A New Intermediate-scale Fire Test for Evaluating Building Material Flammability

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ABSTRACT: A new intermediate-scale fire test has been developed as a screening tool to evaluate wall and ceiling assemblies for material flammability. The scale of the test is large enough for the tested materials to reveal their behavior in a full-scale fire, but still small enough to provide substantial cost savings compared to 25-ft and 50-ft corner tests used for decades to evaluate wall/ceiling panels and other building materials. The test consists of parallel panels of the material assemblies being evaluated, which are each 1.07 m wide and 4.9 m high and separated by 0.53 m. A 360 kW propane sand burner is used as the ignition source. The parallel panel test is conducted under a 5-MW fire products collector to measure fire heat release rate (HRR). Materials used during development of the new test include various thicknesses of: polyvinylchloride, fire retardant plywood, fiberglass-reinforced melamine and panels with metal facings over foamed polyurethane, polystyrene, and polyisocyanurate. Comparisons with the 25-ft and 50-ft corner tests indicate that fire propagation behavior in the corner tests correlates well with the maximum HRR in the parallel panel test as follows: fire will not propagate to the end of the test array in the 25-ft corner test with combustible wall panels and a noncombustible ceiling if the HRR in the parallel panel test is <1100 kW; fire will not reach the top of the test array in the 50-ft corner test if the HRR in the parallel panel test is less than 830 kW; fire propagation will not reach the ends of the horizontal ceiling in the 25-ft corner test with both combustible wall and ceiling panels if the HRR in the parallel panel test is <830 kW.

KEY WORDS: intermediate-scale fire test, 25-ft and 50-ft corner test, flammability, building construction materials.

INTRODUCTION

IN 1972, FM Global introduced a 25-ft corner test as a means of evaluating the fire hazard associated with wall and/or wall and ceiling assemblies in

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industrial and commercial buildings [1]. This large-scale test was designed to determine the fire performance of materials under conditions and scales typical of such buildings. One of the first applications of the 25-ft corner test was a fire study undertaken for the Society of the Plastics Industry (SPI) of rigid cellular plastic materials for insulated wall and/or roof/ceiling construction [2–4]. A key motivation for the study was the concern that smaller-scale tests, such as ASTM E-84 [5], did not reliably and consistently reflect the fire performance of foamed plastics under actual conditions. A major conclusion of the study was that 'the ASTM E-84 flame ratings of less than 25 for foamed plastics (polystyrene, polyurethane, polyisocyanurate) show no correlation to actual building fire performance of wall or ceiling foamed plastic products in these tests.' It was further concluded that 'extensive use of the Building Corner Test Procedure was absolutely essential . . . ,' [3]. The 25-ft corner fire test was, therefore formalized at that time as a building corner fire test procedure [2], which eventually became part of certification tests [6,7] evaluating fire performance of insulated wall or wall and roof/ceiling panels, plastic interior finish materials, plastic exterior building panels, wall/ceiling coating systems, and interior or exterior finish systems.

In the 25-ft corner test [6,7], samples are attached to steel frames 7.6 m (25 ft) high, 15.2-m long on one side and 11.6-m long on the other side. The test fire load consists of conditioned oak pallets, the total mass of which are 340 kg and are stacked 1.5-m high at the intersection of the assembly walls. During the 15-minute test period, the flames from the burning material should not reach any of the limits of the corner test structure. A wall panel passing the 25-ft corner test is approved for use on walls up to 9.1 m high [6,7].

Due to the considerable effort and extensive material required to conduct the 25-ft corner test, a recommendation of the study for the SPI [2] was that 'the development of a small-scale fire test having direct correlation to the full scale building corner test be initiated as soon as possible.' Such a correlation was developed for the limited case of inert-faced thermoset plastic foam core (typically metal sandwich) panels [8] using a small-scale apparatus known as the Fire Propagation Apparatus (FPA, standardized as NFPA 287 [9] or ASTM E-2058 [10]). A correlating parameter was developed consisting of the ratio of the peak convective heat release rate (HRR) of a $100\,mm \times 100\,mm$ horizontal sample exposed to a heat flux of $50\,kW/m^2$ to a parameter characterizing the foam's propensity to ignite [11]. For the circumstance of inert-faced panels with thermoset plastic foams, use of the 25-ft corner test was no longer required and the small-scale measurements from the FPA were incorporated in a revised version of the certification standard in 1994 [12].

During the early 1990's, however, there was a need to approve building materials for industrial and commercial applications for heights $>9.1\,m$.

This need resulted in the development of a 50-ft corner test, which was also incorporated in the revised 1994 standard [12]. In the 50-ft corner test, the test structure is 15.2-m (50-ft) high with walls 6.1-m in length. The test fire load is the same as that of the 25-ft corner tests described above. For an assembly to be approved for use to a height of 15.2 m, the flames from the burning material cannot reach any of the limits of the corner test structure during the 15-minute test duration. If flames do not reach and ignite the ceiling of the assembly, the assembly can be used with no height restriction. Figures 1 and 2 show fire-propagating panels in the 25-ft and non-fire-propagating panels in the 50-ft corner test, respectively. (Note the test shown in Figure 1 is a research test in which only areas of the wall with initial fire involvement were covered).

The costs associated with a large-scale fire test emphasized the need for methodologies other than such tests to approve building materials for end-use applications. A physics-based model using material properties obtained

Figure 1. *The 25-ft corner test with PVC panels. (The color version of this figure is available online.)*

Figure 2. The 50-ft corner test with polyisocyanurate foam panels covered with a steel facing. (The color version of this figure is available online.)

from a small-scale apparatus such as the FPA would be ideal; however, as indicated in a position paper of the International FORUM of Fire Research Directors, such a solution is not currently practical due to unresolved issues such as the need for accurate models of buoyancy-driven turbulent convection, turbulent combustion with soot formation/oxidation and radiation [13]. The FORUM suggested as an interim solution the development of an intermediate-scale test, which correlated with a large-scale end-use fire test and was amenable to modeling. The FORUM noted that 'an appropriate intermediate-scale test would be sufficiently smaller in scale to allow for more extensive testing, but would include enough of the fire phenomena expected at the end-use scale that it was likely to correlate well with the large-scale fire test results.' The current study focuses on the development of an intermediate-scale test in the spirit of the FORUM's approach to flammability testing. Future work will concentrate on modeling based on inputs from measurements at a small-scale such as reported in [14] and [15] for smaller parallel panel configurations. Because fire propagation is the primary phenomenon in the corner tests, a fire test involving a fire source between two parallel vertical panels was selected as the intermediate-scale test to correlate with the 25-ft and 50-ft corner test results. Parallel panel fire tests had been used extensively to evaluate fire performance of materials under a variety of conditions. The background of the parallel panel test and details concerning the specific test investigated for this study are given below.

BACKGROUND OF PARALLEL PANEL TESTING

Parallel panel fire tests have a long history of applications in either small-scale or intermediate-scale tests. A small parallel panel configuration had been used in the early 1980s as a demonstration tool to educate field engineers on flame propagation along a vertical wall and to provide a degree of evaluation of materials in many facilities. In 1988, the parallel panel test was used for the first time in an industrial application to quantitatively evaluate fire propagation behavior of electric cables [16]. This cable test method [16] consisted of 4.9-m long vertical cables forming a parallel panel-like configuration. The objective of the test was to select electrical cables that would not support fire propagation to the top of an array of cables facing each other when exposed for 30 minutes to a 60-kW propane burner at the base of the array. The fire test configuration, in effect, simulated vertically facing cable trays. Occupancies using cables approved through this process do not require automatic sprinklers to be installed in the absence of other more severe hazards. The cables approved in this manner have been shown to be suitable for use in plenums where sprinkler protection is not provided [17].

Subsequent to this development, there was a need to approve materials for use in clean rooms of semiconductor fabrication facilities where fire propagation and smoke generation would result in severe property damage. The parallel panel configuration was extended to approve materials for clean room applications in 1997 with 2.4-m high panels [18,19]. The objective of the tests was to select materials, which would not support fire propagation beyond the flame zone of a 60 kW propane burner at the bottom of the test array. Thus, involvement in the fire was limited to the ignition zone of the facing panels. Simulated wet bench tests have shown that materials selected in this manner would result in self-extinguishment when the wet benches were exposed to flammable liquid fires associated with such facilities [20].

THE NEW PARALLEL PANEL TEST

Two important aspects that guide the use of parallel panel tests as an intermediate-scale test correlating fire behavior in the corner tests are: (1) maintaining a comparable view factor for the radiative heat transfer from the burning walls in the corner and parallel panel tests, and (2) providing a comparable heat flux to the test panels as in the corner tests. In order to meet the condition of item (1), the ratio of the parallel panel width to the clearance between the panels was kept equal to 2 to 1, which provides a view factor for the parallel panel of approximately 0.4 compared to about 0.3 in the corner tests. In regard to item (2), the heat flux from the 1.5-m high stack of wood pallets used as a fire source in the 50-ft corner tests was measured [21] to be $\sim$120 kW/m^2 at the top of the wood pallets, decaying to $\sim$40 kW/m^2, 6 m above the pallets. The maximum heat flux, 120 kW/m^2, when compared to the flux of $\sim$40 kW/m^2 in the 2.4-m high parallel panel test used for semiconductor applications, suggested that a scaled-up parallel panel with a higher heat flux would be needed to correlate with the corner tests. Indeed, an attempt to correlate the 2.4 m parallel panel (60-kW fire source) with the 25-ft corner test, along with analysis using a model with inputs from small-scale flammability measurements, confirmed the need to scale up the parallel panel test [15]. Guidance for scaling is given in [22].

The dimensions of the test apparatus were determined as follows:

(1) The aspect ratio between the width of the panel and the clearance between the panels was fixed at 2:1 due to the view factor consideration as mentioned above.
(2) Although most commercial panels were produced at 1.22 m $\times$ 2.44 m a piece, panels with a width of 1.07 m still could be found. In order to accommodate both sets of panels, the width of the apparatus was fixed at 1.07 m so that the tests could be run with a minimum preparation of the panels.
(3) Items 1 and 2 above determined the cross-sectional area of the apparatus at 1.07 by 0.53 m. The height of the apparatus was determined at 4.9 m based on experience associated with the 2.4-m high apparatus used earlier in order to accommodate the increased volume of flames.

To provide a heat flux of at least 120 kW/m^2 in the parallel panel test, a propane sand burner, 1.07 m by 0.53 m by 0.30 m high, was built to be located at the bottom of the panels. The burner is capable of generating up to 810 kW. Panels were mounted on 25-mm thick Marinite (calcium silicate board) attached to 13-mm thick plywood. The total HRR from the burning panels during the test was measured by a 5-MW capacity fire-products collector (FPC) located above the panel apparatus. Figure 3 and Figure 4 show photos of the apparatus and fire-propagating panels in the test, respectively. Figure 5 provides a schematic of the new parallel panel. The profiles of heat flux along the vertical centerline of the parallel panel as a function of the HRR of the propane burner are shown in Figure 6. The heat fluxes were measured with Gardon heat flux gauges cooled with a 55°C water flow.

Figure 3. New 4.9-m high parallel panel test apparatus under 5-MW FPC. (The color version of this figure is available online.)

CORRELATION WITH THE 25-FT CORNER TEST

Several parallel panel tests were conducted for different materials, material thicknesses, and HRRs of the propane burner. This series included a total of 31 tests, the results of which are given in Table 1. The '$\dot{Q}_b$' and 'Peak $\dot{Q}_{ch}$' labels in the third and fourth columns denote, respectively, the heat exposure from the gas burner and the maximum chemical HRR from the burning panels measured by the fire products collector in the test. HRRs were measured at 10 scans per second, with values shown in the table being 5-second-averages. The burner HRR is that averaged over the entire duration of a test. The last column labeled 'Fire Propagation' indicates whether the flames ever reached all the way to the top of the 4.9-m high panels during the test, and if yes, then the elapsed time to reach the top is also given. The samples used in the tests include various types of wall-panel materials up to Test 29, and wall/ceiling dual-purpose panel materials in Tests 30 and 31. The materials used in the tests were homogeneous and nonhomogenous;

Figure 4. *Fire propagation over material in 4.9-m high parallel panel test. (The color version of this figure is available online.)*

behaving as thermally thick and thermally thin during the test; with and without inert facings; melting and nonmelting; charring and noncharring. Materials evaluated include (thicknesses in parentheses): polyvinylchloride (6 mm, 13 mm, and 19 mm); fire retardant plywood (6 mm, 13 mm, and 19 mm); polyurethane foam core wall panels (76 mm, 127 mm, and 152 mm) with metal facings; fiberglass-reinforced melamine (2 mm); polystyrene foam (254 mm) with metal facing; and polyisocyanurate foam (152 mm) with metal facing for wall and ceiling panels. When the panels covered with inert facings were tested, the seams were always located at the center of the parallel panels so that the seams of the test panels coincided with the center-axes of the panels. That would have exposed the potentially weakest joints to the maximum heat exposure from the sand burner.

Based upon the heat flux results shown in Figure 6, it was expected that the parallel panel results obtained with the propane sand burner at a nominal HRR of 360 kW would correlate best with fire behavior in the 25-ft corner tests since the maximum flame heat fluxes were comparable. This expectation was confirmed by the experiments. The 25-ft corner test results are listed in Table 2 and are compared with the results for corresponding

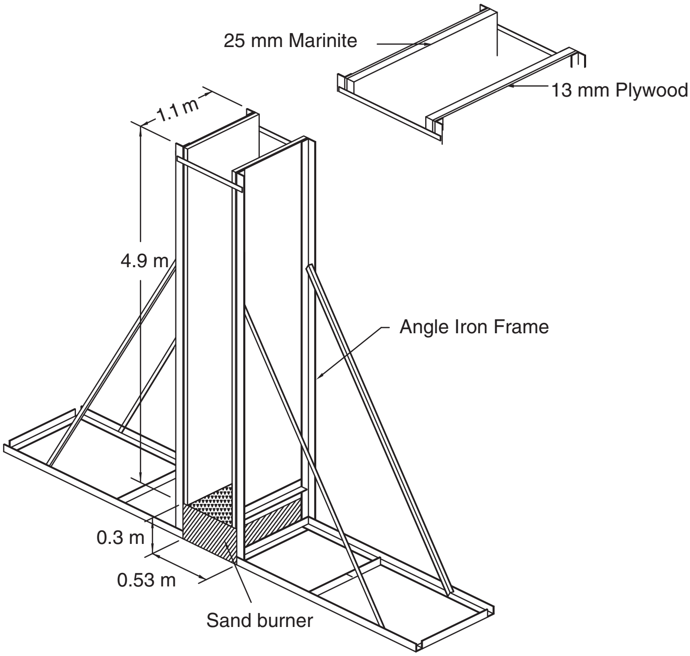

Figure 5. *Schematic of the new parallel panel test apparatus.*

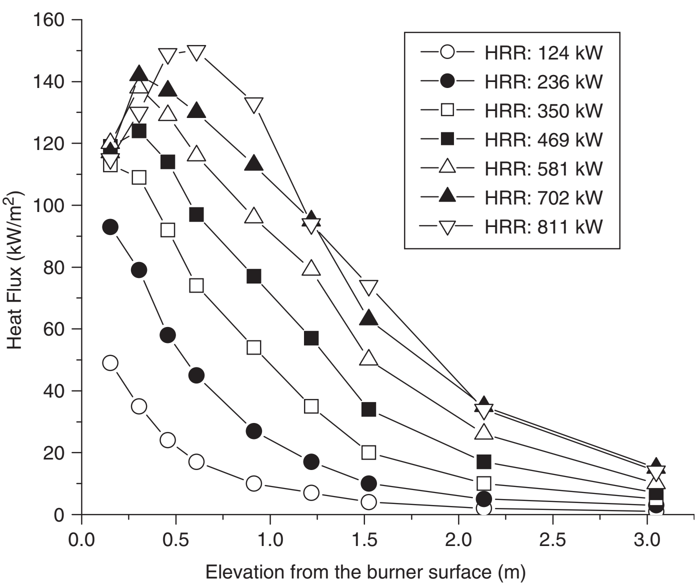

Figure 6. *Flame heat flux along panel centerline as a function of height for various HRRs of the propane burner.*

Table 1. List of the parallel panel tests.

Test no.	Material	$\dot{Q}_b$ (kW)	Peak $\dot{Q}_{ch}$ (kW)	Fire propagation
1	6 mm PVC	350	1115	Yes in 160 s
2	19 mm PVC	360	1362	Yes in 178 s
3	19 mm PVC	124	180	No in 900 s
4	19 mm PVC	232	1226	Yes in 870 s
5	19 mm PVC	185	1142	Yes in 1000 s
6	13 mm PVC	180	963	Yes in 790 s
7	13 mm PVC	60, 90, 120	No Data	No in 3100 s
8	13 mm PVC	120, 150	313	No in 1800 s
9	13 mm PVC	160,170, 180	611	No in 1500 s
10	6 mm PVC	160	731	No in 720 s
11	6 mm PVC	170	593	No in 900 s
12	6 mm PVC	180	823	No in 910 s
13	76 mm polyurethane foam core panels with steel facing	349	502	No in 900 s
15	152 mm polyisocyanurate foam core panels with steel facing	349	530	No in 900 s
16	152 mm polyisocyanurate foam core panels with steel facing	344	432	No in 900 s
17	19 mm FR-plywood	342	835	No in 1200 s
18	19 mm FR-plywood	457	955	No in 980 s
19	13 mm FR-plywood	343	943	No in 900 s
20	13 mm FR-plywood	461	906	No in 950 s
21	6 mm FR-plywood	344	1494	Yes in 164 s
22	6 mm FR-plywood	228	1218	Yes in 187 s
23	6 mm FR-plywood	180	678	No in 540 s
25	2-mm-fiberglass-reinforced melamine w/inert facing	344	527	No in 1200 s
28	254 mm polystyrene foam core panel with 26-gage steel facing	360	2100	Yes in 210 s
29	152 mm polyisocyanurate foam core panel with 26 gage steel facing	360	610	No in 1200 s
30	152 mm thick polyurethane foam core panel with 0.045-mm thick steel facings	360	809	No in 900 s
31	127 mm thick polyurethane foam core panel with 24 gage steel facing	360	595	No in 900 s

Table 2. Fire propagation correlation between the 25-ft corner test and parallel panel test.

	Fire propagation?		
	25-ft corner test	Parallel panel test ($\dot{Q}_b = 360$ kW)	
Material	Flames along 11.6 m horizontal eave	Reached $\dot{Q}_{ch} = 1125$ kW?	Max vertical visual flame propagation
19 mm PVC	Exceeded 11.6 m	Yes in 3 minutes	4.9 m
6 mm PVC	Exceeded 11.6 m	Yes in 2.7 minutes	4.9 m
254 mm polystyrene foam core panels with inert facing	Exceeded 11.6 m	Yes in 4 minutes	4.9 m
19 mm FR-Plywood	5.5 m	No in 20 minutes $(HRR)_{max}$ = 853 kW at t = 109 s	2.4 m
13 mm FR-Plywood	7.0 m	No in 15 minutes $(HRR)_{max}$ = 960 kW at t = 390 s	3.4 m
6 mm FR-Plywood	9.8 m	Yes in 2.7 minutes	4.9 m
76 mm polyurethane foam core panels with steel facing	6.1 m	No in 15 minutes $(HRR)_{max}$ = 513 kW at t = 88 s	1.8 m
2-mm fiberglass reinforced melamine with inert facing	5.2 m	No in 20 minutes $(HRR)_{max}$ = 543 kW at t = 91 s	3.7 m

materials from the parallel panel test with the 360-kW burner. Note that the 360-kW sand-burner alone generated flames about 1.1 m high between the panels. The HRR from the panels shown in the table are values adjusted by adding the small differences between the average HRR of the sand burner and 360 kW in order to have a consistent comparison. In the table, 'Fire Propagation' was defined as flames reaching 11.6 m from the corner along either eave in the corner test, and flames reaching the top of the panels in the parallel panel test. The length of the flame extension along the horizontal eaves in the corner test was determined from video taken during the tests except for the polyurethane core insulated wall with an inert facing. No video was taken in that test and the flame extension lengths were visually determined from the post-test burn mark on the surfaces.

In the parallel panel tests, however, in addition to the visual flame propagation, the performance was also determined based on the total HRR from the 5-MW Fire Products Collector. It was observed that a maximum total HRR >1125 kW, while the sand-burner HRR was maintained at 360 kW (i.e., a net contribution from the burning panels >765 kW) resulted in flames propagating all the way to the top. A case in point was Test 1 in Table 1. The peak HRR in the test was 1115 kW when the flames touched the top of the panels, while the average sand-burner HRR was 350 kW. Thus, if the sand-burner HRR had been 360 kW, then the total HRR measured in the test would be slightly greater than the threshold value, 1125 kW. In certain cases during parallel panel tests, flames reached the top of the panels in an early stage and then retreated, only later to propagate again to the top of the panels. If that happened, the flames in the later stage were in general much more intense, and yielded much higher HRR than that of the earlier ones, mainly because more fuel, i.e., combustible gas, was available at that stage. Thus, the HRR curve revealed multiple peaks. In those cases, the maximum HRRs associated with the flames in the early stage, i.e., the first peaks (still $>$1125 kW), were given in Table 1. This HRR metric is a more reliable way of determining fire propagation than the visual observation that tends to be subjective under highly smoky environments. When the maximum HRR was $<$1125 kW, then the maximum HRR and the corresponding time during the test are given. In the corner tests, test duration was 15 minutes as specified in the certification test standard [6]. In the parallel panel tests, the test duration was generally extended to 20 minutes. However, when the total HRR clearly indicated that there was no chance of fire propagation, then the test was terminated after 15 minutes.

The materials most extensively tested were PVC and fire retarded plywood. Some details of these tests are discussed below. In the 25-ft corner test with the 19-mm thick PVC panels, flames appeared above the top of the pallets at 140 seconds and reached the 11.6-m limit of the test frame at around 320 seconds after ignition. Thus it took about 180 seconds from when the first flame started to impact the panel to the complete propagation of the flames along the south eave. In the corner test with the 6 mm PVC panels, it took about 172 seconds from when the first flame started to impact the panel to the complete propagation of the flames along the 11.6-m long horizontal eave. In the corner test with the 254 mm polystyrene sandwich panels, it took $\sim$140 seconds to have flames from the wood pallets appear above the pallets and took $\sim$280 seconds from the first flame starting to impact the panel to the complete propagation of the flames along the 11.6-m long horizontal eave. In all the three cases as shown in Table 2, where the parallel panel test results properly indicated that flame propagation should occur in the corner tests, the times required for the flames to reach to the top of the panels in the parallel panel tests and that to reach to the horizontal end of the test frame in the corner tests were comparable, indicating similar flame propagation mechanisms and an appropriate scale of the parallel panel test.

The fire propagation correlation between the corner tests and corresponding parallel panel tests shown in Table 2 is excellent except for the case of 6 mm FR-Plywood. While the corner test showed that the flames did not propagate all the way to the end of the 11.6-m long wall, the parallel panel test indicated otherwise. Considering that the flames extended to 9.8 m along the horizontal eaves in the 25-ft corner test, just 1.8 m shy of the 11.6-m fail criterion, the prediction based on the parallel panel test is only slightly more conservative. Thus, the overall comparison in Table 2 supports the positive correlation between the 25-ft corner tests and the parallel panel tests.

CORRELATION WITH THE 50-FT CORNER TEST

In addition to correlating parallel panel tests with results from the 25-ft corner tests, a correlation was attempted with 50-ft corner test results. Insight into the latter correlation can be gained by comparing the results from the 25-ft and the 50-ft corner tests. A large body of test data was evaluated to determine if the outcomes of both of the 50-ft and 25-ft corner tests can be correlated and whether they could be predicted by the parallel panel tests. For example, the parallel panel test should be able to predict whether flames from wall assemblies in the 50-ft corner test would reach and ignite its combustible ceiling, thus restricting these assemblies to heights of <15.2 m (50 ft) or allowing them to be used in applications with unlimited height if flames do not reach the 50-ft corner ceiling.

Comparison of 25-ft and 50-ft Corner Tests

It is proposed that the sum of the vertical flame height and the extent of lateral flame spread in the 25-ft corner test can be translated into the extent of fire spread in the 50-ft corner test. A rationale for this method is provided by results [23] relating vertical flame height to flame length along a ceiling, a case that differs from the corner test configuration. However, the ultimate validity of the method depends on the empirical results from comparisons of the 25-ft and 50-ft corner tests.

If the vertical flame length in a 50-ft corner test is <15.2 m, then the flames will not touch the ceiling (at 15.2-m high) and the material can be used with no restriction with respect to height. If one simply translates the flame height in the 50-ft corner test to the sum of the vertical flame height in the 25-ft corner test and the flame extension along the eaves, the maximum flame extension in the 25-ft corner test that would result in flames just reaching the ceiling in the 50-ft corner test would be 7.6 m. (As aforementioned, the same result, albeit less straightforward, can be obtained using [23]). Since the length of flame extension along the eaves can be asymmetric, the total combined length of the flame extensions along both eaves would be convenient in practical applications. Thus, if the total length of the flame extension along both eaves in the 25-ft corner test is shorter than 15.2 m, then it is hypothesized that the material meets the performance required for approval with 'unlimited height.' If the total flame extension along both eaves is >15.2 m in the 25-ft corner test, but flames do not extend beyond the structure of the 25-ft corner test, then the flames generated by these material assemblies will not extend beyond the structure of the 50-ft corner test. This is expected following the same logic as above since the total height plus ceiling extension along one wall in the 50-ft corner test is 21.3 m (15.2 m + 6.1 m) which is greater than the 19.2 m (7.6 m + 11.6 m) in the 25-ft corner test.

Table 3 shows materials that were exposed to both 25-ft and 50-ft corner tests. The flame extension along the eaves in the 25-ft corner test and the vertical flame height in the 50-ft corner tests are given. The lengths of flame extension along the eaves in Table 3 were determined through the post-test burn marks the flames left on the walls; thus, they are expected to be somewhat shorter than the real flame extensions during the tests. All the combined flame extensions along the horizontal eaves in Table 3 were <15.2 m. Note that with FRP panels in Table 3 and Fr-Plywood panels in Table 2, the thinner or lighter a panel was, the further was the flame propagation. This supports the view that materials/assemblies need to be tested at their installed thickness as it impacts ignition propensity and fuel availability; hence, propagation behavior. Also note that in all cases, the the flame extension along one horizontal eave added to the vertical flame height of 7.6 m in the 25-ft corner test is slightly greater than the vertical flame height in the 50-ft corner test, which adds a degree of conservatism to the approach. Thus, the data support the proposition discussed above.

Relationship to Parallel Panel Test

The discussion above indicates that the 25-ft corner test can be used to provide a preliminary estimate of whether a material can be accepted for 15.2-m high maximum or unlimited height. Based on the correlation between the corner tests and the parallel panel tests, if a material generates more than 1125 kW at any time during the parallel panel test with the

Table 3. Comparison of results from 25-ft and 50-ft corner using the same wall assemblies.

Material	Flame extension along the eaves in the 25-ft corner test	Vertical flame height in the 50-ft corner test
FRP Composite (4.9 kg/m^2)	5.5 m (south wall); 6.7 m (east wall)	10.7 m
FRP Composite (5.2 kg/m^2)	4.9 m (south wall); 4.9 m (east wall)	12.2 m
FRP Composite (3.7 kg/m^2)	5.5 m (south wall); 5.5 m (east wall)	11.3 m

exposure of 360 kW, the material is expected to generate flames propagating beyond the structure of the 25-ft corner test. Thus, all the materials that are expected to pass both the corner tests will generate less than or equal to 1125 kW in the parallel panel tests with $\dot{Q}_b = 360$ kW. It is also clear that less flammable materials will generate a lower $\dot{Q}_{ch}$ in the parallel panel test and would pass the corner test with a greater height limit than that for more flammable materials. This suggested that the $\dot{Q}_{ch}$ in the parallel panel test should be used for determining whether the fire performance of a material should be expected to require no height restriction or be restricted to a height of 15.2 m.

Applying the conditions regarding the combined flame extension along the horizontal eaves in the 25-ft corner test to the data in Table 2 indicates that the 19 mm FR-Plywood, the 13 mm FR-Plywood, the 76 mm polyurethane core panels with steel facing, the 2-mm fiberglass reinforced melamine with inert facing, and the 152 mm polyisocyanurate foam with 26 gage steel facing could be expected to generate flames that would not reach the ceiling in the 50-ft corner test. The results for these materials from the 25 ft corner test and the maximum HRR generated in the parallel panel tests are shown in Table 4. In addition, note that the 152 mm polyisocyanurate foam with 26-gage (0.455 mm) steel facing, which is the last item in Table 4, was also tested in the 50-ft corner test and observed to require no height restriction.

The 19-mm thick FR-Plywood, which meets the proposed approval criterion for no height restriction in the 25-ft corner test, generated a maximum HRR of 853 kW in the parallel panel test with the 360-kW exposure. Although the condition specified earlier indicates that the 13-mm

Table 4. Results from parallel panel tests using materials with limited flame spread (< 7.0 m along one wall) in the 25-ft corner tests.

Material	Flame spread along the eaves in 25-ft Corner test	$\dot{Q}_{ch}$ in parallel panel test with $\dot{Q}_b = 360$ kW
19 mm FR-Plywood	5.5 m along both eaves	853 kW
13 mm FR-Plywood	7.0 m along both eaves	960 kW
76 mm polyurethane foam core panels w/steel facing	6.1 m along both eaves	513 kW
2-mm fiberglass reinforced melamine with inert facing	5.2 m along both eaves	543 kW
152 mm polyisocyanurate foam core with 26-gage steel facing	Passed the 50-ft corner test** with unlimited height approval	601 kW

**The 25-ft corner test was not conducted for this material.

thick FR-Plywood also would be accepted for no height restriction, the flame propagation along either horizontal eave was 7.0 m long, which was quite close to the 7.6-m criterion established above. Thus, to provide a degree of conservatism, a HRR of <853 kW in the parallel panel test with the 360-kW exposure appears to be appropriate as the criterion for approval of a material for 'unlimited height' without conducting full-scale corner tests. After conducting an uncertainty analysis associated with the HRR measurements using the fire-products collector, the two critical values mentioned above, 1125 kW and 853 kW, were further adjusted to 1100 kW and 830 kW, respectively. Thus, in conclusion: (1) if a wall panel generates, in the parallel panel test, a maximum total HRR less than or equal to 830 kW with the 360-kW exposure, it is expected to behave as a wall panel approved in the 50-ft corner test with no height restriction, (2) if the panel generates a maximum HRR >830 kW but <1100 kW, then it is expected to pass the 50-ft corner test with a height restriction of 15.2-m, and (3) if it generates >1100 kW in the parallel test, then the panel is expected to propagate flames beyond the structure of the 25-ft corner test.

EXTENSION TO WALL AND CEILING PANEL COMBINATIONS

As the 25-ft and the 50-ft corner tests also can incorporate combustible ceilings, a way of extending the parallel panel test to combustible wall/ceiling panels was sought. The selected approach was to conduct the parallel panel tests with panels that are approved for the dual use on walls and ceilings. The rationale was that by doing so, the test results of the materials approved for wall panels only can be compared with those approved for ceiling and wall panels. Thus, Tests 30 and 31 in Table 1 were conducted with the panels that are approved for wall/ceiling dual purpose.

Compared with the flame extension along the horizontal eaves in the 25-ft corner test in which the ceiling is noncombustible, the flame extension in the corner tests with combustible ceilings would be greater mainly due to the following: (1) as the ceiling is combustible, the wall panels along the horizontal eaves would be exposed to more radiative heat flux during active burning at the ceiling than otherwise, and this effect would enhance the flame propagation, (2) as the ceiling also participates in generating pyrolyzed materials, there would be more combustible gases than otherwise, and that would enhance the flame propagation, and (3) when the ceiling is participating in combustion, the flames along the eaves would receive heat from, rather than losing heat to, the burning ceiling; thus, this effect would enhance the flame propagation. Therefore, it is reasonable to expect that the critical HRR in the parallel panel tests corresponding to the pass/fail criteria of the corner test with combustible ceilings should be <1100 kW.

The previous study showed that one can relate the flame length along the ceiling-wall panel intersection to that along a vertical wall. Tests indicate that the vertical flame height in the 50-ft corner test would be less than the flame extension along the horizontal eave plus the vertical flame length, 7.6 m, in a corresponding 25-ft corner test. The 19-mm FR-Plywood test in Table 4 indicates that the vertical flame length would be <13.1 m (7.6 m + 5.5 m), while the total HRR of the panels was about 853 kW, or 830 kW adjusted after an uncertainty analysis (see the previous section). In contrast, the total allowable length of the flame (vertical + horizontal) for the threshold case mentioned above would be 19.2 m (7.6 m + 11.6 m) to pass the 25-ft corner test. Therefore, the panels that generate <830 kW of the total HRR in the 4.9-m high parallel panel test with the 360-kW sand-burner exposure would perform as ceiling/wall panels because: (1) the flames in the 50-ft high corner tests would not reach the ceiling, and (2) in the 25-ft corner test, the flames will not reach 11.6 m along the horizontal eaves, which is the threshold length for the pass/fail criterion.

For the reasons given above, the expected critical HRR in the parallel panel test that would correspond to results in the 25-ft corner tests with combustible ceilings must be <1100 kW; but it could be >830 kW. However, the HRR did not exceed 830 kW in either Test 30 or Test 31. Thus, as a conservative requirement prior to gaining additional experience, a HRR limit of 830 kW for both ceiling and wall panels is taken as an indication that the combination of the ceiling and wall materials would not generate fire propagation beyond the limit of the test structures in the 25-ft corner test in addition to not igniting the ceiling in the 50-ft corner test. When the ceiling and the wall panels are different, two separate parallel panel tests with each panel should be conducted and both tests should meet the requirement mentioned above.

MODELING THE PARALLEL PANEL TEST

The new parallel panel test can serve as a tool to validate a physical model that uses bench-scale test data for input. Developing a physical model requires many validation tests at each stage. If such tests have to be conducted at full scale, the cost would be prohibitively high. Employing intermediate-scale tests at relevant scales is vital to the successful development of a physical model. Once the model is proven reliable, it will eventually be able to represent results from full- and intermediate-scale tests with bench-scale test input. Earlier analyses [14,15] indicated that the ratio of the heat of combustion to the heat of gasification and the smoke yield mainly control fire growth. Similar methods will be used to analyze the test results in Table 1 in conjunction with the bench-scale test data providing the material properties of the panels listed in Table 1. These modeling efforts should result in a more advanced assessment of material flammability than is currently available.

CONCLUSIONS

A new intermediate-scale fire test has been developed as a screening tool to evaluate wall and ceiling assemblies for material flammability. Comparisons with the 25-ft and 50-ft corner tests indicate that fire propagation behavior in the corner tests correlates well with the maximum HRR in the parallel panel test. Fire will not propagate to the end of the test array in the 25-ft corner test with combustible walls and noncombustible ceiling if the HRR in the parallel panel test is <1100 kW; fire will not reach the top of the test array in the 50-ft corner test if the HRR in the parallel panel is <830 kW; fire propagation will not reach the ends of the horizontal ceiling in the 25-ft corner test with combustible walls and ceiling panels if the HRR in the parallel panel test is <830 kW. The current study provides an example of a way of developing an intermediate-scale test that will serve as a stepping stone to reach the final destination – an engineering model that can predict the outcome of full-scale tests by using material properties measured in a bench-scale apparatus.

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