Fire Exposure to Exterior Walls and Flame Spread on Combustible Cladding

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Abstract

A segment of the on-going research program on fire spread via exterior walls conducted at the Institute for Research in Construction of the National Research Council of Canada is described. The research includes full-scale experimental studies of fire exposure to exterior walls, fire hazards associated with the use of combustible materials, and the development of new test methods for assessing the flammability of combustible cladding. Correlations between the results of a new full-scale test and standard flame spread tests (Steiner tunnel test, radiant panel test, roof deck test) were investigated. A prototype of a reduced-scale test, the vertical channel test, is described. It was found that, at present, the full-scale test is the most appropriate method to evaluate the fire hazards of combustible wall assemblies.

Introduction

Scope of Work

The Institute for Research in Construction of the National Research Council of Canada is currently investigating fire exposure to exterior walls and fire hazards associated with the use of combustible materials in exterior walls. The investigations also include an evaluation of standard and modified standard fire tests and new test methods for flame spread over combustible exterior walls.

The research does not address some of the other important issues related to fire spread on building facades, such as "leap frog" fire spread via window openings and fire spread to an adjacent building. The scope of the described work is limited to fire exposure to exterior walls as a

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means to ignite combustible exterior cladding systems and to vertical flame spread over such walls.

Background

A fire on an exterior wall of a building can be viewed as a phenomenon which can inflict losses by damaging the wall or as a potential path for the spread of fire to compartments above or to an adjacent building. There have, however, been few reports of exterior wall fires as such. The following would appear to be responsible for this: The use of combustible materials in exterior walls has been restricted by building codes in most countries to low buildings thus reducing such losses to an insignificant level. An exterior wall fire usually results from an intense fire within the building and the wall fire is masked by the primary building fire.

A wall fire is usually reported when it has explicitly contributed to fire spread, as was the case in the major residential fires that occurred in Canada.[1,2] Yet, despite the low number of the reported exterior wall fires, combustible exterior wall systems have been intensively discussed over the last decade. In North America, there has been increasing pressure to change building codes to permit the use of newly developed combustible exterior wall systems that are claimed not to propagate fire. The resistance to the acceptance of such wall systems by the building codes committees stems from the lack of statistical data and, until recently, from the lack of systematic research in this area. In the past, fragmented research was conducted.[3,4,5] The pace of the research increased after the energy crisis, when insulating values and ease of installation of retrofit exterior insulation systems became significant issues. Since then, a number of large research programs was initiated[6,7,8,9] including the research described in this paper.

Exposure of Exterior Walls to Fire

There are three primary fire threats to a building's exterior walls:

- an interior compartment fire venting through a window.
- a fire in combustibles accumulated near the wall (burning trash, vehicle fire, bush fire).
- a fire in an adjacent building.

Of these, the first – a fire within the building and venting through a window – is perceived to be the most severe and statistically the most significant.[10] The high severity of this exposure results from direct impingement of an intense fire plume on the outer face of the exterior wall.

Exposure of an exterior wall to fire can be expressed in terms of the density of heat flux to the wall and the duration of the exposure. Data on such fire exposure is needed for the assessment of hazards such as ignition of combustible materials in exterior walls, flame spread over combustible cladding, and glass destruction in windows above the story of fire origin.

Full-scale fire experiments to collect that fire exposure data were conducted using two burn facilities and two different fuels, namely wood cribs and propane gas. Wood cribs were used to provide flames with heat transfer characteristics (emissivity) similar to those produced in real fires. One disadvantage of using wood cribs as a fuel is the lack of control over the heat release rate during an experimental fire. Propane burners were used later to study the impact of heat release on exterior wall fire exposure. Window dimensions were also evaluated as factors affecting heat transfer from flames to the wall above the window.

One experimental fire was conducted to assess the effect of facade geometry on heat flow to the wall. During that fire, two types of projections were used: one was a horizontal panel attached immediately above the window, and the second was a pair of vertical panels attached along both sides of the window.

Wood Crib Fires

Six full-scale experimental fires were conducted using wood cribs as fuel. Three experiments were conducted using each of two facilities of different dimensions. In the first two experiments using the smaller facility, radiant and convective components of heat transfer to the wall above the window were studied. In the third experiment, the effect of facade geometry was studied. In the experiments conducted using the larger facility, total heat transfer to the wall above the window was studied. The wood crib fires in the larger facility were also used as the reference for the propane gas fires that were conducted in the larger facility.

The smaller facility consisted of a 2.4 m wide by 3.6 m deep by 2.4 m high room with the front wall extended to 6.1 m in height and 3.6 m in width (Figure 1). The exposed wall was concrete blocks covered with 13 mm thick noncombustible board (density: 770 kg/m^3). Wood cribs, distributed uniformly over the floor area and representing a fire load of 25 kg/m^2 were used as fuel. The cribs were made of 41 mm × 41 mm pine sticks. Ventilation was provided by the window opening only, with the opening dimensions selected so that the intense burning phase lasted for 15 to 20 minutes. In the first and the third tests, a 1.13 m square window opening was used. In the second test, a tall narrow (1.50 m × 0.69 m) window opening was used. The dimensions of the window in the second test were selected to provide approximately the same ventilation to the fire as that provided by the window in the first and the third tests.

Measurements of the total heat flux density were taken on the center line of the wall, at 0.25 m, 1.0 m, 1.75 m, and 2.5 m above the top of the

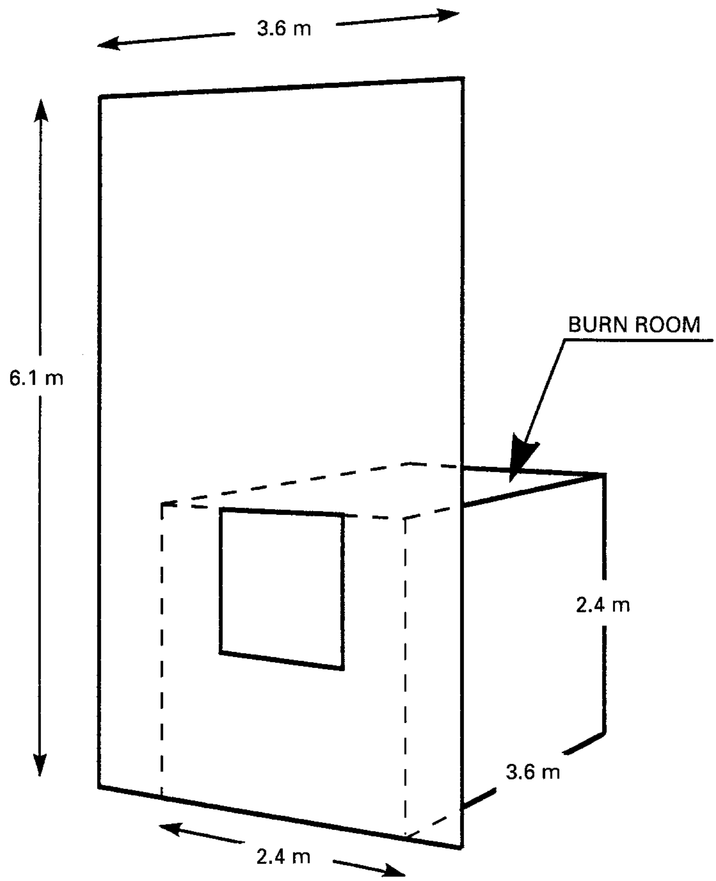

Figure 1: Smaller burn facility used to study fire exposure to exterior wall.

window. The transducers used were water-cooled Medtherm 64 Series, range 200 kW/m^2, 100 kW/m^2, 100 kW/m^2, and 50 kW/m^2, respectively. Irradiance was measured using air-purged, water-cooled radiometers (Medtherm 64 Series with sapphire window, range 100 kW/m^2) installed on the center line of the wall at 0.25 m and 1.0 m above the top of the window. Condensation on the transducers was prevented by supplying cooling water at the temperature of 50°C from a thermostatically controlled circulator. Sooting of the radiometer windows occasionally occurred despite the air-purge system. Readings were not used when a radiometer was found, after the experiment, to have its window sooted.

Figure 2 shows heat transfer data collected during the first test. The solid line represents total heat flux density 0.25 m above the top of the window. The radiant heat flux density was measured by the air-purged

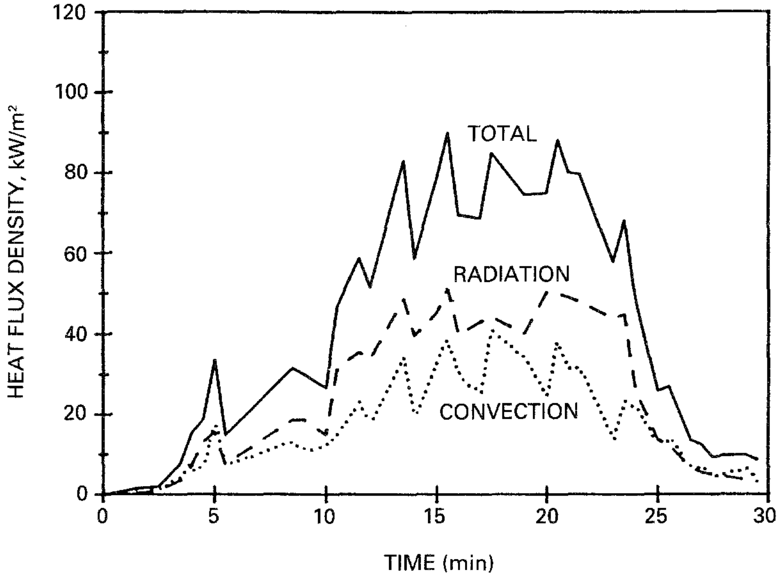

Figure 2: Heat flux density as measured at 0.25 m above window, wood crib fire, 1.13 m square window.

radiometer installed adjacent to the total heat flow transducer. The convective heat flux density was calculated as the difference between the total heat flux density and the radiant flux density. The maximum recorded values of the total and the radiant heat flux densities were 90 kW/m^2 and 51 kW/m^2, respectively. The maximum calculated convective heat flux density was 41 kW/m^2. The radiant heat flux density constituted approximately 60% of the total heat flux density for most of the experiment. Figure 3 shows the heat transfer data obtained from the measurements taken during the second test (with a tall, narrow window), 0.25 m above the top of the window. The radiant portion, however, was much higher and briefly exceeded 90 kW/m^2. Total heat flux density exceeded 100 kW/m^2 for a substantial portion of the experiment. Only one test was conducted using each window opening, and the statistical significance of the above data is not known at this time.

Another series of three wood crib fires was conducted using the larger facility. That facility (Figure 4) consisted of a three-story high (10.3 m) reinforced concrete frame, a burn room located on the ground floor, and a concrete block front wall covered with 13 mm thick noncombustible board (density: 770 kg/m^3). The burn room consisted of a reinforced concrete floor, concrete block walls, and a precast concrete panel ceiling. The walls and ceiling were covered on the room side with 25 mm thick

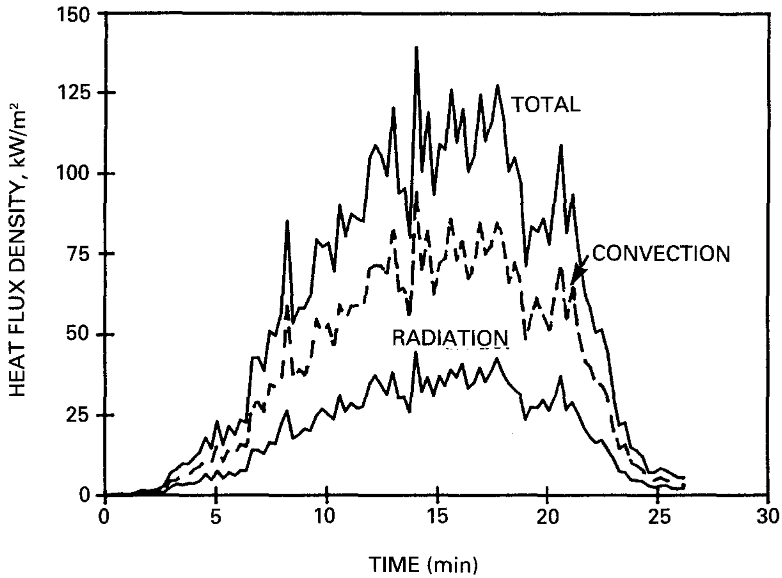

Figure 3: Heat flux density as measured at 0.25 m above window, wood crib fire, 0.69 m wide by 1.5 m tall window.

ceramic fiber insulation. The floor was covered with 57 mm thick fired clay paving stones. The inside dimensions of the burn room were 5.95 m wide, 4.4 m deep, and 2.75 m high. One 1.37 m high × 2.60 m wide window opening was provided in the front wall of the burn room. This was the only opening in the room boundaries.

A 25 kg/m^2 fuel load comprising six wood cribs made of 41 mm × 89 mm pine sticks was used. The cribs were uniformly distributed in the burn room.

The total heat flux density to the wall was monitored by four water-cooled heat flow transducers (the same units used in the smaller facility) installed in the wall with their sensing faces flush with the outer wall surface. Transducers were located on the vertical center line at 1.0 m intervals starting at 0.5 m above the window opening. Two radiometers were also installed in the wall, but their readings aren't reported because of sooting of the radiometer windows. Figure 5 shows heat flow data collected in one of the tests at various heights above the top of the window.

Propane Gas Fires

A series of experimental fires using propane gas as the fuel was carried out in order to study the impact of heat release in conjunction with window opening dimensions on fire exposure to the exterior wall. The experimental fires were conducted using the larger (three-story)

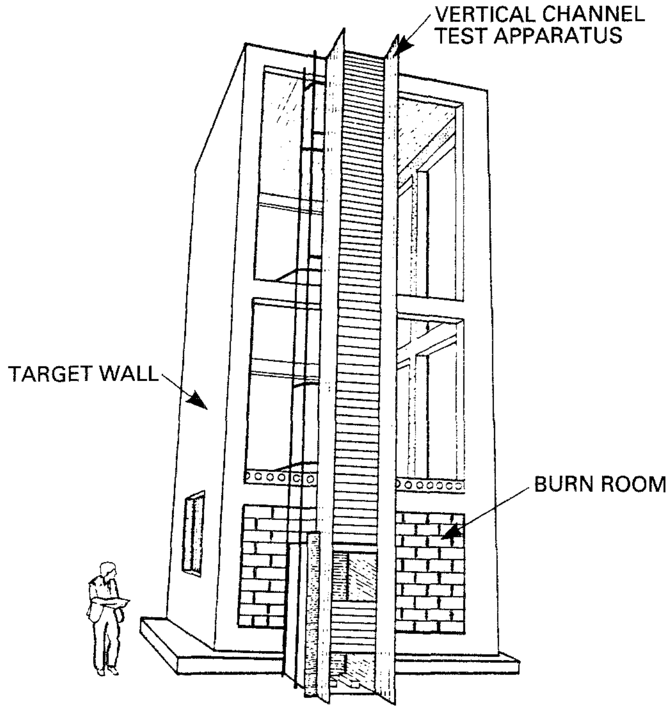

Figure 4: Exterior wall fire test facility and vertical channel flame spread test apparatus.

test facility equipped with four 3.8 m long linear propane diffusion burners, spaced equally along the width of the room and elevated 0.6 m above the floor. The propane mass flow rate was manually controlled and monitored by a hot wire type flowmeter. The total heat flux density was measured at four levels at 1.0 m intervals, starting 0.5 m above the window. The heat release rate was calculated from the gas supply rate assuming complete combustion.

Figure 6 shows the total heat flux density measured at 0.5 m above the top of the window opening versus the rate of heat released in the fire for five different window dimensions. The heat transfer to the exterior wall depends on both the window opening dimensions and the room heat release rate. The low, wide window opening (2.6 m wide by 1.37 m high) had the highest heat transfer for every heat release rate except 5.5 mw. Video records show that, with this heat release rate, the smallest window had a substantial flame issuing from the window while the bigger windows allowed combustion to be completed within the burn room.

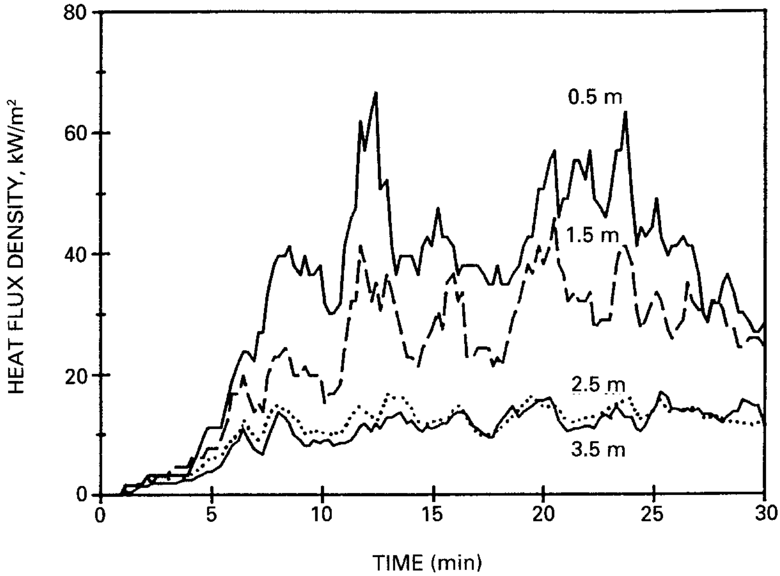

Figure 5: Heat flux density as measured at different heights above the window, wood crib fire, three-story burn facility, 2.6 m wide by 1.37 m high window.

Figure 7 shows the total heat flux density versus height above the window for one window (2.6 m wide by 1.37 m high) and for different heat release rates.

It is interesting to see how the data obtained in wood crib fires compare with the data obtained in propane fires. The comparison has to be approximate since the fuel consumption rate was not measured in the wood crib fires. Assuming after Heselden[11] that 50% of the wood was consumed at a steady rate over the fully developed period, one can estimate that the heat release rate in the fires conducted using the three-story facility was approximately 6 MW. For this room heat release rate and the 2.6 m wide and 1.37 m high window opening (used in the wood crib fires), the heat flux density at 0.5 m above the window can be estimated at 36 kW/m^2 for the propane fire compared with 45 kW/m^2 for the wood crib fire (Figure 5). A propane fire produces somewhat lower exposure than the wood crib fire at the same heat release rate. This can be explained by the lower emissivity of the propane flame. As Figure 6 shows, the difference can be easily compensated by increasing heat release rate (gas flow) in the propane fire.

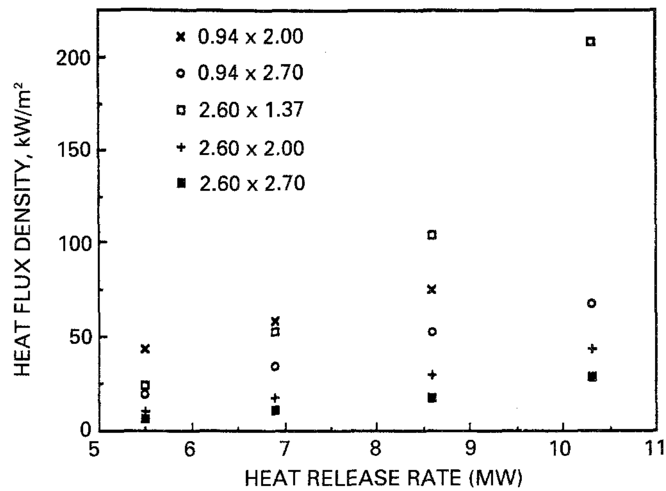

Figure 6: Variation of time-averaged heat flux density at 0.5 m above window with heat release rate and window dimensions, propane gas fires.

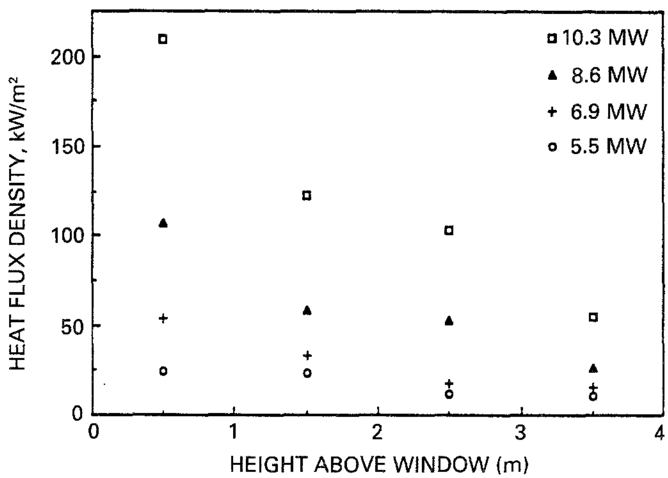

Figure 7: Variation of time-averaged heat flux density with height above window and heat release rate, 2.6 m wide by 1.37 m high window, propane gas fires.

Facade Geometry

One test was conducted to assess the effects of the facade geometry on heat transfer to the facade. The test was conducted using the smaller burn facility. The window opening was 1.13 m square and the fuel load comprised wood cribs (24 kg/m^2) made of 41 mm × 41 mm pine sticks.

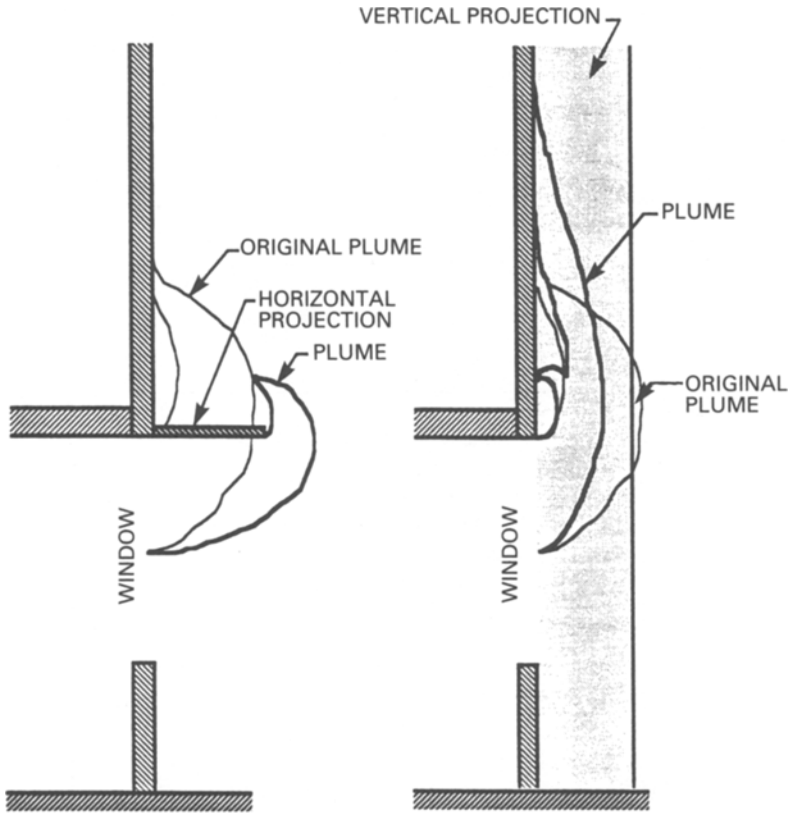

Figure 8: Window plume changes due to application of horizontal and vertical projections.

During the test, two types of projection were applied to the exterior wall. One was a horizontal panel, 1.22 m deep and 2.44 m wide, attached to the wall immediately above the window opening. The second was a pair of 1.22 m deep vertical panels perpendicular to the wall, attached along both sides of the window opening. Figure 8 shows the changes to the plume due to the presence of these projections.

Figure 9 shows readings of the total heat flow transducers installed on the wall at various levels above the top of the window. It is clear, despite the scatter of the data, that the horizontal projection offered substantial protection for the wall above the window. This data supports the assumptions proposed by Harmathy[12] who stated that a device, called a flame deflector, could protect windows from fire plumes issuing from

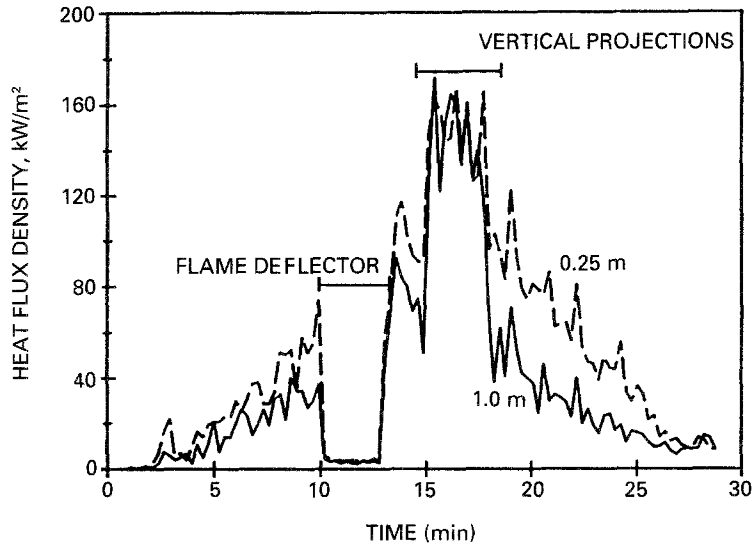

Figure 9: Variations of heat flux density at different heights above window, caused by application of wall projections. Horizontal projection (flame deflector) was applied between 10 min and 13 min, vertical projections were applied between 15 min and 18 min.

stories below. On the other hand, Figure 9 shows that the vertical projections increased heat transfer to the facade. They restricted lateral air entrainment to the plume causing a vertical extension of the combustion zone within the plume. Although no gas velocity measurements within the plume were taken, the video recording seems to indicate an increased vertical velocity of the gases within the plume, which may increase the convective heat transfer.

Flame Propagation over Combustible Exterior Walls

Flame propagation over the outer face of an exterior wall may itself create a problem for firefighters or may cause a fire to spread to the stories above the story of fire origin. The hazard is extremely high for very tall buildings because a wall fire may extend beyond the reach of fire services.

Not all combustible walls can support vertical flame spread. Factors such as the amount of combustibles per unit area, their heat of combustion, the ignition temperature of the combustible components of the wall, thermal inertia, the composition of the wall (e.g. the presence of a protective layer), and preservation of integrity when exposed to fire are factors determining the propensity for vertical flame spread.

A representative set of combustible wall assemblies was subjected to a battery of tests in order to evaluate the applicability of the test methods in the assessment of flame spread potential. The tests included a full-scale test and four smaller-scale tests.

Wall Assemblies

The tested assemblies included wood frame walls with various insulations, sheathings and sidings, composite panels with plastic foam cores and FRP membranes, and a large group of combustible exterior insulation systems applied to a noncombustible wall. An exterior insulation system typically comprised plastic foam insulation coated with glass fiber mesh and synthetic plaster. Table 1 incorporates descriptions of some of the tested assemblies, including the noncombustible wall (marinite), which was used for calibration and reference purposes. The assemblies are grouped according to the flame spread distance recorded during the full-scale test. Assemblies 4.1, 4.2, and 4.3 showed flame spread to the top of the wall. Assemblies 3.1 to 3.8 showed flame spread above the extent of the flame issuing from the window, but eventually the flame stopped and, in most instances, receded before the end of the test. Assembly No. 2 did not show flame spread above the exposing flame, and Assembly No. 1 is the noncombustible, reference wall.

Full-scale Tests

The full-scale tests were conducted using the three-story facility equipped with propane burners. The window opening was 2.6 m wide and 1.37 m high. The fire exposure lasted 25 minutes, comprising a five-minute gradual buildup, followed by a 15-minute period of steady fuel supply rate, and a five-minute cool down period. The fire exposure duplicated that recorded in the wood crib fires and the 15-minute average (the steady gas supply rate period) of the heat flux density was 45 ±5 kW/m^2 measured 0.5 m above the opening and 27 ±3 kW/m^2 measured 1.5 m above the opening, on the noncombustible (marinite) wall. The chosen severity of fire exposure represents a wide range of fire conditions in terms of heat release rate and window dimensions (Figure 6). The exposure was limited to a representative level rather than to seek a "worst case scenario" in order to prevent the heat carried by the impinging flame from masking the contribution of the tested wall specimen and making the evaluation of the tested specimen very difficult. An extreme exposing plume is also of little relevance to fire spread on combustible claddings since such a plume would most likely cause spread of fire by windows, irrespective of the wall construction materials.

The tested wall assemblies were instrumented with thermocouples

Table 1: Vertical flame spread distance and maximum heat flux densities recorded in full-scale tests

Assembly	Flame dist. (m)	Heat flux density, kW/m^2 @ 3.5 m	@ 5.5 m
1–Marinite over concrete block wall	2.0[a]	16	10
2–Gypsum sheathing on glass fiber insulated wood frame wall	3.0	15	10
3.1–Vinyl siding on gypsum sheathing on glass fiber insulated wood frame wall	3.0	23	17
3.2–Aluminum siding on wood chip board on glass fiber insulated wood frame wall	4.5	70	20
3.3–12.7 mm flame retardant treated plywood on untreated wood studs, with phenolic foam insulation in cavities	3.0	29	20
3.4–Aluminum sheet (0.75mm) on flame retardant treated wood studs, with phenolic foam insulation in cavities	3.2	20	12
3.5–76mm expanded polystyrene insulation, glass fiber mesh, 7mm synthetic plaster, on gypsum sheathing, glass fiber insulated steel stud wall	4.5	31	8
3.6–Composite panels (6mm FRP membranes, 127mm polyurethane foam core) attached to concrete block wall	4.0	24	10
3.7–102mm expanded polystyrene insulation bonded to gypsum sheathing, covered with glass fiber mesh embedded in 4mm synthetic plaster	4.5	48	37
3.8–76mm expanded polystyrene insulation bonded to gypsum sheathing, covered with glass fiber mesh embedded in 4mm synthetic plaster	2.0	27	11
4.1–8mm wood chip board on glass fiber insulated wood frame wall	7.5	61	79
4.2–Vinyl siding on 8mm wood chip board on glass fiber insulated wood frame wall	7.5	82	111
4.3–Aluminum siding on 25mm strapping, 25mm expanded polystyrene, 19mm plywood, glass fiber insulated wood frame wall	7.5	30	31

[a]height of exposing flame

and heat flux transducers. Thermocouples (Type K, bare-beaded) were located on the vertical center line of the wall at five levels above the top of the window at 1.0 m intervals, starting 1.5 m above the window opening. Thermocouples were installed on the outer face of the wall and on the outer face of each distinctive layer within the assembly. The density of the total heat flux to the wall above the window was monitored by two transducers (water-cooled Medtherm 64 Series, range 100 kW/m^2) installed in the tested assembly, 3.5 m and 5.5 m above the top of the window on the center line of the wall.

The results of some of the full-scale tests are shown in Table 1. The maximum flame spread distance was determined from video recordings of the tests and refers to the distance between the top of the window opening and the highest observable instance of flaming along the wall. The maximum heat flux values in Table 1 were determined by performing a one-minute running average calculation on the original data and recording the highest calculated value.

Figure 10 shows a bar chart of heat flow measurements recorded for the specimens tested. An interesting feature of the heat flow data is the relation between the readings at 3.5 m and 5.5 m above the window opening. For all the specimens that did not support the spread of flame to the top of the wall, the readings at the lower level (closer to the window) were higher than those at the higher level (farther from the window). For the specimens that allowed flame to travel to the top of the wall, this was reversed indicating a significant heat output from the burning of the portion of the wall between the levels at which the transducers were located. Relatively poor consistency of heat flow measurements was the result of using a single transducer at a given level above the window. In some cases the single sensor was missed by the bulk of the fire plume. Since the presented data were recorded, the single sensor has been replaced by a set of three transducers spaced 0.5 m horizontally.

Reduced Scale Tests

Conducting full-scale tests is costly and most testing organizations do not have the facilities needed to carry out such tests. Consequently, IRC is developing a less expensive reduced scale test. The most important criterion guiding the selection of the reduced scale test candidate is that it must prove adequate in discriminating between good and bad performing exterior wall assemblies in terms of their flame spread propensities in real fire scenarios. This IRC study investigated the following four reduced scale test methods.

IMO Surface Flammability Tests

The International Maritime Organization (IMO) flame spread appa-

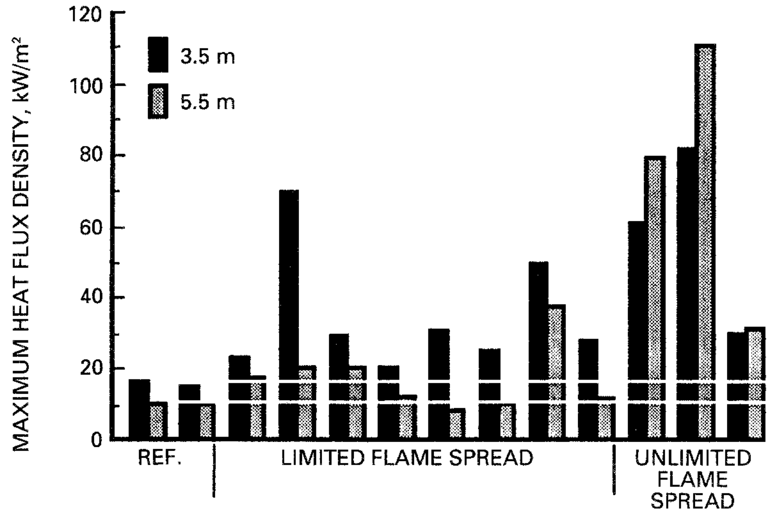

Figure 10: Maximum one-minute averaged heat flux density at 3.5 m and 5.5 m above window for specimens identified in Table 1.

ratus[13] was used to measure flame spread characteristics. There was not a good correlation between these results and those of the full-scale tests. This is attributed to the small size of the apparatus, which does not permit testing of the full thickness of a representative wall assembly nor does it allow the inclusion of all typical elements and features of the wall assembly (e.g. fasteners, studs, reinforcing ribs).

Modified Roof Deck Tests

The standard (CAN4-S107, UL 790, ASTM E-108) test apparatus was modified to provide exposure to a vertically mounted specimen, with its bottom edge adjacent to the burner slot. A steel grid was added above the burner to protect the burner from falling debris.

This investigation indicated that this test method could not adequately and reliably predict the real fire performance of exterior wall assemblies because the lower heat exposure was insufficient to adequately challenge the specimens. Fire penetration through protective membranes and into test assemblies was generally less than that observed in the full-scale tests. Consequently, assemblies with multiple layers of composite materials incorporating a thin outer protective layer performed better in the roof deck test than in the full-scale test. Finally, problems arose with assemblies that produce falling debris in fire, as the debris obstructed the burners.

Vertical Channel Tests

The vertical channel test apparatus was developed at IRC to simulate

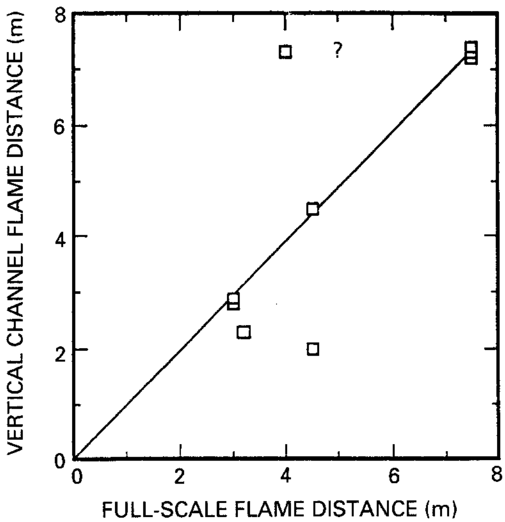

Figure 11: Comparison between maximum flame spread distances recorded in full-scale test and in vertical channel test for specimens identified in Table 1.

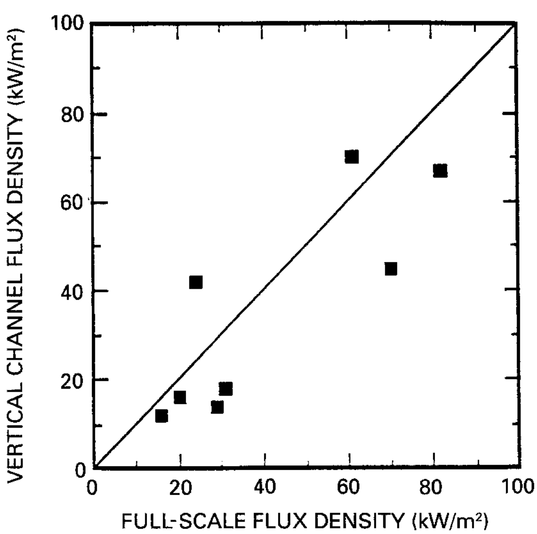

Figure 12: Comparison between maximum one-minute averaged heat flux density at 3.5 m above window in full-scale test and in vertical channel test for specimens identified in Table 1.

the heat exposure of the full-scale tests on a specimen that is much narrower (0.85 m wide) and slightly shorter (7.3 m high). Figure 4 shows the apparatus attached to the full-scale test facility.

The test gave indications of flame spread propensities qualitatively similar to those obtained from the full-scale tests. Figures 11 and 12 show correlations of the full-scale maximum flame spread distances and heat fluxes at 3.5 m above the opening with those from the vertical channel tests. Although some fine tuning of the vertical channel test is evidently needed to improve the correlation, this method discriminates between good and bad performers (with the exception of Specimen 3.6). Work will continue on the vertical channel test method to improve the quantitative results while reducing the height of the specimen to a size that can be more easily accommodated by other testing laboratories.

Steiner Tunnel Tests

Standard CAN4-S102/S102.2 flame spread tests were conducted on all specimens to determine their flame spread ratings. In Figure 13, the tunnel test results (flame spread ratings) are plotted against maximum

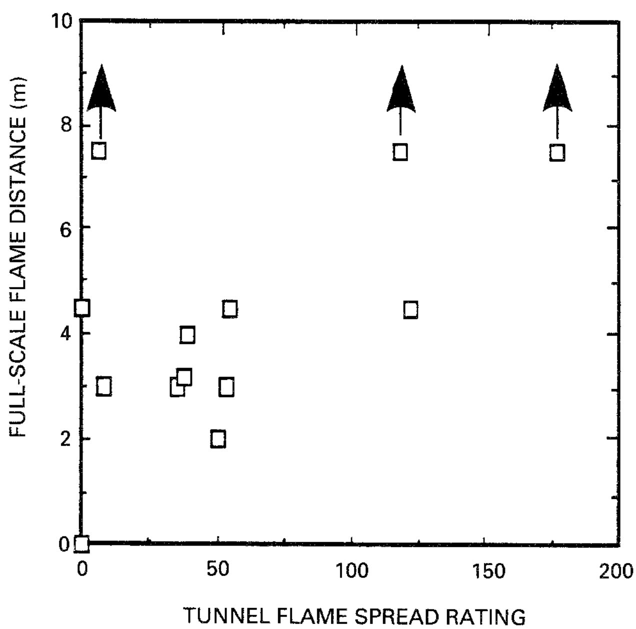

Figure 13: Maximum flame spread distances recorded in full-scale test versus Steiner tunnel flame spread rating.

flame spread distance measured during the full-scale tests. The scatter in the data suggests that the overall correlation between the two tests is poor. Although the tunnel test method is able to differentiate among some of the specimens tested on the basis of their flame spread propensities, it is not able to adequately predict the full-scale performance of other types of wall assemblies (those that are made of multiple layers of composite materials incorporating a protective skin).

Conclusions

Fire Exposure to Exterior Walls. Fire venting through a window can create a severe thermal exposure to the outer face of an exterior wall. The fire heat release rate, window dimensions, and facade geometry are equally important factors influencing the level of thermal exposure to the exterior wall.

The exposure grows with the growth of the heat release rate. The increase in exposure is more than just proportional to the increase in the heat release rate because an increasing portion of combustion takes place outside the fire compartment in the vicinity of the exposed wall.

For a given heat release rate, window dimensions control the intensity of the fire plume and its attachment to the exterior wall. Large windows allow more fuel to be burned inside the fire compartment than the small windows allow, thus decreasing the fire plume intensity. The ratio of the window opening height to its width controls the shape of the plume. Tall windows tend to project flames away from the wall, decreasing heat transfer from the flames to the wall and causing relatively low thermal exposure to the wall.

Combustible Claddings. It was shown that certain combustible claddings can support unlimited vertical flame spread. It was also shown that some combustible claddings are not capable of sustaining flame spread on their own (at a distance from the igniting window plume); these claddings may be only marginal contributors to vertical fire spread.

The described research indicates that in their present forms, the Steiner tunnel test, the IMO surface flammability test, and the modified roof deck test methods are not suitable for the assessment of the flame spread propensity of combustible claddings.

At this time, a full-scale test designed to produce high fire exposure seems to be an appropriate test to distinguish between acceptable and unacceptable combustible wall assemblies. A smaller, less expensive test is being developed.

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