1	Flame-resistant material	Flame-resistant material
R4-1	4	Inflammable material	Inflammable material
R4-2	4	Inflammable material	Flame-resistant material
R4-3	4	Flame-resistant material	Flame-resistant material
R6-1-3m	6	Inflammable material	Inflammable material
R6-2-3m	6	Inflammable material	Flame-resistant material
R6-3-3m	6	Flame-resistant material	Flame-resistant material
R6-1-2m	6	Inflammable material	Inflammable material
R6-2-2m	6	Inflammable material	Flame-resistant material
R6-3-2m	6	Flame-resistant material	Flame-resistant material



(a) (b) (c)

Fig. 3. (Color online) Fire HRR simulation result of Case 1: (a) No. R1-1, (b) No. R1-2, and (c) No. R1-3.

In the case where partition boards are made of flame-resistant material but the decorative material is inflammable [Fig. 3(b)] at about 70 s, the HRR is almost 5000 kW. However, as the partition boards are flame-resistant, the fire behavior is suppressed, and the HRR cannot increase continuously, meaning that there is sufficient time for people to evacuate.

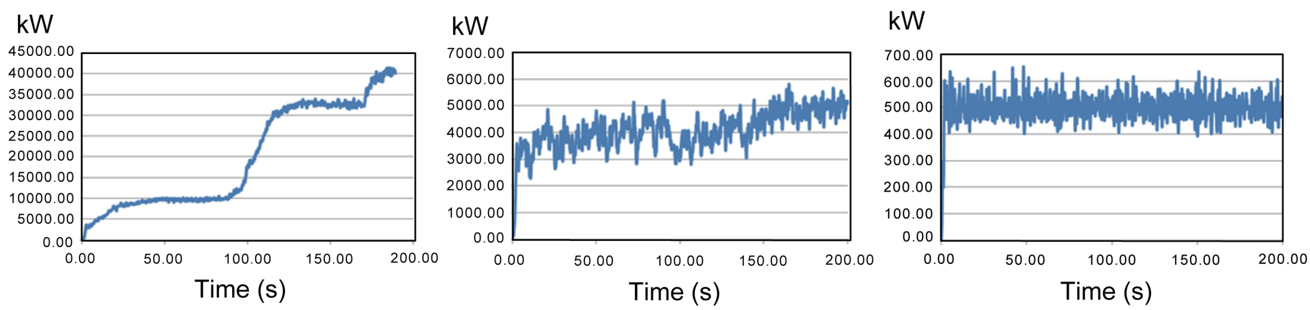
In the case where both the partition board and decorative materials are flame resistant materials [Fig. 3(c)], the HRR at the fire scene is maintained at about 500 kW; the fire spread is suppressed as the partition board, table, and chair materials are flame resistant, the HRR cannot rise continuously, and there is abundant evacuation time for people in the exhibition to escape.

4.2 Case 2: 2 by 2 booths

Figure 4 shows the simulation results for four compartments of different materials. According to the simulation results, in the case where the partition board and decorative materials are inflammable, at 50 s of fire in the compartment of origin, the HRR of the fire reaches 10 MW, which is similar to the fire HRR of Case 1. At 100 s, the fire spreads to the next compartment, the HRR rises sharply to 30 MW, and four booths are on fire at about 150 s. In the case where the partition boards are flame resistant but the decorative material is inflammable [Fig. 4(b)], the HRR of the burning booth is almost 5 MW, owing to the combustion of the inflammable tables and chairs. Afterwards, as the fire spread is suppressed by the flame-resistant partition boards, the HRR does not increase continuously. In the case where the partition board and decorative materials are flame resistant, as shown in Fig. 4(c), the HRR at the fire scene is only 500 kW, the fire spread is suppressed by the flame-resistant partition boards, tables and chairs, and the HRR does not increase continuously.

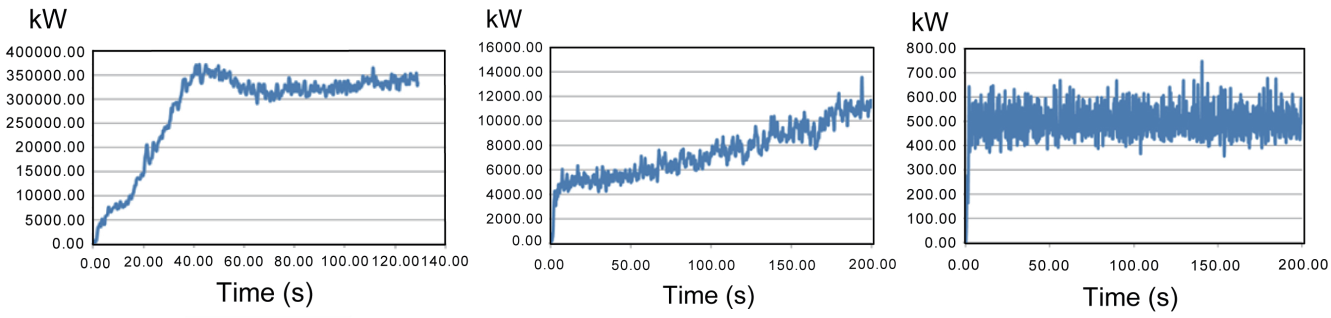
4.3 Case 3: two line booths

In order to discuss the effects of different exhibition layouts on the fire HRR, the combustion of two lines of booths with an aisle in between was evaluated in this study. Figure 5 shows the simulation result of a 2 m-wide aisle: the fire spreads fast, the HRR is almost 35000 kW at 40 s of burning, and HRR is kept at 30000 to 35000 kW after 60 s. While there is a 2 m-wide aisle partitioning the 6 booths into two lines in this case, as the partition board and decorative materials are inflammable, the six compartments catch fire in succession, and the booth temperature is higher



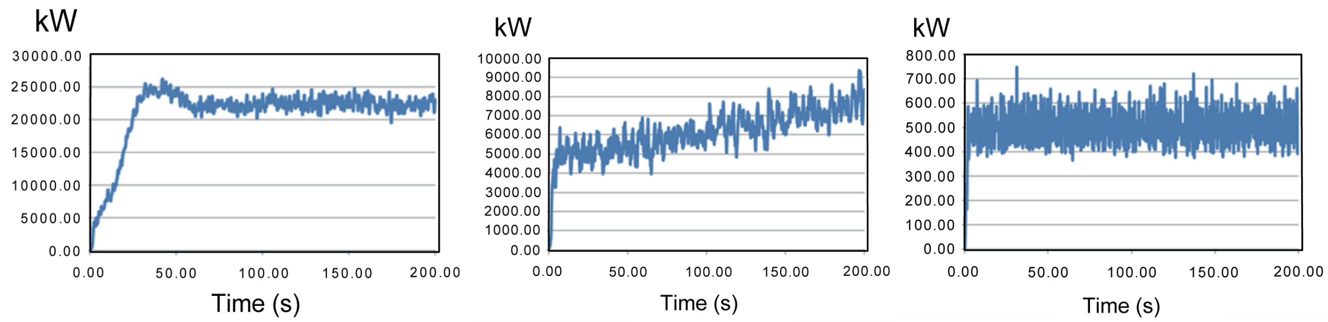
(a) (b) (c)

Fig. 4. (Color online) Fire HRR simulation result of Case 2: (a) No. R4-1, (b) No. R4-2, and (c) No. R4-3.



(a) (b) (c)

Fig. 5. (Color online) Fire HRR simulation result of Case 3 (2 m-wide aisle): (a) No. R6-1-2m, (b) No. R6-2-2m, and (c) No. R6-3-2m.



(a) (b) (c)

Fig. 6. (Color online) Fire HRR simulation result of Case 3 (3 m-wide aisle) : (a) No. R6-1-3m, (b) No. R6-2-3m, and (c) No. R6-3-3m.

than 1200 ℃ after 20 s of combustion. If the compartments are made of flame-resistant material, while the HRR quickly increases to 6 MW during burning, it is only 11 MW at the end of 200 s. However, the 2 m-wide aisle cannot prevent the fire from spreading outwards. The simulation result in Fig. 5(c) shows that, from 10 s of burning to the end, the HRR at the fire scene is 400–600 kW, which is similar to the HRR of the previous case.

Figure 6 shows the simulation result of a 3 m-wide aisle. The simulation result in Fig. 6(a) shows that, in the case where the partition board and decorative materials are inflammable, when the origin of the fire is still burning, the other five booths catch fire in succession. Even if the middle aisle is 3 m-wide, it cannot prevent the fire from spreading to the opposite booths, the aisle accelerates the fire growth, and the HRR is almost 25000 kW at 40 s. If the compartments are flame resistant [Fig. 6(b)], only the tables and chairs in the booth at the origin of the fire burn, and the HRR is about 5 MW. Furthermore, when there is a 3 m-wide aisle space, the fire cannot spread to the opposite booths, meaning that the aisle space retards the fire spread. If the tables, chairs, and compartments are flame-resistant [Fig. 6(c)], the HRR at the fire origin is about 500 kW, meaning that the fire spread is suppressed by the flame-resistant partition boards, tables, and chairs, and the HRR does not increase continuously; thus, it is unlikely to develop into a disaster or spread. These results prove the importance of flame-resistant materials, and additional aisle space contributes to fire control and increases the time for people to evacuate.

5. Conclusions

In this study, we used FDS to simulate an exhibition fire and discussed the correlation of different exhibition booth layouts and partition board materials to the HRR. The conclusions are as follows:

1. Effect of decorative material: when decorative and partition board materials are inflammable foam, the fire spreads very quickly, the fire scene HRR is 30000 kW at 40 to 50 s on average, and the fire scene temperature reaches 1200 ℃ in only 20 to 40 s, which is very hazardous for people and rescuers. When the decorative and partition board materials are flame-resistant, the fire behavior is clearly suppressed, the fire scene HRR reaches 500 kW at 200 s on average, and the fire scene temperature reaches 45 to 70 ℃ at about 200 s. Owing to the 1200 ℃ fire scene temperature and a dense smoke height lower than 0.5 m, people must crawl to evacuate; thus, it is difficult to escape. Therefore, the use of inflammable materials in exhibition halls should be minimized.
2. Effect of exhibition layout: a wide aisle in the exhibition can prevent fire from spreading to opposite booths, thus, reducing the HRR of the fire.
3. As the objects in current exhibitions are diversified and changing, selecting incombustible or flame-resistant partition board materials is one of the most feasible options at present; however, fire extinguishing and smoke exhaust systems for such places are still required to further enhance the fire safety of the exhibitions.

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