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Wei-Ting Chung
Department of Safety, Health and Environmental Engineering, National Kaohsiung First University of Science and Technology, Kaohsiung, Taiwan, R.O.C.

Ming-Yuan Lei
Architecture and Building Research Institute, Ministry of the Interior, New Taipei City, Taiwan, R.O.C

Kuang-Chung Tsai
Department of Safety, Health and Environmental Engineering, National Kaohsiung First University of Science and Technology, Kaohsiung, Taiwan, R.O.C., tsaikc@nkfust.edu.tw

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EVALUATING CURRENT FIRE TEST METHODS FOR DETERMINING FLAMMABILITY PERFORMANCE OF CEILING MATERIALS

Wei-Ting Chung[1], Ming-Yuan Lei[2], and Kuang-Chung Tsai[1]

Key words: ceiling material, fire test, fire behavior.

ABSTRACT

Many fire tests have been developed to evaluate the flammability performance of lining materials. According to the test methods, specimens are traditionally mounted vertically as a wall or horizontally as a floor. The only exception is the ISO 9705 room corner test in which ceiling material is installed beneath a ceiling. This study was accordingly designed to discuss the test results of ceiling materials in the ISO 9705 room corner test with the testing capacity of the traditional tests to evaluate the feasibility of the traditional tests to rank materials mounted beneath a ceiling. Materials used were gypsum board and particle board, which are ranked the best and the worst classes by the cone calorimeter, a commonly used testing apparatus. Our results showed that the fire behaviors cannot completely perform those tested in the ISO 9705 room corner test. A penetration occurred in the gypsum test and led to a severe fire although flashover was not observed. The results from the traditional tests are obtained from tests that are primarily concerned of the potential of a material leading to flashover. The penetration of flames through ceiling materials cannot be assessed in the other tests. A modification of the traditional test is recommended when ceiling materials are tested.

I. INTRODUCTION

The space inside a building can be divided into sub-spaces by horizontal and vertical barriers which form floors, ceilings and walls. Interior finishing materials are often constructed on the barriers for decoration and other uses. These materials are often combustible and provide suitable surfaces on which burning can start and sustain in an event of fire. Heat, smoke and toxic gases are subsequently generated and threaten the safety of resident and property. Therefore, the fire performance of an interior finishing material has to be evaluated and the choice of materials can be made accordingly.

Fire tests are consequently designed to provide information related to the “reaction-to-fire” properties of materials. Noticing the necessity of establishing suitable fire test methods, many national and local governments have developed different apparatuses in which specimens with various sizes and orientations are exposed to different fire scenarios. Classified by the specimen size and fire scenario, fire test methods can be grouped into small, intermediate and full scales. Basic properties of a material can be determined by small-scale tests whereas complete performance of a material encountering from ignition to fully developed fire is considered by full-scale tests. However, carrying out full-scale tests costs much more money and time, and the outcomes from intermediate-scale or small-scale tests may not represent the complete performance of a material in full-scale tests. There always exists a challenge to keep a balance between expenses and effectiveness and complete performance of a material while a suitable fire test method for regulatory use is selected. A principle to require test results capable of demonstrating necessary information of the fire performance of a material in a full-scaled test should be kept even when intermediate-scale or small-scaled tests are employed. Additional help of supplementary tests or judgments from experts is often accepted to form an adequate system for ranking an interior finishing material.

An interior finishing material can be mounted on a floor, on a wall or beneath a ceiling. This study focuses on the fire performance of ceiling materials. However, specimens in traditional fire tests are horizontal or vertical. The only exception is the ISO 9705 room corner test in which ceiling

Paper submitted 05/11/12; revised 01/08/13; accepted 03/11/13. Author for correspondence: Kuang-Chung Tsai (e-mail: tsaikc@nkfust.edu.tw).
[1] *Department of Safety, Health and Environmental Engineering, National Kaohsiung First University of Science and Technology, Kaohsiung, Taiwan, R.O.C.*
[2] *Architecture and Building Research Institute, Ministry of the Interior, New Taipei City, Taiwan, R.O.C.*

material is installed beneath a ceiling. This study is accordingly designed to discuss the test results of ceiling materials that are tested in the ISO 9705 room corner test with the testing capacity associated with traditional tests to evaluate the feasibility of traditional tests to rank materials mounted beneath a ceiling. Traditional "reaction-to-fire" tests are reviewed first and the orientation of specimen is highlighted. The behavior of a fire on a floor, on a wall and beneath a ceiling is described. Afterwards, full-scale experiments are conducted and the feasibility of employing traditional intermediate-scale and small-scale test methods for evaluating the fire performance of ceiling materials is discussed according to the comparison of the experimental observations from the full-scale tests and traditional intermediate-scale and small-scale test methods.

II. REVIEW OF WIDELY USED "REACTION TO FIRE" TESTS

The test principles, specimen sizes, specimen orientations and associated fire scenarios of five representative test methods are described herein. These methods include the ISO 9705 room corner test [14], the ASTM E 84 Tunnel test [3], the EN 13823 Single Burning Item (SBI) test [9], the ISO 5660 cone calorimeter test [13] and the Chinese National Standard (CNS) 6532 surface test [6]. Among them, the ISO 9705 room corner test [14] is a full-scale test, the ASTM E 84 Tunnel test [3] and the EN 13823 Single Burning Item (SBI) test [9] are intermediate tests, and the ISO 5660 cone calorimeter test [13] and Chinese National Standard (CNS) 6532 surface test [6] are small-scale tests.

1. The Room Corner Test and Its Classification

A schematic instruction of a room corner test apparatus is given in [14], mainly consisting of a test room and facilities to analyze combustion product. The test room is formed by non-combustible boards with inner dimensions of 2.4 × 2.4 × 3.6 m. One 0.8 × 2.0 m doorway is placed in one of the 2.4 × 2.4 m walls. The specimens are attached on the walls and ceiling. A propane burner that produces 100 kW for the first 10 min and 300 kW for a further 10 min is placed on the floor in a corner opposite to the wall with doorway and is in contact with the specimen on the wall. The facilities to analyze combustion product contain a hood and an exhaust duct to collect combustion products leaving the fire room through the doorway during a test. The heat release rate (HRR) and $O_2/CO_2/CO$ concentrations are measured by associated $O_2/CO_2/CO$ analyzers and software, according to the oxygen consumption principle. Additionally, the time to flashover is determined by eye and HRR measurements. The test method is used in Australia to rank finishing materials into four classes. Table 1 lists the classification system [15]. Moreover, because of the size and geometry that form a complete compartment, the room corner test is regarded as a reference test for all other small and intermediate scale tests.

Table 1. Classification of the room corner tests in Australia.

Class	Criteria
Group 1	Materials that do not reach flashover following exposure to 300 kW for 600 seconds, after not reaching flashover when exposed to 100 kW for 600 seconds;
Group 2	Materials that do reach flashover after exposure to 300 kW for 600 seconds, after not reaching flashover when exposed to 100 kW for 600 seconds;
Group 3	Materials that reach flashover in more than 120 seconds but less than 600 seconds after exposure to 100 kW;
Group 4	Materials that reach flashover in less than 120 seconds after exposure to 100 kW.

2. The Tunnel Test and Its Classification

The ASTM E 84 tunnel test [3] measures the flame spread of a specimen material relative to that of asbestos cement board and red oak flooring under similar test conditions. The test tunnel is 7.6 m long, 0.46 m wide and 0.31 m high and a 0.51 m wide and 7.3 m long specimen is attached to the last 7.3 m of the ceiling of the tunnel. The first 0.31 m of the ceiling at the fire end of the tunnel is asbestos cement board. Two gas burners locate 0.31 m from this end, which produce a diffusion flame that extends 1.6 m along the tunnel. Air is supplied at a rate of 170 L/s through a 76 mm high opening at the fire end. One side of the tunnel is equipped with viewing windows through which the distance between the flame front and the burner flame can be continuously monitored during the 10 min test. The purpose of this test method is to determine the relative burning behavior of a material by observing the flame spread along the specimen. In plotting the flame spread distance *vs*. time, the value of A_T is obtained and used to calculate "flame spread index" (FSI).

$$\text{FSI} = 0.0281\, A_T, \text{ if } A_T \leqq 1780 \text{ m} \cdot \text{s} \tag{1}$$

$$\text{FSI} = \frac{89700}{3560 - A_T}, \text{ if } A_T > 1780 \text{ m} \cdot \text{s} \tag{2}$$

The FSI is 100 for red oak and zero for non-combustible materials. Materials can be ranked into A, B and C levels according to the FSI value.

3. The Single Burning Item (SBI) Test and Its Classification

The Single Burning Item (SBI) test [9] is a method to determine the reaction to fire behavior of a material when exposed to a single burning item. The facility for the test primarily consists of a test room, test apparatus (trolley, frame, burners, hood, collector and ducting) and smoke exhaust system. The specimen includes two pieces of material, forming a corner to simulate a very rapid fire growth condition. A

Table 2. Classification of the SBI test.

Euro Class	Criteria for compliance	Other parameter
A2	FIGRA ≤ 120 W/s; and LFS < edge of specimen; and THR_{600s} ≤ 7.5 MJ	Smoke production Flaming droplets/particles
B	FIGRA ≤ 120 W/s; and LFS < edge of specimen; and THR_{600s} ≤ 7.5 MJ	Smoke production Flaming droplets/particles
C	FIGRA ≤ 250 W/s; and LFS < edge of specimen; and THR_{600s} ≤ 15 MJ	Smoke production Flaming droplets/particles
D	FIGRA ≤ 750 W/s	

Table 3. Classification of the cone calorimeter test.

Class	Heating time (min)	Criteria		
		Total heat release (MJ/m^2)	Peak HRR (kW/m^2)	Penetration of crack
non-combustible	20	< 8	< 200	No penetration over entire thickness
semi-non-combustible	10			
fire-retardant	5			

Table 4. Classification of the surface test.

Class	Heating time (min)	Criteria					
		t_c (min)	$T \cdot d\theta$ (°C · min)	C_A (-)	t_l (s)	C_k	Crack penetration
non-combustible	10	No exceed	0	< 30	< 30	< one tenth of specimen thickness	No penetration over entire thickness
semi-non-combustible		≧ 3	≦ 100	< 60			
fire-retardant	6		≦ 350	< 120			

propane supplied sand-box burner is placed on the floor at the corner and is in contact with the specimen. After igniting the burner, the heat and smoke release rates are measured instrumentally and physical characteristics are assessed by observation. This test method is used in Europe and Table 2 lists its classification.

4. The Cone Calorimeter and Its Classification

The cone calorimeter is an apparatus capable to provide information of material reacting to fire [13, 16-21]. The size of the specimen is 100 × 100 mm and located horizontally below a cone-shaped heater by which a specific heating irradiance can be produced. An electrical spark is set up above the specimen as a pilot ignitor. After the radiant heating applies onto the specimen, the ignition time can be determined visually according to the appearance of a sustained flame and burning gases are analyzed to demonstrate the history of heat release rate (HRR) according to the oxygen consumption principle with associated software. The measurements of smoke production, and concentrations of carbon dioxide, carbon monoxide and other gases are optional. The data of the cone calorimeter have been used to rank materials in Taiwan and Japan according to the values of total heat release, peak HRR under the irradiance of 50 kW/m^2 and judgment from penetration appearance during the non-combustibility test (ISO 1182 [10]). Table 3 lists the classification system of the cone calorimeter test, ranking materials from “non-combustible”, “semi non-combustible”, “fire retardant” to “out of class” [15].

5. The Surface Test and Its Classification

The surface test apparatus [6] mainly consists of a furnace, a smoke accumulation chamber and an optical density measuring system. A 220 × 220 mm specimen is vertically located before the furnace. In the furnace, heat is provided by a propane line burner with a flow rate of 0.35 l/min for the first 3 minutes. Subsequently, additional heat is supplied by two quartz lamps (total output: 1.5 kW). The total heating time for qualifying fire-retardant materials is 6 minutes and 10 minutes for non-combustible and semi-non-combustible materials. The averaged heat flux onto the specimen from the propane and quartz lamps for the whole 10 minutes from zero up to 13.71 kW/m^2 [11]. This range of the heating intensity corresponds to fire scenarios from ignition to a growing fire. Measurements made include the exhaust gas temperature, back surface temperature, smoke production (giving the coefficient C_A), duration of sustained flame (t_l), total length of cracks (C_k) and presence of penetration over the entire thickness. The time curve of exhaust temperature of the specimen will be plotted with that of a standard board to determine the time when the former curve exceeds that of the latter (t_c) and the area between them, giving $t \cdot d\theta$. The classification of the surface test is summarized in Table 4. Elementary Test (similar to ISO 1182 non-combustibility test [12]) is additionally used to rank non-combustible materials.

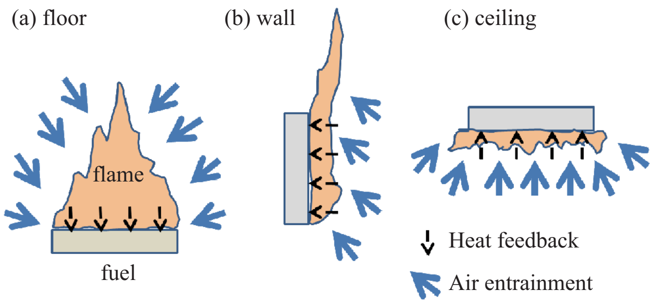

Fig. 1. The behaviors of pool, wall and ceiling fires.

III. FIRE BEHAVIOR ASSICIATED WITH A CEILING

A fire typically begins on the floor and then generates a fire plume. The plume is weak at the early stage of a fire and gradually becomes strong as the fire grows. When a fire plume reaches the ceiling, the fire plume impinges on the ceiling, and horizontal flows of hot gases, called "ceiling jets," form. You [25] indicated that three main regions develop during the flow process: (1) the fire plume region, (2) the impingement region, and (3) the ceiling-jet region. The fire plume transfers convective and radiant heat to the ceiling and its surroundings. Only fire plume impingement and ceiling jets are present before ceiling material is ignited. A ceiling fire occurs after ceiling material is ignited.

1. Fire Plume Impingement and Ceiling Jets

In the impingement region, heat transfer from the fire plume to the ceiling is of major interest. Several investigations [1, 22-25] have been conducted to analyze the temperature, velocity, and heat flux distributions along the ceiling radius because these parameters are related to the actuation of fire detectors and sprinklers. In addition, You [24] stated that a ceiling in the impingement region poses the highest potential of structural failure, but did not discuss this further.

2. Comparison of the Behaviors of Fires on a Floor, on a Wall, and beneath a Ceiling

As described, lining materials are often mounted on walls and beneath a ceiling. However, the specimens in the fire tests were installed horizontally or vertically. The fire behavior on a floor (pool fire), on a wall (wall fire), and beneath a ceiling (ceiling fire) are discussed in this section. Fig. 1 shows the shape, air entrainment pattern, and heat transfer pattern associated with the three geometries. The fire plumes were buoyancy-driven, and moved upward. The shape of the fires was consequently formed. The thickness of the three types of fire differed; the fire on the floor was the thickest, whereas the fire beneath the ceiling was the thinnest. The thickness of a flame influences the radiant heat feedback [8] to the burning fuel, neighboring unburned fuel, and surroundings. The radiation to the burning fuel affects the burning rate of the fuel. Among the three types of fire, the heat feedback to fuel from the pool fire was the strongest, whereas that from the ceiling fire was the weakest. In additional, radiation preheats the neighboring unburned fuel that may subsequently be ignited and then enhance the rate of flame spread. Among the three types of fire, the flame spread associated with the wall and ceiling fires was concurrent whereas that associated with the pool fire was counter-current [22]. Concurrent flames spread faster than counter-current flames because the directions of the fire plume and flame spread associated with the concurrent flames are consistent, increasing the heat intensity and extent [18, 21] to which neighboring unburned fuel is set alight. Zhou and Fernandez-Pello [26] indicated that the heat transfer from a flame to a solid surface was enhanced because the flame was near the surface when they determined the effect of buoyancy on the flame spread process of a ceiling fire and pool fire. Wall fires consequently spread faster than ceiling fires [2]. Furthermore, radiation from a fire preheats the surroundings. Tsai and Chen [20] observed that heat feedback to the compartment enhanced the occurrence of flashover. Hinkley *et al.* [11] reported that radiation from a hot ceiling and the gases beneath it to the floor enhanced the flame spread on the floor.

Because of the different patterns and amounts of heat transfer and air entrainment, the fire behavior associated with the three fires differed considerably. In addition, the specimens in the cone calorimeter can be installed vertically or horizontally; however, horizontal specimens are usually used. Tsai and Chen [20] discussed the different effects caused by the orientation of specimens in the cone calorimeter. This study focused on ceiling materials.

IV. EXPERIMENTAL AND RESULTS

To evaluate whether the aforementioned fire tests could reveal the complete fire performance of ceiling materials, full-scale ISO 9705 room corner tests were conducted. The designs of other small- and intermediate-scale tests are discussed in regard to the data and observations from the full-scale experiment. Two materials were used: 9-mm-thick gypsum board and 12-mm-thick particle board. The nominal class of the fire performance of the two materials was non-combustible and out of class based on the cone calorimeter test criteria (Table 3). This selection of materials was representative of favorable and unfavorable materials. The materials were mounted on the walls and ceiling of the test room according to the ISO 9705 test standard by using light-frame wood assemblies at a span of 60 cm. The geometry of the cross section of the wood strips was 5×5 cm.

According to the ISO 9705 room corner test method, a burner was placed in a corner to produce 100-kW heat for the first 10 min and 300-kW heat for the subsequent 10 min. The heat release rate (HRR) and time to flashover were measured. In this study, additional measurements (Fig. 2) were performed using three thermocouples installed 10 cm below the ceiling and two or six thermocouples installed

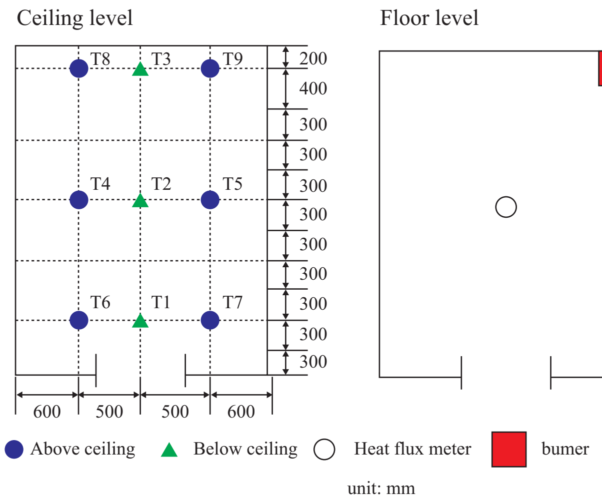

Fig. 2. Positions of thermocouples.

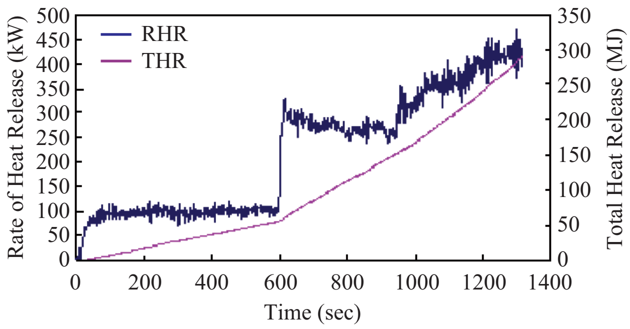

Fig. 3. Heat release rate and total heat release of the gypsum board test.

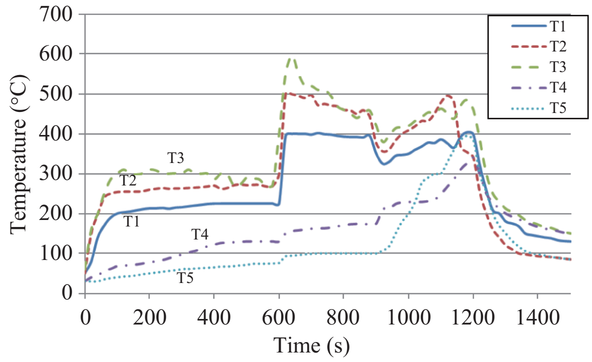

Fig. 4. Temperature measurements of the gypsum board test.

Fig. 5. Penetration of gypsum board beneath the ceiling by the flame from the burner.

above the ceiling materials to comprehensively understand the fire behavior and ceiling material behavior in a full-scale fire.

1. Gypsum Board Test

Fig. 3 shows the HRR and total heat release of the gypsum board test. Evidently, for the first 10 min, the HRR remained 100 kW. The heat was completely generated from the burner. After 10 min the HRR increased to 300 kW but decreased gradually. At 920 s, the HRR increased suddenly and remained increased until the end of the test. Based on visual observations, the specimen just above the burner cracked at 920 s and the flame penetrated the ceiling material. Fig. 4 presents the temperature measurements. T1 to T3 represents the central line temperatures below the ceiling. The readings of T1 were the lowest and those of T3 were the highest because of a short distance between T3 and the burner. For the first 10 min, the temperatures below the ceiling were almost constant. T4 and T5 corresponded to the temperatures above the ceiling and increased gradually for the first 10 min. After 10 min, T1 to T3 increased substantially because of the increase in the HRR of the burner but decreased until approximately 920 s. T1 to T3 subsequently increased after 920 s. In addition, T4 and T5 increased substantially at 920 s until the end of the test (1200 s).

Based on the temperature readings and visual observations, the complete fire scenario was constructed. For the first 10 min, heat and smoky gases were released from the burner, filled the upper part of the test room, and exited through the opening. Some heat was transferred through conduction to the back surface of the ceiling material, and convection occurred because the ceiling material leaked. After 10 min, the heat produced increased substantially. The temperatures T1 to T3 increased suddenly but then decreased, and T4 and T5 continued to increase. The increase in temperature may have been caused by additional leakage through which heat consequently was lost across the ceiling material. At 920 s, a crack occurred and the flame from the burner penetrated the ceiling. The smoky gases began to fill the space above the ceiling. T1 to T3 consequently decreased, and T4 and T5 increased. Subsequently, additional combustible items, such as wooden studs used to fix the specimen to the boundaries, were involved. The combustion was enhanced and increased the temperatures below and above the ceiling. Flashover did not occur. Fig. 5 shows the penetration across the gypsum board specimen above the burner.

Craft *et al.* [7] reported the material behavior of a gypsum board. The gypsum board contained 21% chemically bound water, and a vast amount of energy is required to release

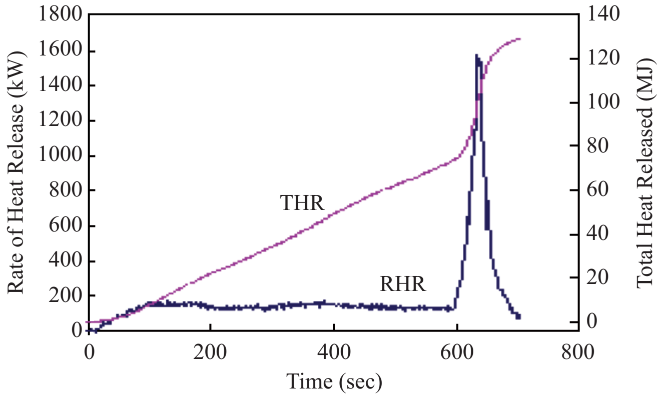

Fig. 6. Heat release rate and total heat release of the particle board test.

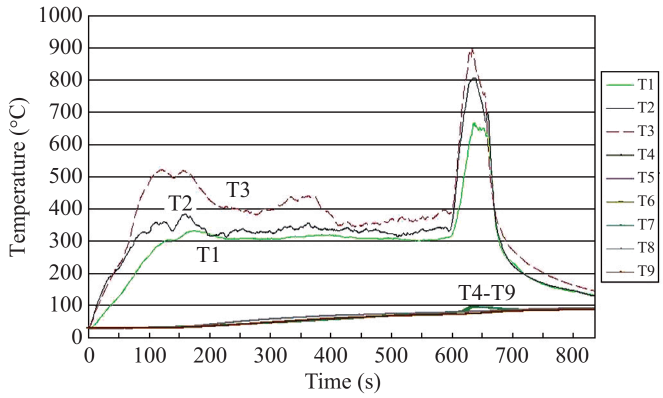

Fig. 7. Temperature measurements of the particle board test.

and evaporate this water. The release of water, called calcination, is a two-step process and occurs at approximately 100-150°C. The first reaction converts the calcium sulfate dehydrate ($CaSO_4$+$2H_2O$) to calcium sulfate hemihydrate ($CaSO_4$+$0.5H_2O$), and the second step converts calcium sulfate hemihydrate ($CaSO_4$+$0.5H_2O$) to calcium sulfate anhydrate ($CaSO_4$). In additional, decarbonation of calcium carbonate ($CaCO_3$) occurs at temperatures higher than 600°C, as indicated by another substantial mass loss, causing strength reduction. In this test, although the temperature of the gypsum board above the burner was not measured, it was determined to exceed 600°C according to the readings of T1 (the temperature above the burner should be higher than that at the position of T1 because T1 was farther from the flame). Therefore, decarbonation should have occurred after 10 min, reducing the strength of the material and subsequently causing penetration of the flame.

2. Particle Board Test

Figs. 6 and 7 show plots for the HRR and temperature histories of the particle board test. The HRR remained at 100 kW for the first 10 min and increased substantially at 10 min to 1.6 MW. Flashover was observed at 10 min and 37 s because flames were emitted from the opening. The test was then terminated manually because of exceedingly severe burning. The readings of T1 to T3 exceeded 600°C, the flashover threshold [20]; however, readings from T4 to T9 increased gradually. The temperatures above the ceiling were not high (less than 100°C). Additionally, no flame penetration across the material or flashover occurred at 10 min and 37 s.

The primary content of the particle board was wood. Craft *et al*. [7] reported the material behavior of wood exposed to elevated temperatures and undergoing thermal degradation. At 100°C, chemical bonds began to break. Between 100°C and 200°C, primarily non-combustible products such as carbon dioxide, traces of organic compounds, and water vapor were produced. At temperatures higher than 200°C, cellulose broke down, producing tars and flammable volatiles. At temperatures higher than 450°C, all volatiles were released, leaving behind activated char that could be oxidized to carbon dioxide, carbon monoxide, and water vapor, if oxygen were present. In this study, the particle board was exposed to heat, and its temperatures were between 300°C and 500°C during the first 10 min and reached 900°C after 10 min. The temperature range corresponded to the material behavior of producing tars and releasing large amounts of flammable volatiles. A large amount of heat was generated, and flashover consequently occurred.

3. Discussion

Table 5 lists the specimen orientation and parameters that were evaluated in the ISO 9705 room corner test in this study as well as other five test standards described in Section II. The parameters were grouped into four groups: the heat, smoke, integrity of the specimen, and influence on other items groups. Time to flashover, heat release and flame spread comprised the heat group. Crack and flame penetration comprised the integrity of specimen group. Flame droplets were observed for assessing the thermal effect on other items.

All of the test methods were used to assess the hazard caused by heat release of a material, but different parameters were used. The dependence of the results between the room corner test and others has drawn the attention of fire researchers for decades [4-10]. However, this dependence is not discussed in this paper. Smoke production was measured in some tests but used as criteria only in the SBI test and surface test because the testing method and threshold for ranking the smoke production of a material remains debated. Integrity of specimen is discussed later. Flame droplets are observed only in the SBI test because they are generally considered to affect fire growth only slightly.

Although the crack and flame penetration were observed in the SBI test, cone calorimeter and surface test, they corresponded to those in the burning specimens. However, in the tests used in this study, flames did not penetrate the burning specimens that were located on the corner walls near the burner. The flame in the gypsum test penetrated the unburned specimen beneath the ceiling above the burner. This

Table 5. Test parameter used as criteria in this study and other representative standard test methods.

	Ceiling material tests in the room corner test (this study)	Criterion of the standard test method				
		Room corner test	Tunnel test	SBI test	Cone calorimeter	Surface test
specimen orientation *	H_d	C	C	V	H	V
time to flashover	✓	✓				
heat release	✓			✓	✓	✓
smoke				✓		✓
C/P through burning specimen	✓			✓	✓	✓
C/P through unburned specimen	✓					
flame spread			✓			
flame droplets				✓		

* sample orientation: Hd horizontal face down, C compartment, V vertical, H horizontal, C/P crack and flame penetration

penetration, a structural failure addressed by You [24], became a critical phenomenon that caused a severe fire, and flashover did not occur.

This study evaluated whether the traditional intermediate- and small-scale tests could completely perform the fire hazard of a ceiling material in a full-scale test (the room corner test). Based on the discussion in Section III, the behaviors of pool fires, wall fires, and ceiling fires differ. The fire hazard associated with ceiling fires cannot be assessed using the other test methods in which the specimen is mounted horizontally or vertically. In additional, according to the experimental results presented in Section IV, the penetration of a flame through an unburned ceiling material was not observed. Therefore, the current traditional intermediate- and small-scale fire test methods are inadequate for assessing the fire hazard of a ceiling material.

However, conducting a full-scale test is time-consuming and expensive. A modification is proposed. The SBI test involves using two pieces of material and forming a corner to simulate a markedly rapid fire growth condition. Another piece mounted as a ceiling above the two pieces of materials could work to involve a material oriented as a ceiling. Whether the fire penetrates the ceiling sample in the SBI test could be a criterion for ranking the flammability performance of wall lining materials. Further research is required to determine the size of the ceiling sample.

V. CONCLUSION

This study evaluated whether intermediate- and small-scale tests could completely perform the fire hazard of a ceiling material in a full-scale test. In the traditional intermediate- and small-scale tests, the samples were oriented horizontally or vertically to simulate fires on a floor or wall. First, the behaviors of fires on a floor, on a wall, and beneath a ceiling were discussed. Based on the comparison, the behaviors of pool fires, wall fires and ceiling fires differ. Finally, full-scale experiments were conducted to evaluate whether the fire hazard observed in the experiments was adequately considered in other traditional tests. The experiments revealed that a flame penetrating an unburned ceiling material was not observed in other traditional tests. Consequently, the fire hazard associated with ceiling fires cannot be assessed using test methods in which the specimen is mounted horizontally or vertically. Therefore, the current intermediate- and small-scale fire test methods are inadequate for assessing the fire hazard of a ceiling material.

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REFERENCES

1. Alpert, R. L., “Calculation of response time of ceiling-mounted fire detectors,” *Fire Technology*, Vol. 8, pp. 181-195 (1972).
2. Arvind, A. and Kamel, M., “Heat transfer during wind-aided flame spread on a ceiling mounted sample,” *Twenty-Fourth Symposium on Combustion*, Vol. 24, pp. 1677-1684 (1992).
3. ASTM E 84-05, *Standard Test Method for Surface Burning Characteristics of Building Materials*, ASTM International (2005).
4. Axelsson, J. and Van Hees, P., “New data for sandwich panels on the correlation between the SBI test method and the room corner reference scenario,” *Fire and Materials*, Vol. 29, pp. 53-59 (2005).
5. Chen, C. H., Jang, L. S., Lei, M. Y., and Chou, S., “A comparative study of combustibility and surface combustibility of building materials,” *Fire and Materials*, Vol. 21, pp. 271-276 (1997).
6. CNS 6532: 1994(E), “Method of test for incombustibility of interior finishing materials for buildings,” Chinese National Standard, Taipei, Taiwan (1994).
7. Craft, S. T., Isgor, B., Hadjisophocleous, G., and Mehaffey, J. R., “Predicting the thermal response of gypsum board subjected to a constant heat flux,” *Fire and Materials*, Vol. 32, pp. 333-355 (2008).
8. Drysdale, D., *An Introduction to Fire Dynamics*, John Wiley (1998).
9. EN 13823: 2001(E), “Reaction to fire tests for building products –

Building products excluding floorings exposed to the thermal attack by a single burning item," European Committee for Standardization, Brussels (2001).
10. Hansen, A. and Hovde, A. J., "Prediction of time to flashover in the ISO 9705 room corner test based on cone calorimeter test results," *Fire and Materials*, Vol. 26, pp. 77-86 (2002)
11. Hinkley, P. L., Wraight, H. G. H., and Theobald, C. R., "The contribution of flames under ceilings to fire spread in compartments," *Fire Safety Journal*, Vol. 7, pp. 227-242 (1984).
12. ISO 1182: 2002, "Reaction to fire tests for building products: Non-combustibility test," International Standards Organization, Geneva, Switzerland (2002).
13. ISO 5660: 2002(E), "Reaction-to-fire tests - Heat release, smoke production and mass loss rate -- Part 1: Heat release rate," International Standards Organization, Geneva, Switzerland (2002).
14. ISO 9705: 1993(E), "Fire tests – Full-scale room test for surface products," International Standards Organization, Geneva, Switzerland (1996).
15. Regulatory proposal and regulatory assessment, Fire hazard properties of building materials and assemblies, Proposal to amend the building code of Australia, Australian Building Codes Board (2002).
16. Tsai, K.-C., "Influence of substrate on fire performance of wall lining materials," *Construction and Building Materials*, Vol. 23, pp. 3258-3263 (2009).
17. Tsai, K.-C., "Orientation effect on cone calorimeter test results," *Journal of Hazardous Materials*, Vol. 172, pp. 763-772 (2009).
18. Tsai, K.-C., "Upward flame spread on a flat surface, in a corner and between two parallel surfaces," *Journal of Chinese Society of Mechanical Engineering*, Vol. 28, pp. 341-348 (2007).
19. Tsai, K.-C., "Using cone calorimeter data for the prediction of upward flame spread rate," *Journal of Thermal Analysis and Calorimetry*, Vol. 112, pp. 1601-1606, DOI 10.1007/s10973-012-2735-2 (2013).
20. Tsai, K.-C. and Chen, H. H., "Experimental study of the effect of fuel sootiness on the occurrence of flashover," *Journal of Hazardous Materials*, Vol. 178, pp. 123-129 (2010).
21. Tsai, K.-C. and Drysdale, D., "Using cone calorimeter data for the prediction of fire hazard," *Fire Safety Journal*, Vol. 37, pp. 697-706 (2002).
22. Weng, W. G. and Hasemi, Y., "A numerical model for flame spread along combustible flat solid with charring material with experimental validation of ceiling flame spread and upward flame spread," *Fire and Materials*, Vol. 32, pp. 87-102 (2008).
23. You, H.-Z., "An investigation of fire plume impingement on a horizontal ceiling. 1- Plume region," *Fire and Materials*, Vol. 8, pp. 28-39 (1984).
24. You, H.-Z., "An investigation of fire-plume impingement on a horizontal ceiling. 2- Impingement and ceiling-jet regions," *Fire and Materials*, Vol. 9, pp. 46-56 (1985).
25. You, H.-Z. and Faeth, G. M., "Ceiling heat transfer during fire plume and fire impingement," *Fire and Materials*, Vol. 3, pp. 140-147 (1979)
26. Zhou, L. and Fernandez-Pello, A. C., "Turbulent, concurrent, ceiling flame spread: The effect of buoyancy," *Combustion and Flame*, Vol. 92, pp. 45-59 (1993).