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Reaction-to-Fire of Wood Products and Other Building Materials: Part 1, Room/Corner Test Performance

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Abstract

This project researched the assessment of reaction-to-fire of common materials using the full-scale room/corner test (ISO 9705) protocol and the predictions of time to flashover using results from the bench-scale cone calorimeter test (ISO 5660-1). Using a burner protocol of 100 kW for 10 min, followed by 300 kW for 10 min and the test materials on the walls only, we obtained effective indications of the fire performance for 11 different untreated wood products, three different fire-retardant-treated (FRT) plywood materials, Type X gypsum wallboard, and FRT polyurethane foam. These same materials were tested in cone calorimeters, both at State Forest Products Research Institute and at Forest Products Laboratory, in which thermophysical properties were derived for use in fire growth models.

Keywords: fire, wood, flammability, reaction-to-fire, flashover, heat release rate (HRR)

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Sweet, former chemist at FPL, and Como Caldwell, head technician for fire research at FPL. This report extends the unpublished report written by Dr. Ondrej Grexa in 1999 to the funding institution at the conclusion of his role in the project.

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Executive Summary

The primary objective of this project was to develop a system to assess the reaction-to-fire of building materials based on the EUREFIC approach developed in the Nordic countries but better able to distinguish between common materials. In Part I, we report on a series of room/corner tests. By using the burner protocol of 100 kW for 10 min, followed by 300 kW for 10 min, and placing the test materials only on the walls in the full-scale room test (ISO 9705), we obtained effective indications of fire performance for 11 different untreated wood products, three different fire-retardant-treated (FRT) plywood products, gypsum wall-board, and a FRT polyurethane foam. In contrast, the protocol option of ISO 9705 with both the walls and ceilings covered (normally used in Europe) and the ASTM option with a less severe burner exposure (normally used in the North America) both resulted in flashover times for the different untreated wood products within a fairly narrow range. The relative performance of the different products tested according to ISO 9705 with walls covered only was consistent with their expected performance in the current North America and Slovak regulatory tests for reaction-to-fire. In addition to the primary flashover time measurements, reaction-to-fire assessments also include measurements relating to intoxicating gases, threatening smoke, radiant heat, and heat release rates needed for comparisons of material fire performances and for validating fire growth models. The assessment methodology proposed in this project provides a more technically sound method that can be tied back to more fundamental fire properties that are determined in the bench-scale cone calorimeter test (ISO 5660).

The second objective of this project was to use the cone calorimeter to evaluate the materials in terms of material properties, and in turn use such properties in mathematical models to predict the full-scale room tests. After considerable work on this second objective, Part II reports on the cone calorimeter evaluation, particularly as needed for alternate fire growth modeling and predictions for the room tests. Materials used in the full-scale room tests were tested with the cone calorimeter. As in the full-scale room test,

heat release determination in the cone calorimeter is done by the oxygen consumption method. Using time to ignition data, we obtained the thermal inertia ($\rho c k$) and ignition temperature for the different products for within their thermally thick regime. However, the hardboard required a mixed thermally thick/thin analysis that includes the thermal thickness ($\rho c l$) as a material property. We developed a simple correlation between the times for flashover in the room tests and the global fire parameters derived solely from the cone calorimeter. Such simple correlations are limited to the full-scale test protocol used to develop the correlation. To obtain more fundamental predictive capabilities, this project included development and application of physical models for the full-scale room test. Two physical models were part of this research project. One model was a modification of a numerical model developed by Quintiere for fire growth in the ISO 9705 test. The second model is an analytical model of fire growth that includes adaptation for systematic errors in the heat release rate measured by the oxygen consumption method.

Introduction

In effectively assessing the reaction-to-fire of materials, this project evaluates a protocol of a room/corner test—ISO 9705 (ISO 1993a)—and correlates the results with those obtained in bench-scale cone calorimeter tests—ISO 5660-1 (ISO 1993b). The latter is a bench-scale test that uses a test specimen of 0.01 m²; the former is a full-scale test that uses a test specimen greater than 20 m². The primary measurement of both these test methods is oxygen depletion during the burning of the test specimen that can then be used to evaluate heat release rate (HRR). This method of evaluation is based on the oxygen consumption principle, where it is assumed that a constant amount of heat is evolved for a constant amount of oxygen consumed in burning. This assumption has been shown to work well for common construction materials when insignificant amounts of smoke and carbon monoxide are produced during test specimen combustion. Both test standards propose that for 1 kg of oxygen consumed, 13.1 MJ heat is evolved. However, it was found that wood materials release 13.23 MJ per 1 kg of oxygen

consumed (Dietenberger 2002a). Indeed, ISO 9705 (ISO 1993a) test uses propane for calibration, which generates 12.76 MJ of heat per 1 kg of oxygen used. Despite these variations, the oxygen depletion principle provides a very good method to assess the amount of heat generated during combustion.

One of the most scientifically advanced proposals for evaluating reaction-to-fire of materials was developed in the Nordic countries. Commonly referred to as the EUREFIC proposal, its classification system is based on performance (time to flashover) in the ISO 9705 room/corner test (ISO 1993a). This performance can be measured directly in the full-scale test or it can be evaluated with a simple computer model with input data from the bench-scale measurements in the ISO 5660 cone calorimeter test (ISO 1993b), as explained further in the Part II report. Work on the appropriate room test protocol and the relationship between full-scale tests and bench-scale tests such as the cone calorimeter were conducted in Finland (Kokkala 1993), Sweden (Östman 1993), Canada (Sumathipala and others 1994), and elsewhere. This European room test protocol (ISO 1993a) involves an ignition burner protocol of 100 kW for 10 min, followed by 300 kW for another 10 min, and the test materials on both the walls and the ceiling. However, we believe that the EUREFIC proposal needed modification mainly because the severity of the room test protocol resulted in the highest sensitivity for materials with low combustibility. The severity of this protocol made it difficult to separate time-to-flashover values of wood-based building products.

The room/corner test protocol used during the ISR Round Robin exercise (ASTM 1982) uses the same test facility as ISO 9705 (ISO 1993a) but a different ignition burner scenario: 40 kW for 5 min followed by 160 kW for another 10 min (Beitel 1994). Also, the test materials were placed only on the walls. For most wood products, flashover occurred shortly after the ignition burner changeover to the 160 kW setting. As such, this protocol too made it difficult to separate wood-based building products. Furthermore, materials with low to moderate combustibility did not flashover with this protocol. FPL had used this 40/160 kW ignition protocol in some of its previous work (Tran and Janssens 1991).

The work reported here involves a series of room/corner tests conducted on a number of building materials. The primary objective was to develop a system to assess the reaction-to-fire based on the EUREFIC approach but better able to distinguish between wood-based materials. The test protocol used in these room/corner tests was an alternative provided in ISO 9705 (ISO 1993a) protocol. The test protocol involved an ignition burner protocol of 100 kW for 10 min followed by 300 kW for another 10 min and the test materials installed only on the walls. The ceiling was gypsum wallboard. In essence it is a hybrid between the EUREFIC and ISR protocols.

The implementation of the ISO 9705 (ISO 1993a) protocol involved converting our ISR room to the ISO room, updating the measurements and process techniques, and developing an effective data reduction technique, all of which are detailed in this report. The tests involved 17 building products, 15 of which were wood-based products. The remaining two were gypsum wallboard and FRT rigid polyurethane foam. The room/corner tests (ISO 9705) (ISO 1993a) were done at the USDA Forest Service Forest Products Laboratory (FPL) in Madison, Wisconsin. The results of the room/corner tests are presented here (Part I).

A second objective of this project was to use the bench-scale apparatus known as the cone calorimeter to evaluate the same materials tested in the room/corner test in terms of material properties and use such properties in appropriate mathematical models to predict the room/corner fire test results. The first series of bench-scale measurements on the cone calorimeter was performed at the State Forest Products Research Institute (SDVU), Bratislava, Slovakia. Additional cone calorimeter tests were performed at FPL. These tests also involved the use of Type X gypsum wallboard as the backing material to the test specimen, consistent with the room/corner tests. Results for the cone calorimeter tests are reported in Part II of this series of papers (Dietenberger and others, in press). Using the material properties derived from the cone calorimeter tests as input, two mathematical models for the room/corner test were developed and evaluated as reported in Part II. A simple correlation of the data obtained in the cone calorimeter with the time to flashover measured in the full-scale test was developed as a part of this project.

Past Work at FPL

Early work on a corner-wall flame spread test was conducted using a wood crib in the corner made from two 2- by 8-ft panels (FPL 1953; Holmes 1978). This test was done in a smaller room with the ignition source placed at the same location as the ISO 9705 (ISO 1993a) tests. Subsequent room/corner tests were conducted using a protocol with an ignition source of 40 kW for 5 min followed by 160 kW for 5 min. These FPL tests were conducted to develop input data, validation data, and model algorithms for compartment fire models. A sensitivity study was conducted to evaluate the effects of various parameters including two burner locations, four gas burner programs, and ceramic fiber or gypsum wallboard on walls not in contact with the burner (Tran and Janssens 1989). Six wood products having different ASTM E 84 flame spread index values were tested (Tran and Janssens 1991) and are also the same materials used in the current work. New techniques were developed to calculate the neutral plane height, vent flow rates, uniform upper and lower layer temperature, and interface height from measured temperature profiles (Janssens and Tran 1992). Research was also conducted to better characterize the burner flame and plume (Tran and Janssens 1993). The current

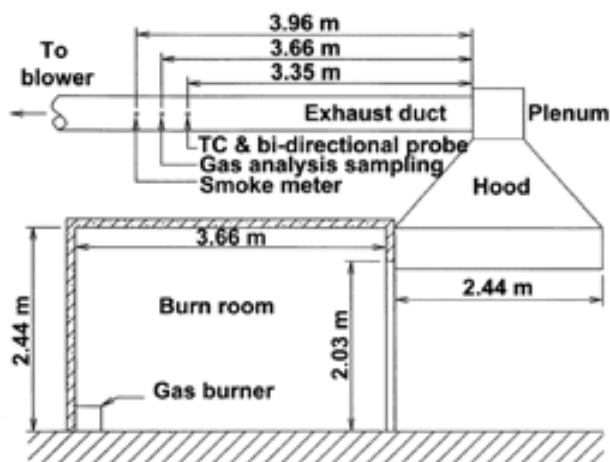


Figure 1. Illustration of FPL room and exhaust system.

project is in a sense a continuation of their work, which will be referred to frequently in this report.

Methods

Description

The ISO 9705 (ISO 1993a) standard room/corner test is a full-scale reaction-to-fire test for evaluating building materials. This standard, however, provides for an alternative burner scenario and an option for lining the ceiling with a test material. The tests were conducted according to the ISO protocol and some features of the ISR protocol. The ISO standard is ISO 9705 “Fire tests—Full-scale room test for surface products” (ISO 1993a). The ISR protocol was a proposed standard in the 1980s (ASTM 1982) and used for the ASTM ISR inter-laboratory test program (Beitel 1994).

Both the ISO and ISR protocols prescribe a standard room that is 3.6 m long, 2.4 m wide, and 2.4 m high (Fig. 1). The room has a single door opening for ventilation in the center of one 2.4- by 2.4-m end wall. Dimensions of the door opening at FPL were 0.76 by 2.03 m, within requirements of the standards. The test materials were installed on the two 3.6- by 2.4-m sidewalls and the back 2.4- by 2.4-m end walls. The wall with the door opening is not lined with the test material, according to both protocols. The floor is covered with a non-combustible material. A unique FPL design of a non-combustible exterior shell for safety reasons leaves just enough room for a person to slip in and install sensors through the interior shell. The actual interior dimensions with linings installed were slightly smaller than the stated dimensions shown in Figure 1 because of a fixed framing for the interior shell.

A propane burner in the corner of the room provided the ignition source for the room/corner test. A 100-kW flame emitting from the ISO burner is shown in Figure 2. The dimensions of the two squares and burners were 170 by 170 mm (ISO) and 305 by 305 mm (ISR). The two output levels used were 40 kW for 5 min followed by 160 kW



Figure 2.
100-kW flame
at start of test.

for 5 min or 100 kW for 10 min followed by 300 kW for 10 min. Propane flow to the ignition source was controlled by a pair of electronic mass-flow controllers to maintain the required heat output. The cumulative amount of propane used was measured by weighing the propane tanks as a function of time. This was used to confirm the amount of propane consumed for a burner output setting.

The exhaust gas collection hood and plenum combined the burn room's gases and smoke with some ambient air drawn in from below the hood skirt and directed the resulting mixture into the exhaust duct through a flow-mixing orifice. The nominal exhaust flow rate ($1 \text{ m}^3/\text{s}$) was increased during flashover to ensure complete capture of products of combustion into the exhaust gas extraction system. Gas composition of the exhaust duct was continuously monitored for oxygen, carbon monoxide, and carbon dioxide concentrations. Along with continuous measurements of duct centerline flow velocity and temperatures, these measurements were used to calculate HRR with time.

Onset of flashover signified the limit of tenability in the test room. Time-to-flashover was thus used as the principal performance criterion. There are several measures of onset of flashover in the test room, the most obvious being the visual observation of flaming outside the doorway. The photograph in Figure 3 represented the moment of flashover for the test that began with the ignition burner flaming in Figure 2. Downward flame spread as now seen on the wall linings began to accelerate, leading to a much higher HRR and spillover of flames, smoke, and toxic gases. Other flashover criteria were based on measured HRR,



Figure 3.
Flashover
event after
8 min.

temperatures in the doorway, heat flux at the floor, measured CO_2 mass rates, and spontaneous ignition of crumpled newspaper on the floor.

A final set of measurements included a laser-based system in the duct to measure light obscuration from smoke during testing; two heat flux gages placed on the floor to measure floor-level total heat fluxes; thermocouples placed in various locations; and static pressure probes to measure prevailing pressure at different heights in the test room.

Instrumentation

The room test instruments consisted of three main measuring groupings: (1) instruments for calculation of HRR by the oxygen consumption principle, (2) instruments for measurement and control of the flow of propane gas, and (3) the smoke obscuration measuring system. Other measuring groupings include temperature development in the room and heat flux to the floor. Additional changes incorporating the ISO 9705 (ISO 1993a) requirements have updated the room burn facility beyond that of the ISR protocol. We included the adoption of ISO 9705 (ISO 1993a) formula and procedures as far as possible to calculate the HRR. Indeed, a term by term comparison showed the HRR formula given in Annex F of ISO 9705 provide values just 0.7% greater than that of the ISR protocol or the equations developed by Janssens and Parker (1992) for HRR (Appendixes B and C provide additional explanation). Further modified procedures beyond that of ISO 9705 to improve HRR accuracies are discussed subsequently.

Data for HRR calculations: For the HRR calculation, the measured parameters used were O_2 , CO_2 , and CO concentrations, differential pressure of the bidirectional tubes for centerline velocity measurement, and temperature for the mixed gases in the downstream exhaust pipe. Each of these measurements was evaluated as to its impact on the accuracy of HRR calculations. We used the results on uncertainty analysis for HRR in room fires from (Yeager 1986) to guide our analysis, and we also provided some extended error analysis (Appendix B).

The exhaust duct oxygen concentration was measured with the Servomex 1400 oxygen analyzer (Palatine, Illinois). Calibration tests revealed that this analyzer output was linear for its whole range. The exhaust duct concentrations of CO and CO_2 were measured with an infrared CO/CO_2 analyzer that provided a linear output. However, for some tests, an older type of analyzer was used—Beckman 868 (Wooster, Ohio) for the CO_2/CO measurement—when the infrared analyzer was out for repairs. Calibration of the instruments was done with the following three reference gases fed in separately near the gas sampling probe: ambient air, nitrogen gas for zeroing the instruments, and a calibration gas mixture (10.22% O_2 ; 10.14% CO_2 ; 4.89% CO; balance N_2).

It was found that the signal from the analyzers took approximately 20 s to reach 90% of the change to a steady state level (after a time lag of around 60 s for the sampled gas to travel to the analyzers from the gas probe). In a similar but older set-up (Yeager 1986), the HRR uncertainty of between 11% and 30% at flow rates greater than $1 \text{ m}^3/\text{s}$ was dominated by gas analysis equipment inaccuracies at oxygen concentration of 20.7% or higher. In our laboratory, the 12-bit resolution of analog to digital conversion (DAS 8 I/O board from Keithley) (Cleveland, Ohio) also limited the precision of oxygen depletion measurements. This created some noise level that could be reduced only with digital filters. However, we minimized the smoothing of data to avoid contributing more bias error to that already caused by the analyzer response function and drifting of baseline voltage in the data acquisition system. This effect is discussed in the section on data reduction.

The determination of volume flow rate in the exhaust duct required measurements of differential pressure and temperature at a bi-directional probe located centrally upstream of the gas sampling ring. For an accurate evaluation of the calculation of the volume flow rate, it was necessary to know the velocity profile in the duct. The velocity profile was measured in an earlier study (Janssens 1991). Because the duct and exhaust fan were not modified since then, it was decided to use the velocity profile factor found in this study ($k_t = 0.915$). The bi-directional probe was connected with a high-strength hose to a rapidly responding Baratron transducer (Andover, Massachusetts) to measure differential pressure. The linearity ($r^2 = 0.999$) of the differential pressure transducer up to 1-in. water pressure using a vacuum

source was checked with a liquid manometer (U tube). The harmonic damped response of the hose/transducer system to an impulse pressure pulse was measured with an oscilloscope and was found to be effectively damped within one or two cycles for the period of 0.3 s. This means an air turbulence excitation frequency of just over 3 Hz can create a large resonance-type noise that is best reduced with a digital filter. A day-long drifting baseline voltage of the DAS system had been causing a significant bias error of up to 20% in pressure measurement at volume flow rate less than 1 m³/s. Thus the differential pressure signal could be quite noisy and responsive but should not be a source of bias once the zero level was determined. The thermocouple measurement of temperature at steady levels was checked by comparison with a handheld thermometer calibrator. Sudden immersing of a thermocouple into a hot flowing gas resulted in a quick but noisy signal response. The quick and noisy responses of the Baratron transducer (Andover, Massachusetts) and thermocouple was in contrast to the slow response of the gas analyzers, which then must be factored into the data reduction methodologies.

Propane gas flow control and ignition burner: A propane gas burner provided the ignition source in the tests (Fig. 2). In previous tests at FPL, we used the burner specified in the ISR protocol (305 by 305 mm) and different flow rates of propane. The ISR protocol required 40- and 160-kW energy release rates; the ISO protocol required 100- and 300-kW energy release rates. Electronic mass flow controllers were used to regulate the flow of propane from the two gas cylinders. The range of the installed mass flow controller (OMEGA® FMA-776V) (Stamford, Connecticut) was lower than that corresponding to the 300-kW energy release rate for propane. Therefore, two electronic mass flow controllers (OMEGA® FMA-776V) were used to obtain the required burner heat output. These mass flow controllers were connected in parallel. In the propane gas line, the laminar flow device was installed for the independent measurement of propane flow. The difference of the two measuring systems was within 5%, as found in previous FPL work. In addition, the mass of two propane cylinders was measured over time in conjunction with the propane gas output from the electronic mass flow controllers at different levels of flow. In this way we verified the linearity of the mass flow controllers, and in the process the proportionality of the propane mass flow rate to the mass flow sensor voltage was calibrated.

In a later improved procedure, the weights of the tanks were recorded every 10 s with a digital weigh scale during steady burning to accurately calculate the propane mass rate used (less than 1% error). This mass rate was then multiplied by propane's net heat of combustion under complete combustion (46.36 MJ/kg) to obtain a HRR that was in agreement with that determined from the oxygen consumption technique during the steady burning to within 3% error,

as required by the ISO 9705 (ISO 1993a) standard. This also served as a check for malfunctioning of the mass flow controller and/or gas leaks in the propane supply line, even while a test was in progress. During the course of testing, it became apparent that the mass flow controllers needed to be recalibrated periodically to avoid errors from contaminant buildup in the flow controllers and/or drifts in the baseline voltage of the data acquisition system. Occasionally the flow controllers must be cleaned out due to long-term accumulation of contaminants from commercial propane. Furthermore, after the seventh room test, we began the pre-burn safety procedure of purging the propane line between emergency shutoff solenoid and the mass flow controllers to ambient pressure levels. This ensured that the heavier-than-air propane was not covering the test room floor if the mass flow controllers are opened by a computer glitch prior to burner ignition. This procedure had the side effect of delaying burner ignition by several seconds due to fill-up of propane pressure in the purged line. Observation of weights of the tanks every 10 s provided reassurance of the burner output level and, if necessary, notice to shut down a malfunctioning burner.

The standard ignition source as defined in the ISO 9705 (ISO 1993a) was a burner of dimensions 0.17 by 0.17 by 0.145 m. The propane gas burner source was placed in one rear corner in contact with the rear wall and one side wall. The gas burner was programmed to produce 100 kW for 10 min followed by 300 kW for another 10 min. Burner output was terminated at 20 min, or earlier, if there was flashover. Calibration of the system measuring the HRR using the burner placed directly under the hood was done before each test. The burner program for the calibration was 100 kW–300 kW–100 kW, each step lasting 5 min. Before and after calibration, the DAS was on for a few minutes to record baseline voltages of instruments and analyzers.

Smoke measuring system: The design of the laser smoke obscuration measurement system is similar to that of the cone calorimeter (ISO 5660-1) (ISO 1993b) except for an optical platform for holding the laser, photodiodes, and optical accessories. The optical platform was a metal brace hanging from the ceiling such that no optical component was in physical contact with the exhaust pipe. Optical accessories include beam splitters and mirrors installed in optical tubes aligned so the laser beam passes through holes on each side of the exhaust pipe and targeted on the compensate and main photodiodes. In a manner similar to that of the cone calorimeter, optical filters inserted in front of the laser or at the main photodiode were used to calibrate the laser smoke system. A white light measuring system was also available but was not used because of its equivalence to the laser smoke system (Tran and Janssens 1991). Appendix A describes calibration of the laser smoke system from measuring the voltage of the photodiode open circuit rather than measuring the electrical current of the photodiode closed circuit.

Other measurements: A set of thermocouples (TCs) was installed in the room. One TC tree was located in a front corner, and another TC tree was located in the opposite corner. The third TC tree was located in the middle of the door opening. The ceiling thermocouples were located according to the ISR protocol (100 mm below the ceiling at the center and the four quadrants). In addition, four TCs were located on the walls of the room and one TC above the burner.

The fire plumes and upper gas layer flows were measured in various ways. The static pressure difference in and out of the room was measured at four height levels, as done in the previous FPL work. In a limited number of tests with just the ignition burner providing the HRR, the airflow speed entering the room was measured with a hot-wire anemometer. Also, in these tests aluminum streamers were attached to the thermocouple tree located in the middle of the door opening, which were effective in defining regions of in-flow air, the fairly neutral air above it, and the high speed hot gasses jetting out at the top of the doorway. A video camera with a built-in clock was used to observe flame propagation from the ignition source and the development of the smoky hot upper gas layer, and provided confirmation for flaming outside the doorway.

Two radiometers were installed on the floor to measure heat flux from the wall fires and the layer of soot-laden hot gases to the floor. Calibration of these radiometers was done by comparison of their output with the output of the two reference radiometers at a constant heat flux from a 1-in.-diameter hole in the door of a small electric oven. The radiometers are quick responding and low noise, potentially making them a better objective “timing” of flashover than the noisy thermocouple in the doorway, the hard-to-see flames in very sooty gas flow out of the doorway, or delayed measurement of HRR due to long mixing time of product gases in the upper gas layer.

Data Reduction

Optimized signal conditioning and digital filtering was applied to the measurements to reduce bias and noise in the measurements. Most important sources of bias were the drift in baseline voltages of data acquisition system during the day and the in-time response of the analyzers. Most important sources of noise were the 12-bit resolution of the DAS 8 board and the effect of air-turbulence-induced oscillations within the gas and pressure probes. Better hardware technology is now available to significantly reduce some of these experimental errors. For example, Section 9 of ISO 9705 (ISO 1993a) states that the gas analyzers shall have a time constant not exceeding 3 s. Because our room test gas analyzers are of 1980s era technology, we reduced existing experimental errors through a modified test procedure and an effective data reduction method.

First, we incorporated a test start procedure in three phases after beginning the data acquisition. During the first minute phase, the exhaust fan was off so that the baseline value for

the differential pressure measurement was established. At 3 s intervals, this meant 20 data points were obtained for an averaged baseline voltage corresponding to “zero” pressure. In the second phase (for up to 4 min, depending on the need), the initial exhaust flow of 1 m³/s and the full response of the analyzers were achieved before obtaining baseline values for O₂, CO₂, and CO analyzers and other instruments. Baseline values were computed from averaging 20 to 30 data points sufficient to reduce the noise in the measurement signals. The next phase in the test sequence was ignition of the burner through an automatic control by the data acquisition system (via DAS 2 control board from Keithley) (Cleveland, Ohio). The mass flow controllers provided rapid response and precise control of the propane flow rate leading to rapid flame ignition, which was then used for signaling the beginning of the burn test and defining the burn rate profile during an actual test. Our calculations of HRR from consumption of propane gas and from depletion of ambient oxygen were based on formulas in Annex F of ISO 9705. They agreed to within 3% during steady state burning of the ignition burner. This represented an improvement to the 5% uncertainty reported in the previous FPL work (Tran and Janssens 1991). We note the various constants used in the oxygen depletion HRR formula were last obtained during FPL’s 1991 involvement with the ASTM ISR inter-laboratory test program (Beitel 1994), and it has never needed recalibration since that time. In contrast, the proportionality between propane mass flow rate and voltage signal outputs from the propane flow-rate controllers needed occasional recalibrations because of a gradual contamination of the flow sensors.

These two different calculations of HRR, however, sharply disagreed during step changes in propane mass flow rates, even when the ignition burner was located directly under the exhaust hood. The sources of bias between two methods of computing HRR during step changes were time shifting and the time constant of the gas sampling system. While the ignition burner was operative, changes in the pressure of the bi-directional probe caused by step changes in exhaust venting or changes in the exhaust duct temperatures caused by step changes in propane flow rates corresponded to changes in the gas sampling signals to define time shifting of the gas sampling system. As an example, this resulted in a gas-sampling time shift of 48 s for the time lag from exhaust duct/hood to oxygen analyzer for the burner calibration in the case of ISO test 7 (see test material section). Section 10 of ISO 9705 then required an additional time shift that corresponded to reaching within 10% of the final value. This time shift was 21 s for our gas analysis system. In addition, the total time shift was not supposed to exceed 20 s, as compared to the actual 48 + 21 = 69 s in ISO test 7 (and similarly in all other tests). If we simply applied this shift of 69 s to the gas analyzer signal, then the resulting HRR profile is shown in Figure 4. Note that the increase in oxygen consumption HRR occurred 21 s sooner than the corresponding actual step changes in the burner output. This

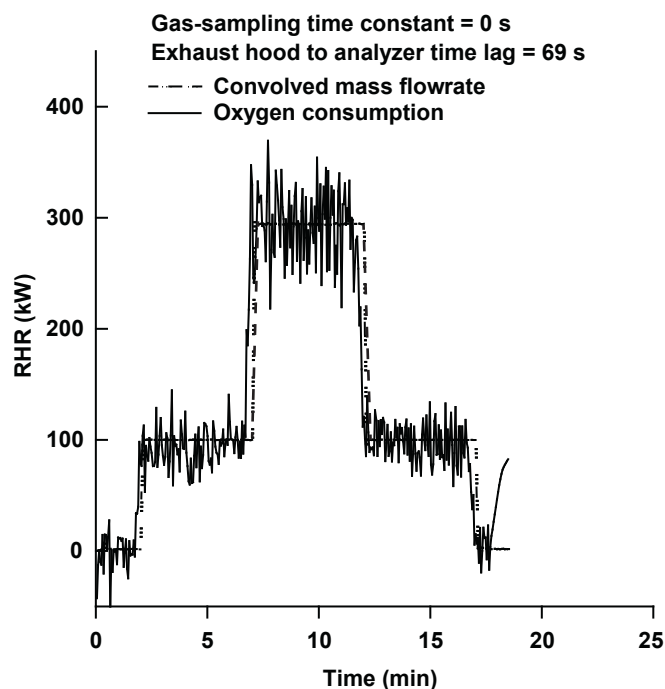


Figure 4. Burner calibration based on ISO 9705 procedure.

is obviously an overcorrection to the gas sampling data. It is also evident that if we require the time constant of gas sampling system to be limited to 3 s (really impractical to achieve) while using a time stepping of 6 s (as recommended in ISO 9705), then the phase shift between oxygen consumption HRR and actual burner profile is limited to 6 s, the same as the time steps themselves. One additional problem noted in Figure 4 was the high noise level of oxygen consumption HRR due to unavoidable oscillations in the differential pressure data.

The HRR profile was improved in an early study by using the actual time shifting of 48 s and a subjective fast Fourier transform (FFT) low-pass digital filtering of noisy data for the differential pressure, temperatures, or various gas concentrations, as was done in the preceding FPL work (Tran and Janssens 1991). However, the HRR calibration profile in this preceding FPL work showed a time response of 50 to 60 s to get within 10% of the HRR change. Examination of the corresponding raw data retrieved from our database indicates that 40 s of this time response was attributed to flow mixing in the gas analysis system and the remaining 10 s to 20 s to data smoothing. However, the gas sampling system was upgraded for the 1991 ASTM ISR work by increasing the gas flow rate to where we now have a 21 s response to get within 10% of the final value. In a further analysis of this problem, we realized that the raw differential pressure and temperatures data must be smoothed by a very specific method that does not add distortions or bias to the HRR profile, and thus also avoid the 10- to 20-s response due to subjective data smoothing.

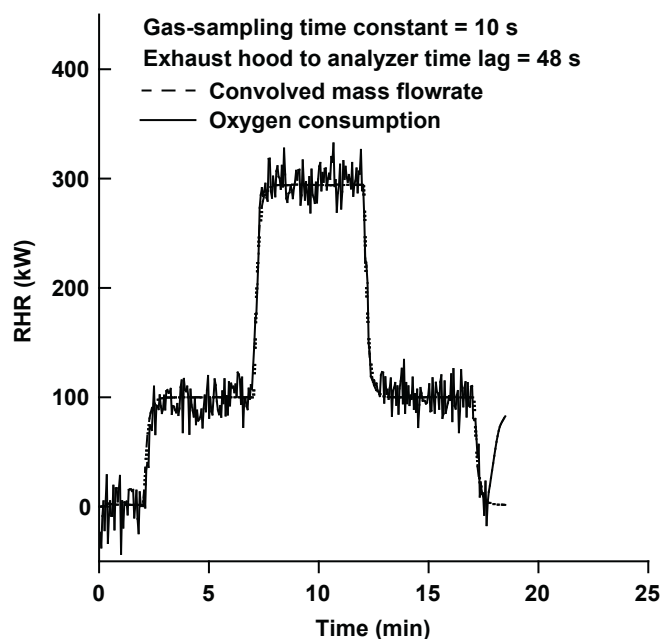


Figure 5. Burner calibration using FPL procedure in ISO test 7.

This analysis was achieved by modeling the effect of the time responses of the instruments on the HRR profile. When span calibration gases were used to obtain step concentration changes of oxygen, carbon dioxide, and carbon monoxide, the deconvolution of their measurement signals to true signals—assuming a first-order system response function—resulted in a time constant of 10 s (see deconvolution methods described by Evans and Breden 1978). However, the data from measurements of gas concentrations during a calibration burn of the ignition burner were relatively noisy, so a deconvolution of these data resulted in greater noise levels that almost overwhelmed the true measurement. Coupling this deconvolved data with the noisy differential pressure data, the corresponding true profile of oxygen consumption HRR was difficult to discern from the high noise level. An optimized data reduction was finally devised that (1) applied a low-pass exponential digital filter just to the data from the mass flow controllers, bi-directional pressure probe, and duct temperatures with a time constant $\tau = 10$ s, (2) shifted the gas analysis data by the actual time lag in the gas lines, and then (3) used this processed data for the computation of HRR. This optimized process is developed in mathematical detail in Appendix B. The result is shown in Figure 5 using the same raw data as used for Figure 4. Note the reduction in HRR noise level without introducing any additional distortion or spurious spikes. Given the unavoidable noise level of the differential pressure signal at low volumetric flows, it seems the accuracies and time responses of the gas analyzers required by the ISO 9705 (ISO 1993a) standard are overly restrictive. The data reduction as described in Appendixes B and C should be applicable to various measurement systems for calculating HRR.

Table 1—Characteristics of the tested materials

Material	Test no.	Thickness (mm)	Density (kg/m ³)	Moisture content (%)	FPL reference test no.
Gypsum wallboard, Type X	1	16.5	662	—	49
FRT Douglas Fir plywood	2	11.8	563	9.48	50
Oak veneer plywood	3	13	479	6.85	51
FRT plywood (Forintek)	4	11.5	599	8.43	52
Douglas Fir plywood (ASTM)	5	11.5	537	9.88	53
FRT polyurethane foam	6	23	29	0.0	54
Gypsum wallboard, Type X	7	16.5	662	—	55
FRT Southern Pine plywood	8	11	606	8.38	56
Douglas Fir plywood (MB)	9	12	549	6.74	57
Southern Pine plywood	10	11	605	7.45	58
Particleboard	11	13	794	6.69	59
Oriented strandboard	12	11	643	5.88	60
Hardboard	13	6	1,026	5.21	61
Redwood lumber	14	19	421	7.05	62
Gypsum wallboard, Type X	15	16.5	662	—	63
White spruce lumber	16	17	479	7.68	64
Southern Pine boards	17	18	537	7.82	65
Waferboard	18	13	631	5.14	66

Test Procedure

The test procedure was done similar to the calibration of the system but with a different burner output. In the tests, the burner program was 100 kW–300 kW each step for 10 min. A time constant of 18 s was measured for the mixing of combusted gases in the combined regions of fire plume, upper gas layer, and hood. This was simply determined by applying another low-pass exponential digital filter to the filtered signals of the mass flow controller and matching it with the ramping of burner's HRR as measured with the oxygen consumption method. In a justification for this procedure, Appendix C provides analytical mathematical modeling of flow mixing of product gases and smoke while being created and moved through the various zones. The results of modeling showed the low-pass exponential digital filter is appropriate for (1) flow mixing in the upper gas layers with a time constant of approximately 18 s and (2) flow mixing during gas treatments for gas analyzers (removal of moisture and carbon oxides from the gas lines) with its time constant a major part of 10 s.

For all materials except the gypsum wallboard, the tests were terminated not long after flashover by shutting down the ignition burner and applying water sprinklers. For the gypsum wallboard the test was terminated after 20 min. The measured data were recorded using LabTech (Toledo, Ohio) commercial software. The tests were also recorded by video camera. Photographs were taken during the tests as well.

Materials

The materials tested are shown in Table 1. As shown, all materials but the gypsum wallboard and FRT polyurethane foam were wood-based products. Materials used in tests 2, 5, 6, and 7 were the same as those for the ISR Round Robin

(Beitel 1994). In the ISR project, the 40 kW for 5 min/160 kW for 10 min program and the 305-mm-square burner were used. Test materials were placed on the walls only. Materials used in tests 3 and 4 were obtained from Forintek Canada Corp. Materials for tests 8 to 14 are from a wood industry material bank (MB) for fire research. Some of these materials were tested previously using the 40 kW for 5 min (0 to 300 s), 160 kW for 5 min (300 to 600 s) burner program (Tran and Janssens 1991).

Results

Flashover Criteria

As a primary indication of reaction-to-fire, the time to flashover can be measured by different criteria. The flashover criterion of 1-MW HRR (including burner) is commonly used, particularly in Europe. In our case, we evaluated and compared other possible criteria: time of total HRR exceeding 600 kW, time when heat flux to the floor exceeded 20 kW/m², time when CO₂ mass rate exceeded 60 g/s, and time of the flaming outside the doorway. In Table 2 the flashover times using the different criteria for flashover are listed.

In tests of untreated wood products, close agreement was found between the flame and flux flashover criteria. This confirmed earlier FPL work (Tran and Janssens 1991). With the FRT wood products and treated polyurethane foam, there were some inconsistencies in the results depending on the flashover criteria. In the test of FRT plywood from Forintek Canada Corp. (test no. 4), the flux and HRR flashover criteria were initially exceeded shortly after the change to the 300-kW burner output, but the fire receded just as rapidly below the flashover criteria. After a period of time, flashover was permanently achieved when the flames extended

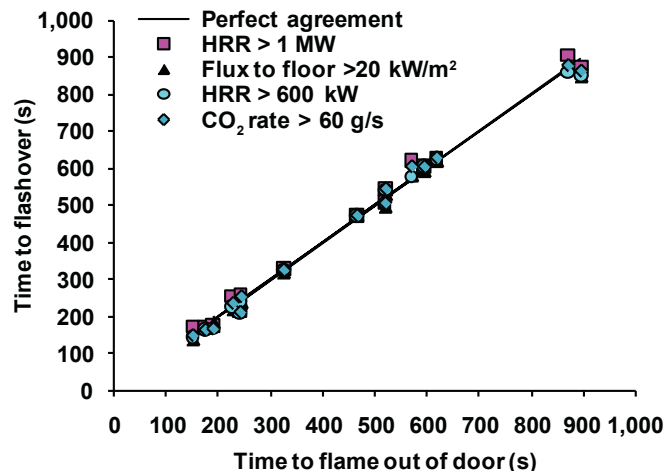
Table 2—Flashover times in room/corner tests based on five different criteria

Material	Test no.	1 MW flashover time (s)	Flames out of door time (s)	Flux to floor >20 kW/m ² time (s)	600 kW flashover time (s)	CO ₂ rate >60 g/s time (s)
Gypsum wallboard, Type X	1	NFO ^a	NFO	NFO	NFO	NFO
FRT Douglas Fir plywood	2	876	895	849	852	864
Oak veneer plywood	3	171	174	174	165	165
FRT plywood (Forintek)	4	906	870	873	861	879
Douglas Fir plywood (ASTM)	5	474	465	474	474	474
FRT polyurethane foam	6	630	618	621	627	630
Gypsum wallboard, Type X	7	NFO	NFO	NFO	NFO	NFO
FRT Southern Pine plywood ^b	8	621	570	582	579	606
Douglas Fir plywood (MB)	9	546	520	531	543	546
Southern Pine plywood	10	330	324	321	327	327
Particleboard	11	216	241	237	210	213
Oriented strandboard	12	177	189	186	168	168
Hardboard	13	255	227	222	228	237
Redwood lumber	14	510	519	498	507	507
Gypsum wallboard, Type X	15	NFO	NFO	NFO	NFO	NFO
White spruce lumber	16	606	594	594	606	606
Southern Pine boards	17	258	243	240	240	255
Waferboard	18	174	150	141	144	150

^aNFO signifies no flashover.^bBurner output program was 100 kW for 5 min followed by 300 kW for 15 min.

out the doorway at 870 s, and the heat flux exceeded 20 kW/m² at 873 s. Criteria such as those based on HRR, heat flux to floor, and temperature provide more objective criteria over the subjective visual observation of flaming outside the doorway but can provide misleading times if used alone. Comparison of the 1-MW HRR flashover criterion with the 600-kW HRR shows that for all tested materials, if the HRR exceeded 600 kW, then shortly thereafter the 1-MW HRR was also reached (on average, about 15 s later). The order of flashover times using these two criteria are in both cases the same except that of the white spruce lumber (test no. 16) and FRT Southern Pine plywood (test no. 8). For test no. 8, however, the burner output program differed from the other tests—in this test the burner output was increased after 300 s instead of 600 s—but even in these two cases the differences were small.

Various flashover criteria are graphically illustrated in Figure 6. The solid line in Figure 6 represents perfect agreement of the time to flashover defined as time to flaming outside the doorway. The HRR = 1 MW criterion appears to have greater noise level than other criteria but is only on average 10 s greater than that of the flame criterion. Had we applied the ISO 9705 (ISO 1993a) time shifting requirements on the gas analyzer signals (by adding 21 s to the actual time lag because of being within 10% of full scale), the difference in flashover time on the average would instead be 10 – 21 = –11 s. Indeed, if the gas analysis system had been redesigned to achieve a time constant of 5 s, so as to take only 10 s to reach 90% of full scale, then the ISO 9705 (ISO 1993a) procedure for time shifting the gas analyzers data would result in the HRR = 1 MW criterion to be

**Figure 6. Comparison of various flashover criteria.**

essentially in agreement with the flame criterion. However, a more serious problem is the mixing time constant of about 18 s (or equivalently 36 s to get within 10% of the change to a steady value) for the combustion products in the upper gas layer. Because the fire growth is being accelerated at flashover, the corresponding HRR is actually much higher than its value derived by the oxygen consumption method because of the exponential time responses due to flow mixings in upper gas layer and within the gas analysis system. This issue is discussed further in Appendix C and on the analytical fire growth modeling of the room tests in Part II. The flashover times for heat flux = 20 kW/m² and HRR = 600 kW criteria are less noisy and are on average 3.7 and

4.5 s, respectively, less than the time to flaming outside the doorway. The $HRR = 600 \text{ kW}$ criterion was chosen partly because of the close agreement with the flux criterion. A choice of a slightly higher HRR criterion would have had agreement with the flame criterion. This would be consistent with the previous FPL work (Tran and Janssens 1991), where it was found that HRR at flaming flashover was about 500 kW in the wall tests and 700 kW in the corner tests.

An interesting good criterion for time to flashover is when carbon dioxide mass flow rate exceeds 60 g/s, as listed in Table 2 and shown in Figure 6. This criterion was motivated by (1) our observation of a close correlation between oxygen consumption and carbon dioxide production for all materials (discussed in the section on beta values for combustion products) and (2) the knowledge that the visibility of the yellow and red flames emitting from the test room doorway has its source from the carbon content during the combustion process. The times for just when the CO_2 mass rate exceeds 60 g/s were on average 1.9 s greater than the time to flaming out the doorway. The noise level of the CO_2 rate flashover criterion is similar to that of the heat flux criterion, as shown in Figure 6.

Part of the reason for the higher noise level for the $HRR = 1 \text{ MW}$ criteria is the presence of a large step increase in exhaust flow that coincides with the $HRR = 1 \text{ MW}$ in most of the tests. We note that the HRR noise level would have been much greater and a spurious large spike in HRR would have appeared had we strictly followed the ISO 9705 (ISO 1993a) data reduction process (an example can be seen in Appendix B). Even in the earlier FPL work (Tran and Janssens 1991) the spurious spike was reported, indicating that the data reduction method had not yet been optimized, as it now is. These increases in the exhaust flow were unavoidable because of the spillover of smoke from the hood and of high temperatures—over 600 °C—at the top of the doorway. The success with an alternate lower level for the HRR criteria for flashover reaffirms the consistency of various flashover criteria for the set of tested materials and given room/corner test configuration. Thus, our results indicate that the most reliable flashover criterion to compare with other test facilities is the combined flame and flux criteria. This modifies the approach of the previous FPL work (Tran and Janssens 1991), which described only the flux flashover criterion as being reliable. Indeed, to improve the objectiveness of the flame criterion, one can use the flux criterion as one of the means to fine-tune observations of flaming outside the doorway. A HRR criterion can also be reliable if it has a very high correlation with the paired flame and flux criteria, as we have obtained with Figure 6. However, the specific value for the HRR criterion will vary considerably among different facilities because each would have their own unique gas analysis system, procedure for increasing exhaust flows, and data reduction approach.

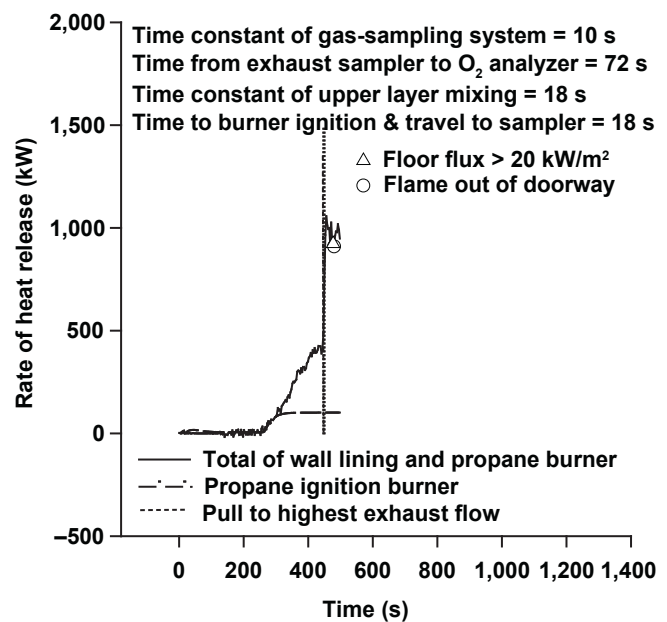


Figure 7. Heat release rate (HRR) of particleboard—room/corner test 11.

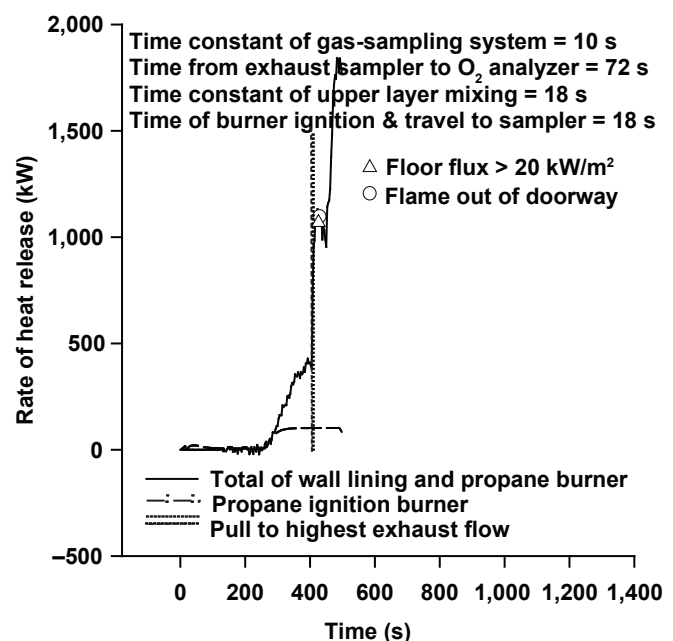


Figure 8. Heat release rate (HRR) of OSB—room/corner test 2.

Heat Release Rate (HRR)

The main time-dependent parameter measured in the room/corner test is HRR. The shortest time to flashover was measured for panel products with continuously increasing HRR (beyond what can be attributed to slow time response of flow mixings): hardboard, particleboard, oriented strand-board (OSB), and waferboard (Figs. 7 to 10). The oak veneer plywood (Fig. 11) had very short time to flashover as

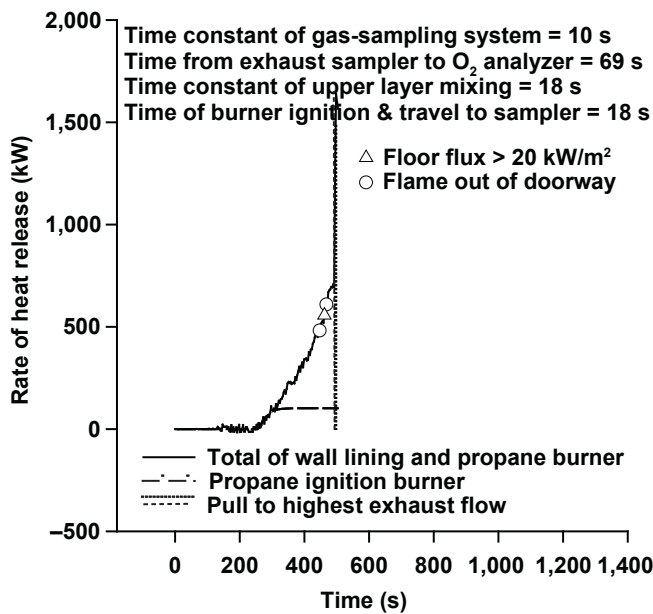


Figure 9. Heat release rate (HRR) of hardboard—room/corner test 13.

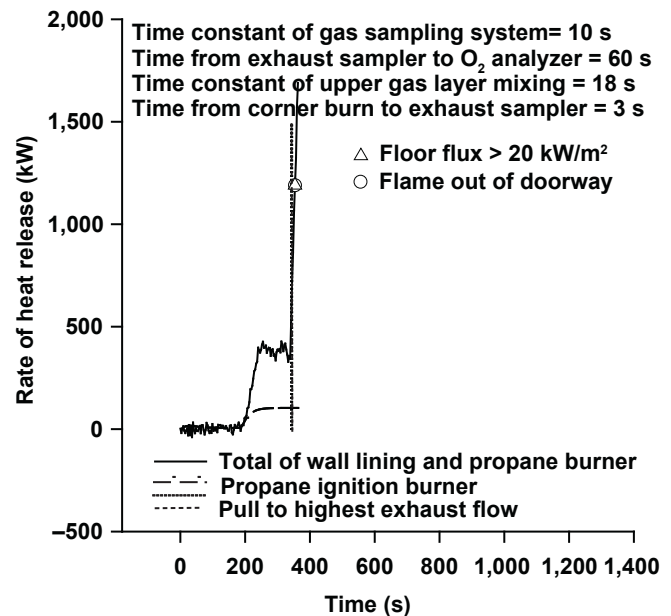


Figure 11. Heat release rate (HRR) of oak veneer plywood—room/corner test 3.

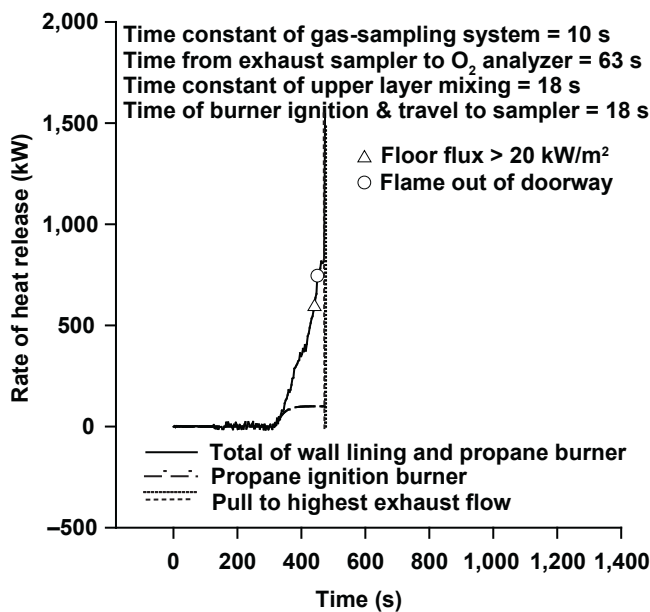


Figure 10. Heat release rate (HRR) of waferboard—room/corner test 18.

well. However, in this case the short time to flashover may be caused by delamination of the veneer's surface layer very shortly after the start of the test (giving an unusually high peak rate of heat release (PRHR) but a low total heat release (THR) for a plywood and accounted for in the fire growth models, as described in Part II, Dietenberger and others, in press).

The second group of materials was untreated plywood materials and lumbers. For these materials, time to flashover was

longer than for the previous group of materials. The HRR after the initial increase became relatively constant and even decreased for five materials as their times to flashover approached 10 min (Figs. 12 to 16). The exception from these materials is Southern Pine flooring lumber for which continuously increasing HRR was observed from the beginning of the test until flashover (Fig. 17). Southern Pine lumber and Southern Pine plywood had the shortest times to flashover from this group of materials. For materials in Figures 12 to 16, small peaks can be observed after the initial rise of the HRR.

The initial HRR rise was due to the step increase in ignition burner output in all the tests. Although the burner flames appeared quite rapidly (as in Fig. 2) with a corresponding rapid increase in HRR, the combustion flow mixing in the upper gas layers/hood with its 18-s time constant and the gas analysis system with its 10-s time constant makes the ignition burner HRR profile appear to be much less responsive (Appendix B provides mathematical details). The further increase in HRR to a value over that of the ignition burner HRR profile (shown by dashed lines in Figs. 7 to 22) is due to the upward fire growth on the specimen material. After the pyrolysis front of the specimen surface burning area reached the ceiling, the lateral wall flame spread then proceeded rapidly or slowly, depending on the properties of the specimen material and conditions near the ceiling. For the panel products with the continuously increasing HRR profile, the flame-spreading rate was observed to remain somewhat high during the lateral flame spreading near the ceiling. For the remaining lining materials, except for the Southern Pine flooring, the lateral flame-spreading rate near

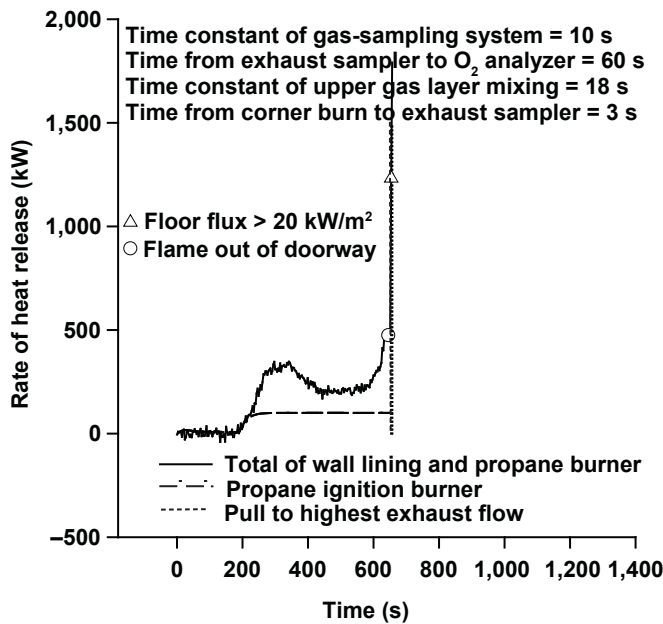


Figure 12. Heat release rate (HRR) of Douglas Fir plywood (ASTM round robin)—room/corner test 5.

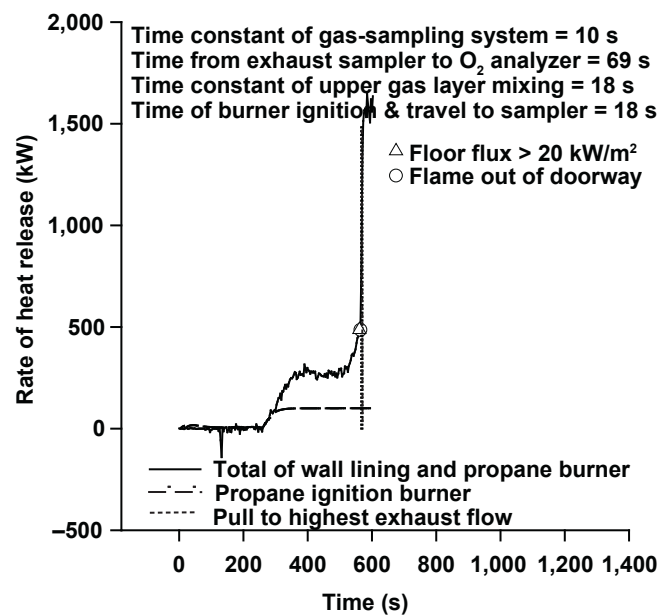


Figure 14. Heat release rate (HRR) of Southern Pine plywood—room/corner test 10.

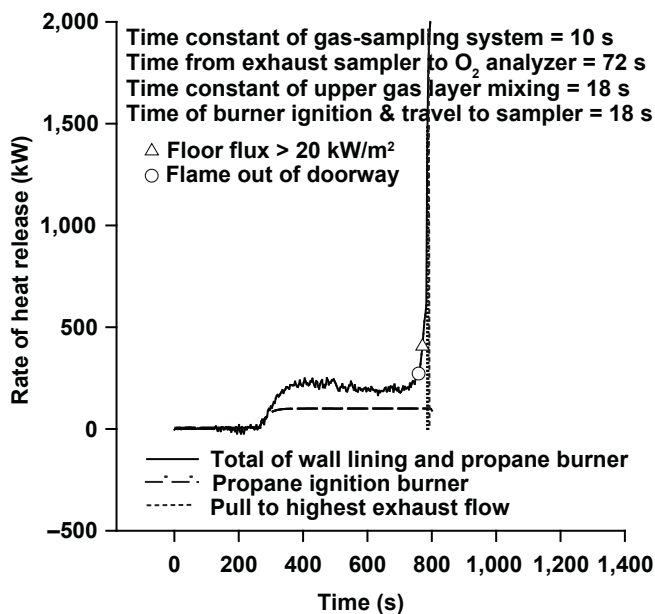


Figure 13. Heat release rate (HRR) of Douglas Fir plywood (material bank)—room/corner test 9.

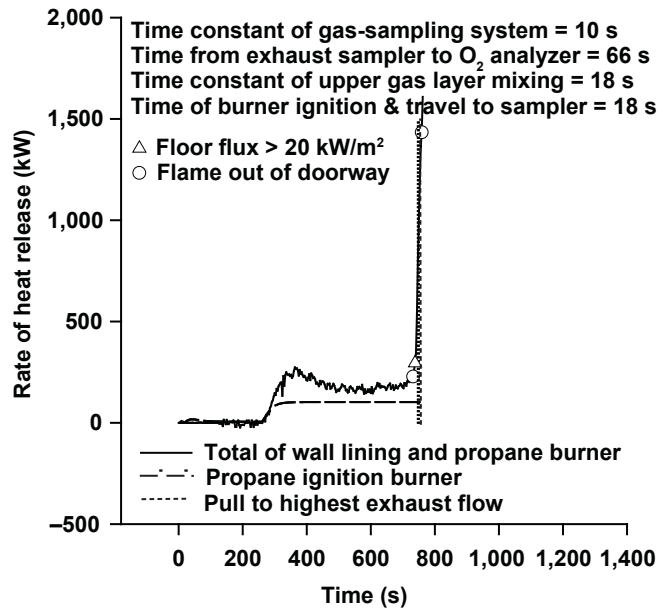


Figure 15. Heat release rate (HRR) of redwood lumber—room/corner test 14.

the ceiling became low enough that HRR gradually decreased as a result of char glowing of the burning material.

The downward flame spread on all combustible walls was always observed just shortly prior to flashover conditions, and also resulted in a final and accelerated rise in HRR (also observed by Tran and Janssens (1991) for the 40 kW/160 kW burner). The transition to downward flame spreading from lateral flame spreading would be very dependent

on the development of thermal radiation from hot regions, particularly that of the upper gas layer, because a significant external heat source is required to maintain creeping flame spread on wood materials (Dietenberger 1995, White and Dietenberger 1999). The flashover times correlated with the acceleration parameter of the upward/lateral flame-spreading process and to specific smoke production in the upper gas layer as affecting the creeping portions of lateral/downward flame spreading (Dietenberger 2002b). For all

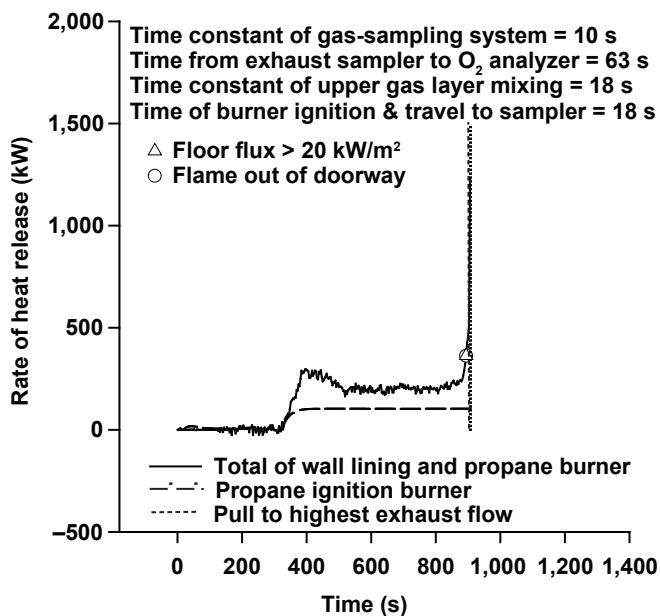


Figure 16. Heat release rate (HRR) of white spruce lumber—room/corner test 16.

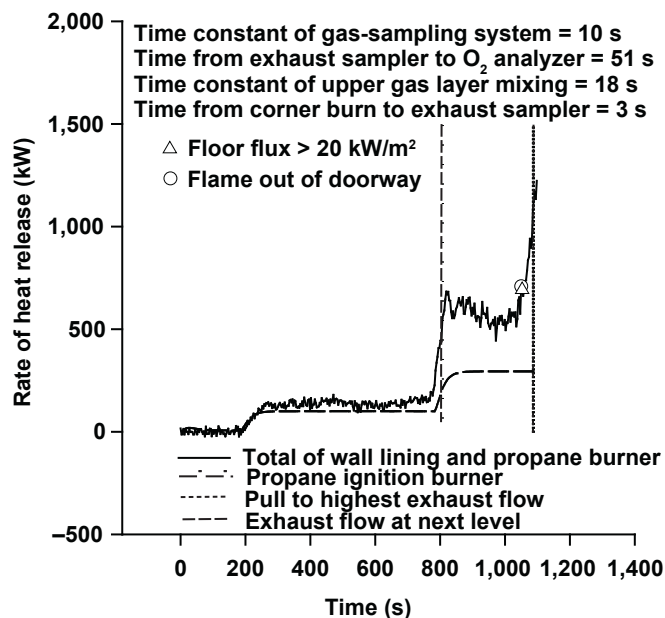


Figure 18. Heat release rate (HRR) of FRT plywood (from Forintek)—room/corner test 4.

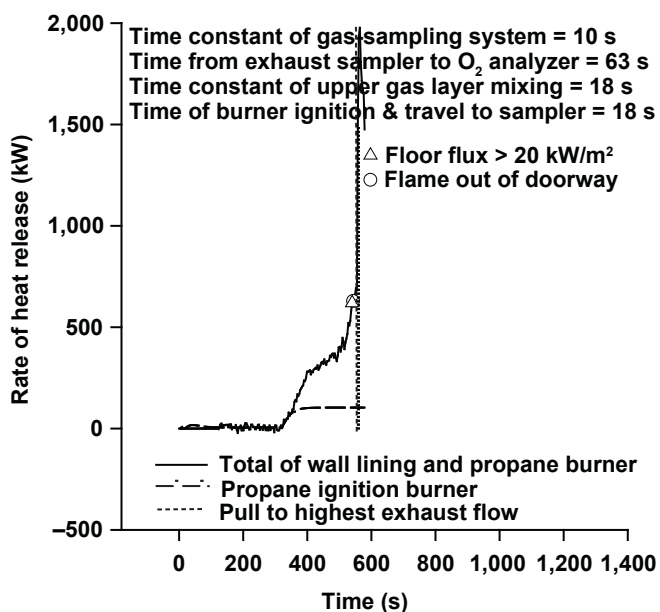


Figure 17. Heat release rate (HRR) of southern yellow pine flooring lumber—room/corner test 17.

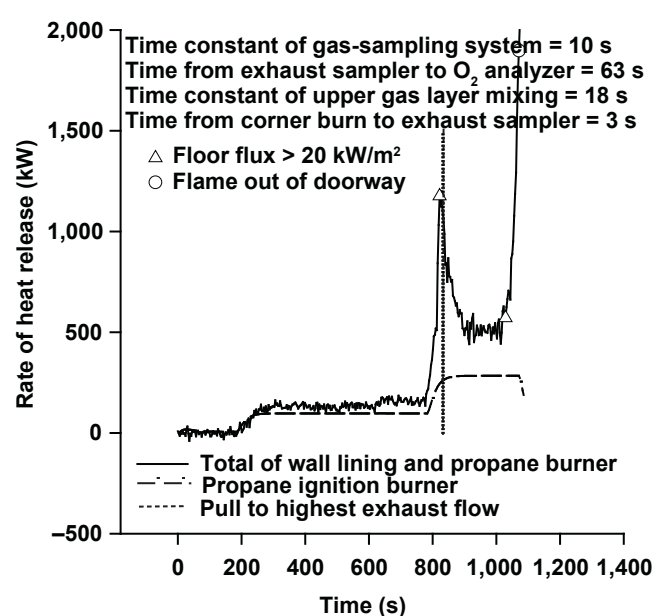


Figure 19. Heat release rate (HRR) of FRT Douglas Fir plywood (ASTM round robin)—room/corner test 2.

untreated wooden materials, flashover took place under the lower burner output (100 kW) within the first 10 min.

Four FRT materials were tested in this project: three FRT plywood materials and one FRT rigid polyurethane foam; results are shown in Figures 18 to 20 and 22. The FRT plywood from Forintek Canada Corp. (Fig. 18) and FRT Douglas Fir plywood (Fig. 19) released little heat during the first 10 min (mostly during the upward flame spread after ignition by the burner). The total HRR was up to 150 kW. The

flame spread beyond the reach of the burner flames was very limited, as verified by examination of the videotape recording of the tests. Flashover took place under the increased burner output (300 kW), and in both cases flashover times had similar values. The FRT Southern Pine plywood, similar to the other FRT materials, contributed little to the fire growth (in terms of HRR) during the 100 kW burner output (Fig. 21). In this case the burner output increase was done at 300 s because of the use of a different burner program by mistake. Flashover took place at 621st second (1 MW heat

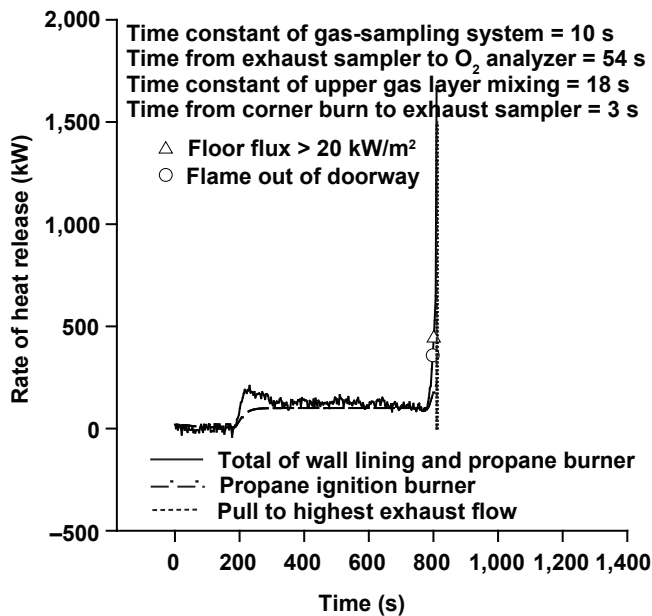


Figure 20. Heat release rate (HRR) of FRT rigid polyurethane foam—room/corner test 6.

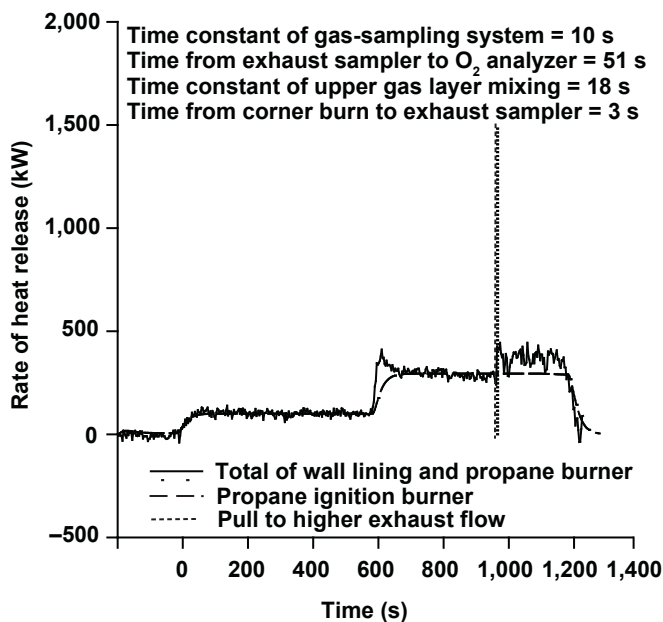


Figure 21. Heat release rate (HRR) of gypsum wallboard—room/corner test 7.

release rate). By hypothetically adding 300 s to the lower burner output time, flashover would take place in the 921st second, which is in good agreement with the other two FRT plywood materials. The FRT rigid polyurethane foam, as with other tested FRT materials, did contribute some HRR to the fire in the first 10 min (Fig. 19). Furthermore, this material had very little total available energy per square meter, which resulted in near burnout, perhaps even before the pyrolysis front had reached the ceiling height. After the

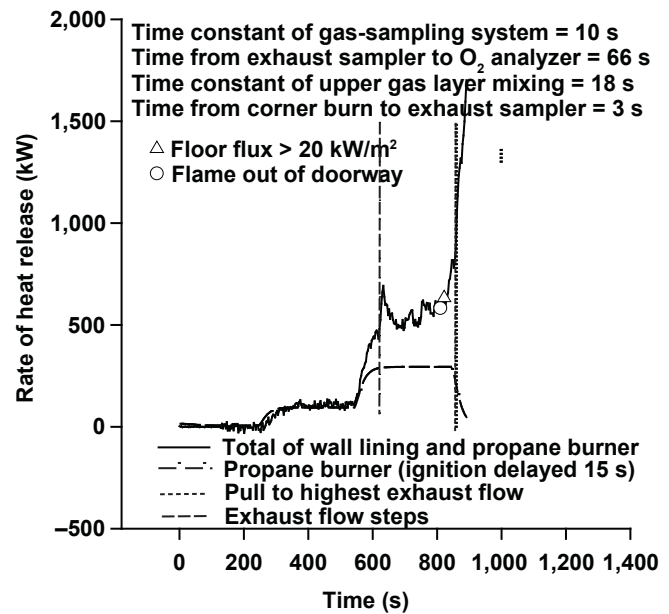


Figure 22. Heat release rate (HRR) of FRT Southern Pine plywood—room/corner test 8.

increase of the burner output to 300 kW, flashover took place within 30 s. This observation can be explained partially by very low density and very low thermal inertia of the tested polyurethane foam, which gave a relatively high flame spread rate associated with a very low time to ignition. Also contributing to rapid flame spread is the high thermal radiation from the very smoky upper gas layer usually associated with foam lining materials. For all combustible materials treated with flame retardant, flashover happened between 10 and 20 min.

The only lining material that did not flashover was the paper-faced gypsum wallboard (Fig. 21). Heat release rate during the test of gypsum wallboard was very close to 100 kW during the first 10 min and 300 kW from 11 to 20 min of the test. The small, but measurable, HRR peak following the burner's increase to 300 kW is due to the virgin paper rapidly igniting within the increased heating region and then burning out within a minute. One also notes the improvement of the HRR profile (Fig. 21) using the computer program in Table C1 (App. C) as compared with the HRR profile (Fig. B-1, App. B) based on the ISO 9705 (ISO 1993a) data reduction procedure. It was enough improvement to also derive combustion properties of the paper facing, as discussed in Appendix D.

Temperature Development

The temperature measurements of one corner TC tree are shown in the Figures 23 to 28. The gas temperature in upper layer depended on the height in the room. The temperatures measured at heights 2.1 and 1.72 m had the highest values, whereas the temperature at height 1.57 m and at lower heights had much lower values before flashover.

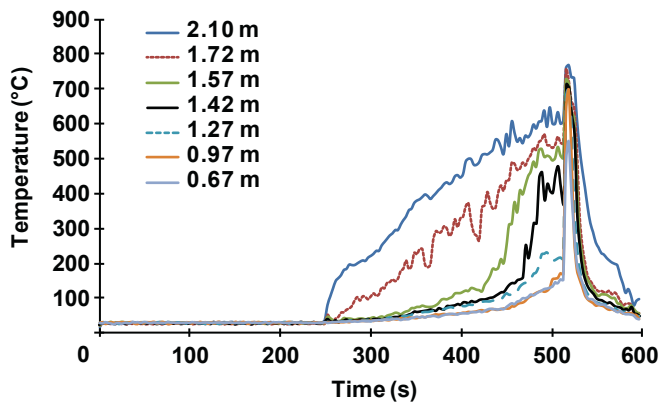


Figure 23. Gas temperature in the room corner versus time measured by ISO thermocouple tree for particleboard (test 11).

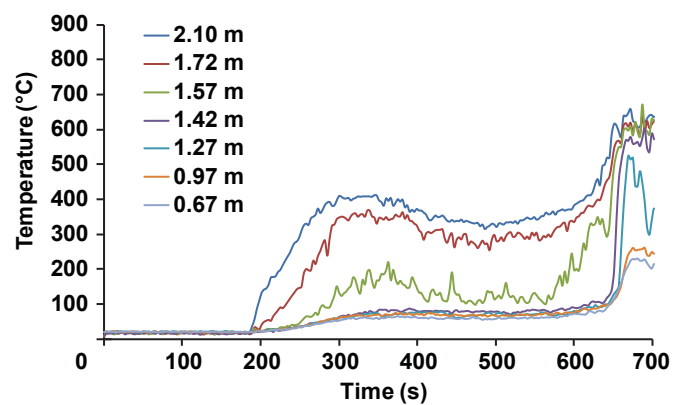


Figure 26. Gas temperature in the room corner versus time measured by ISO thermocouple tree for Douglas Fir plywood (test 5).

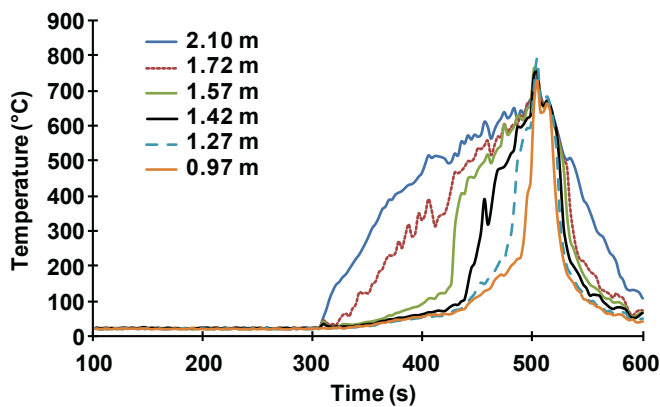


Figure 24. Gas temperature in the room corner versus time measured by ISO thermocouple tree for waferboard (test 18).

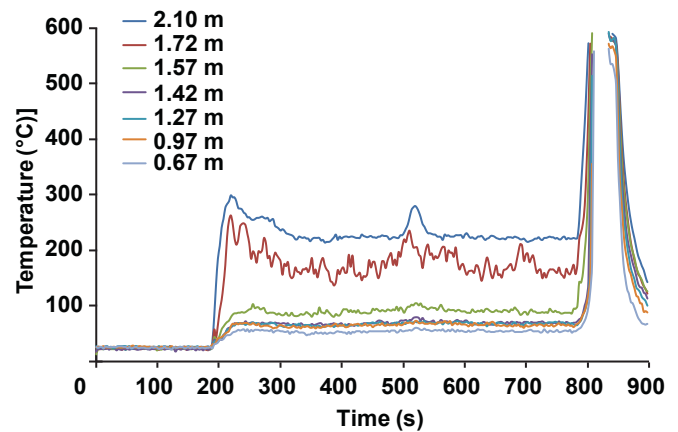


Figure 27. Gas temperature in the room corner versus time measured by ISO thermocouple tree for FRT polyurethane foam (test 6).

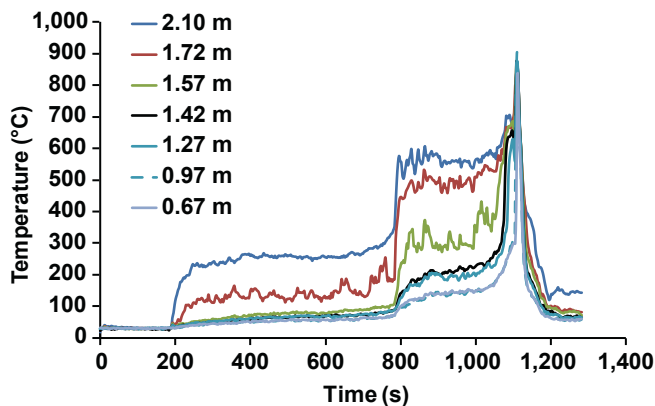


Figure 25. Gas temperature in the room corner versus time measured by ISO thermocouple tree for FRT plywood from Forintek (test 4).

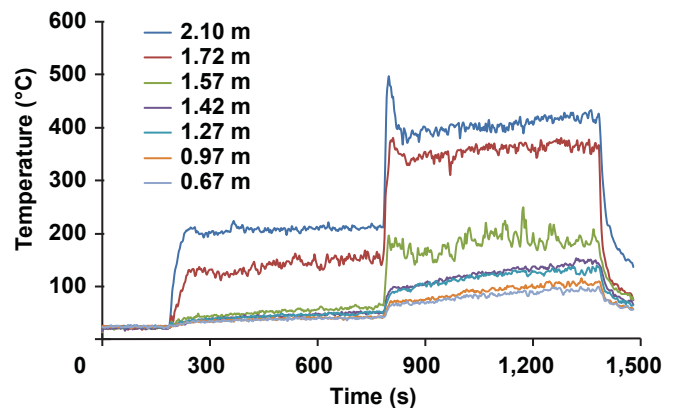


Figure 28. Gas temperature in the room corner versus time measured by ISO thermocouple tree for paper covered gypsum wallboard (test 7).

The shape of the temperature curves measured at the highest point was similar to the shape of HRR curves. For materials in which the accelerating fire growth was observed, temperature was rising from the beginning of the test until

flashover (Figs. 23 and 24). The rate of temperature rise was highest for materials with the shortest flashover times. For the untreated and treated wood materials with the longer flashover times, plateaus in the temperature values

corresponding to stable HRR regions are observed until shortly prior to flashover. This can be seen in Figures 25 to 27. In Figure 26, note that the temperature of room gas below the 1.42-m height is up to 80 °C until the time shortly prior to flashover. The FRT plywood materials (Fig. 25) had the gas temperature below the 1.42 m height with values up to 70 °C for the first 10 min (during the lower burner output), similar to the FRT polyurethane foam (Fig. 27). The gypsum wallboard, with very limited contribution to HRR, in fact represents the gas temperature profile in the room due to the ignition burner (Fig. 28). Thus, for a standing person of average height, the air temperature remains tenable (<100 °C at 1.5 m) until several seconds prior to flashover.

The temperature distribution with height in the room/corner tests is ascertained from Figure 29, which shows the temperature profile as a function of room height for gypsum wallboard at the times of 420 and 920 s. The same figure also shows the temperature profile of the Douglas Fir plywood 100 s prior to flashover and the temperature profile of FRT plywood from Forintek at the time of 420 s. Many mathematical models use a so-called zone approach, in that a room with a fire is divided into several zones with uniform temperatures. For example, the gypsum wallboard in the first part of the test shows that the lower gas layer has a relatively constant temperature. However, with the temperature in the upper gas layer increasing with height, the upper gas layer should at least be divided further into a lower gas recirculation zone with a linearly increasing temperature with height and a ceiling zone with a rapid flowing boundary layer with the highest temperatures. Sharper temperature increase between the lower and upper temperature zones was observed for the FRT plywood and untreated Douglas Fir plywood, respectively. The strongest rise of temperature in the upper gas layer zone was observed for materials with the accelerating HRR. We note that the temperature values shown in Figures 23 to 29 are not corrected for radiation from the flames. Therefore, the real temperature values are slightly lower than those presented in the figures. The overall result suggests a multi-zonal model capable of air recirculation calculations, such as the Fire Dynamic Simulator (FDS) (McGrattan and others 2001), for comparing with extensive temperature data available in our database.

Heat Flux to Floor

Heat flux on the floor as a function of time for various materials is shown in Figures 30 to 45. The heat flux profiles are similar to the corresponding HRR and temperature curves measured at the highest point of the same tested materials. It is seen that four groups of tested materials can again be defined. The materials with the accelerating HRR during fire growth have the accelerating heat flux to floor, as well. The heat flux to the floor rapidly increased shortly after ignition of the burner (Figs. 30 to 33). In contrast, the untreated plywood materials and lumbers took longer to reach 20 kW/m², and their fluxes to floor remained about constant until shortly prior to flashover (Figs. 34 to 40). The FRT materials

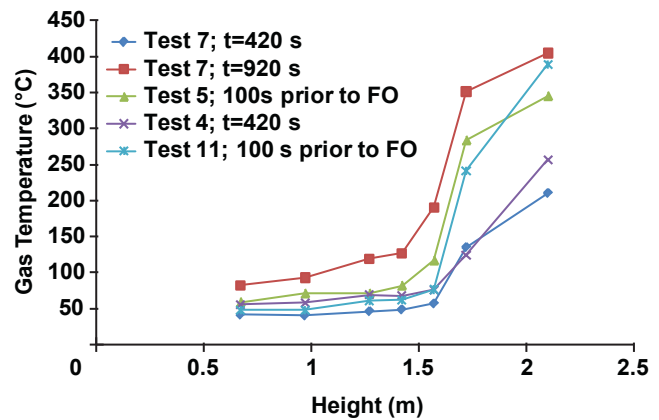


Figure 29. Gas temperature as the function of room height measured by a corner thermocouple tree for various materials in the room.

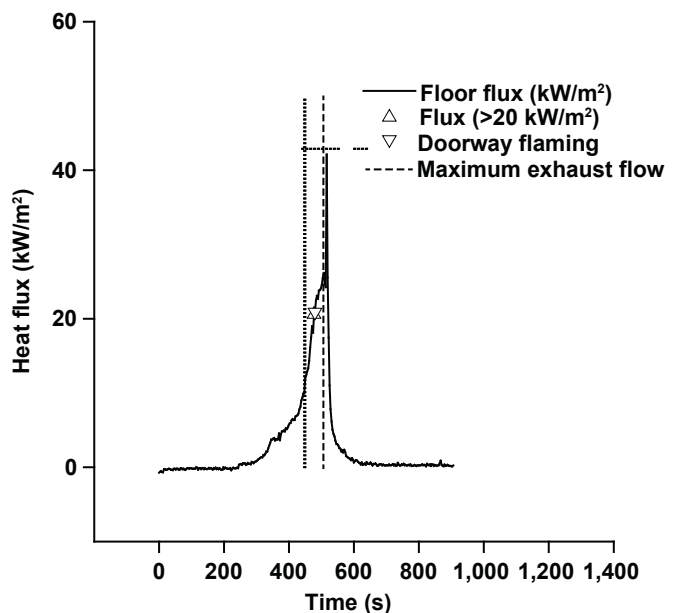


Figure 30. Heat flux to floor for particleboard (test 11).

had very low value of heat flux to floor at an easily tenable level during the first part of the test when the burner output was 100 kW. After increasing the burner output to 300 kW, the step increase in the heat flux also occurred but did not quite reach 20 kW/m² in spite of some burning of the FRT materials. As the fire growth approached flashover, the heat flux to floor once again rapidly increased (Figs. 41 to 43 and 45). For the gypsum wallboard (Fig. 44), a very low heat flux to floor was observed during the first half of the test, as well. The step increase in the flux to a perhaps untenable level was also observed after the step increase of the ignition burner output. The heat flux thereafter rose slowly due to the increasing irradiation from the increasing ceiling and lining temperatures but remained significantly below 20 kW/m² in the remainder of the test. In all tests, the floor heat flux showed no sensitivity to changes in the exhaust flow rate,

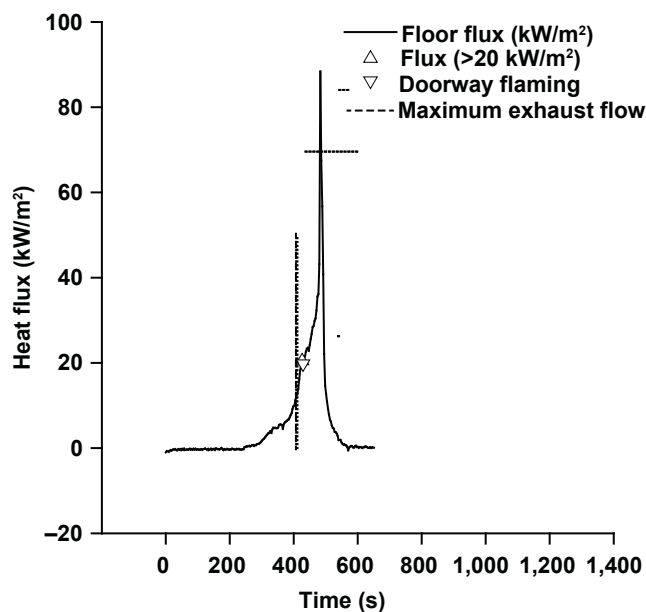


Figure 31. Heat flux to floor for OSB (test 12).

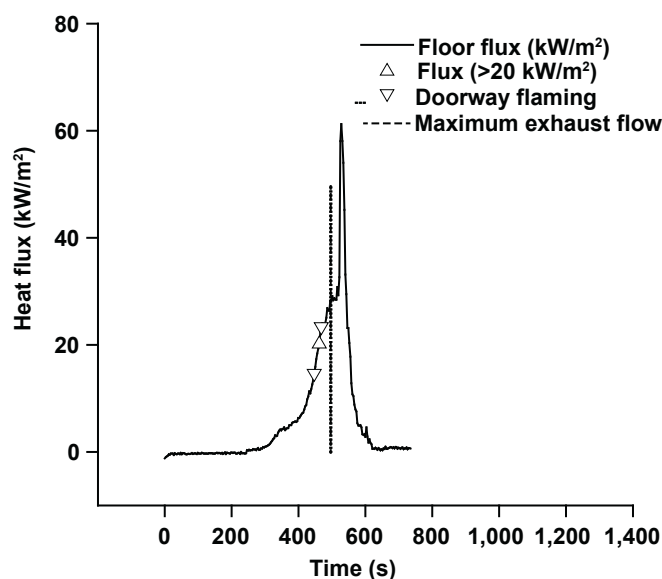


Figure 32. Heat flux to floor for hardboard (test 13).

Table 3—Betas for CO₂, CO, and soot with fuel hydration value (see App. D)

Material	Test no.	Beta CO ₂ ($r^2 = 0.99$)	Beta CO ($r^2 = 0.95$)	Beta soot ($r^2 = 0.90$)	Fuel hydration value
Gypsum wallboard, Type X	1	1.35	0.030	0.00330	1.0
FRT Douglas Fir plywood	2	1.36	0.214	0.00319	1.101
Oak veneer plywood	3	1.36	0.141	0.00394	1.061
FRT plywood (Forintek)	4	1.36	0.175	0.00440	1.080
Douglas Fir plywood (ASTM)	5	1.31	0.109	0.00089	1.012
FRT polyurethane foam	6	1.05	0.181	0.04507	0.889
Gypsum wallboard, Type X	7	1.35	0.030	0.00330	1.0
FRT Southern Pine plywood	8	1.27	0.206	0.00424	1.033
Douglas Fir plywood (MB)	9	1.11	0.090	0.00136	0.863
Southern Pine plywood	10	1.19	0.156	0.00791	0.956
Particleboard	11	1.25	0.143	0.01	0.992
Oriented strandboard	12	1.27	0.123	0.00593	0.994
Hardboard	13	1.19	0.222	0.0105	0.991
Redwood lumber	14	1.19	0.078	0.00318	0.913
Gypsum wallboard, Type X	15	1.35	0.030	0.0033	1.0
White spruce lumber	16	1.31	0.046	0.00292	0.979
Southern Pine boards	17	1.14	0.231	0.00694	0.965
Waferboard	18	1.14	0.177	0.0103	0.937

as one would find with the HRR calculations. However, the floor flux response was rapid at the flashover event. Because of complex three-dimensional thermal radiation processes, the corresponding model needed for comparison to the data is multi-zonal, such as in the more recent versions of the Fire Dynamic Simulator.

Beta Values of Combustion Products CO₂, CO, and Soot

The first step in obtaining these combustion properties is to provide mass flow rates of CO₂, CO, and soot as functions

of time (see Appendix C) so that Equation (D2) from Appendix D can be fitted to the data. The fitted coefficients are the betas (combustion product mass per oxygen depletion mass) for the material of the wall linings (betas for propane had already been obtained). Table 3 lists the beta values for CO₂, CO, and soot obtained from fitting Equation (D2) to the data. Figures 46 to 61 provide plots of CO₂ mass flow rates that correspond, respectively, with HRR plots in Figures 7 to 22. All the CO₂ mass flows have similar features as the corresponding HRR features, except that the propane contribution is relatively less because of its CO₂ beta value

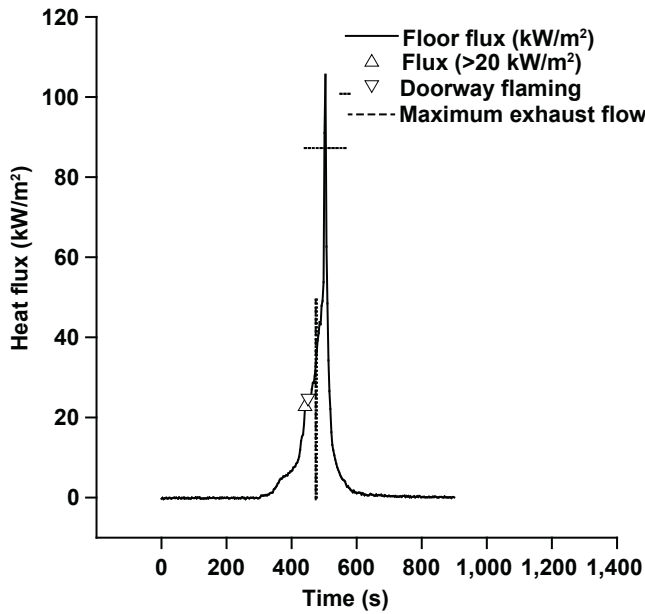


Figure 33. Heat flux to floor for waferboard (test 18).

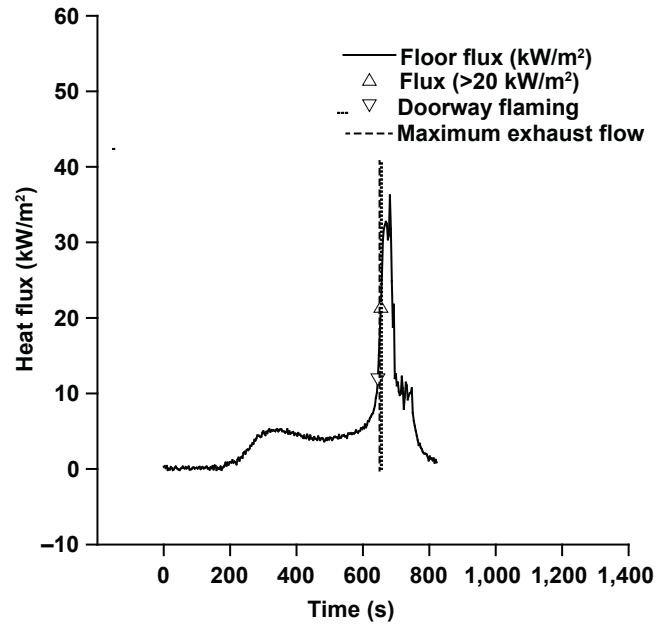


Figure 35. Heat flux to floor for Douglas Fir plywood (ASTM round robin) (test 5).

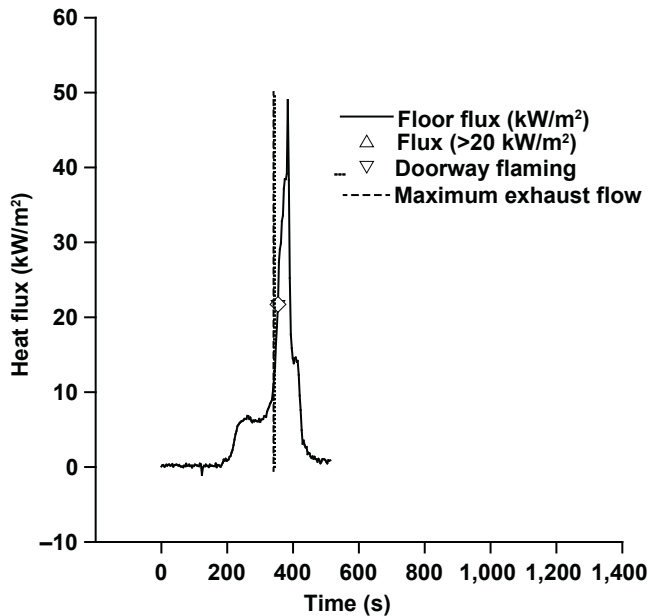


Figure 34. Heat flux to floor for oak veneer plywood (test 3).

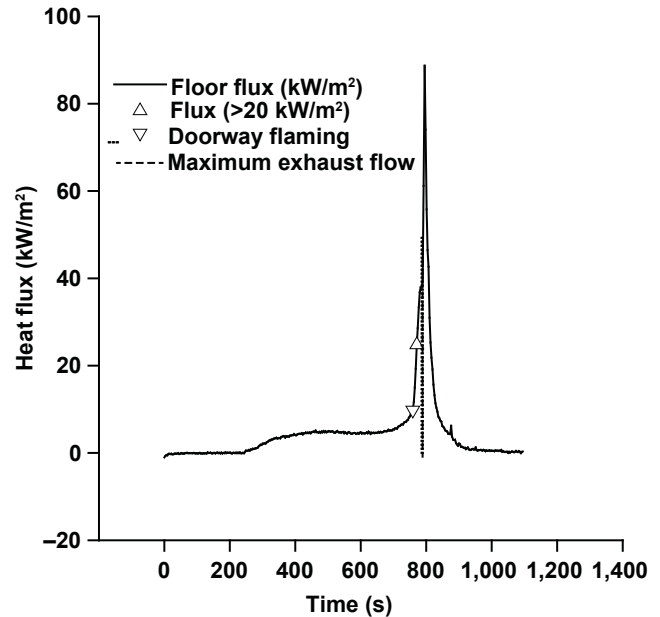


Figure 36. Heat flux to floor for Douglas Fir plywood from material bank (test 9).

being low at 0.802. In these figures, the CO_2 beta of the materials is the sole parameter fitted to the data over the full regime, and the correlation coefficient of $r^2 = 0.99$ is obtained for all the test materials. Also shown in the figures is the flashover criterion of CO_2 rate >60 g/s, as discussed earlier. This result has several implications. First, our CO_2/CO analyzer provided credible, although occasionally noisy, data in all the tests. Second, the beta parameters are independent of global equivalent ratios (GER) less than

unity. Third, we confirmed that the complications of flow mixings in several control volumes are incorporated quite effectively within Equation (D2). Fourth, it is possible that the fuel hydration value (via Equation (D3) and listed in Table 3) is constant with time because of the very high correlation coefficient for its main term, CO_2 beta. Fuel hydration is molar fuel carbon per stoichiometric molar depletion of oxygen.

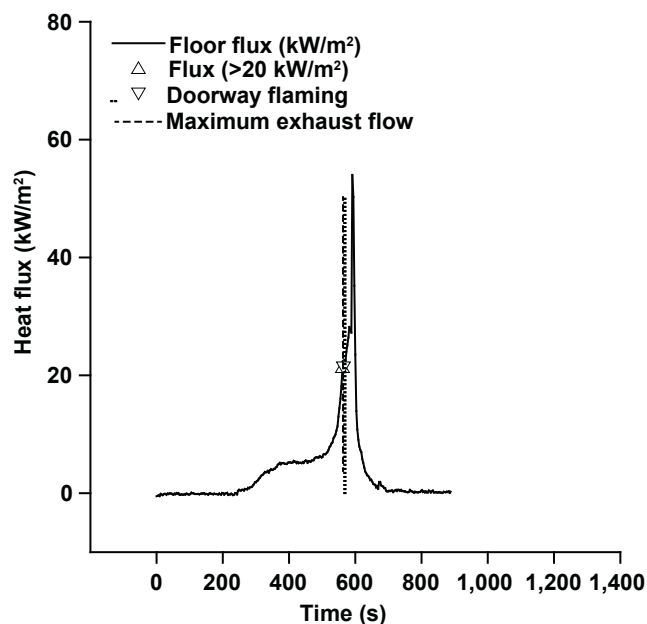


Figure 37. Heat flux to floor for Southern Pine plywood (test 12).

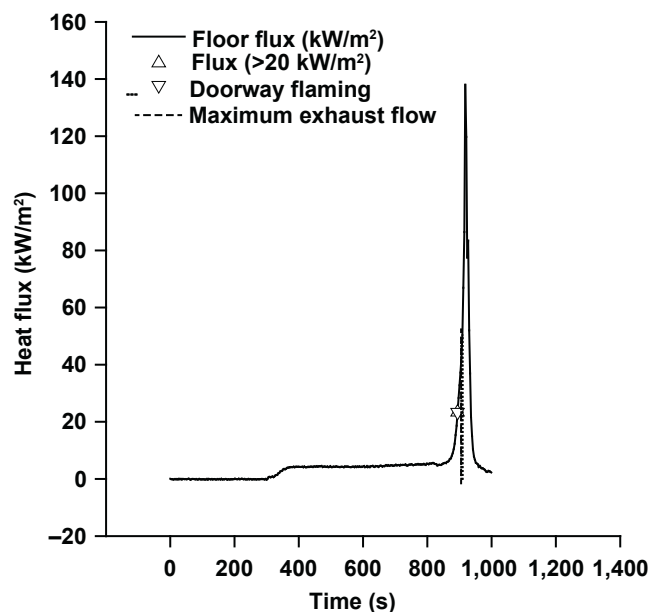


Figure 39. Heat flux to floor for white spruce lumber—room/corner test 16.

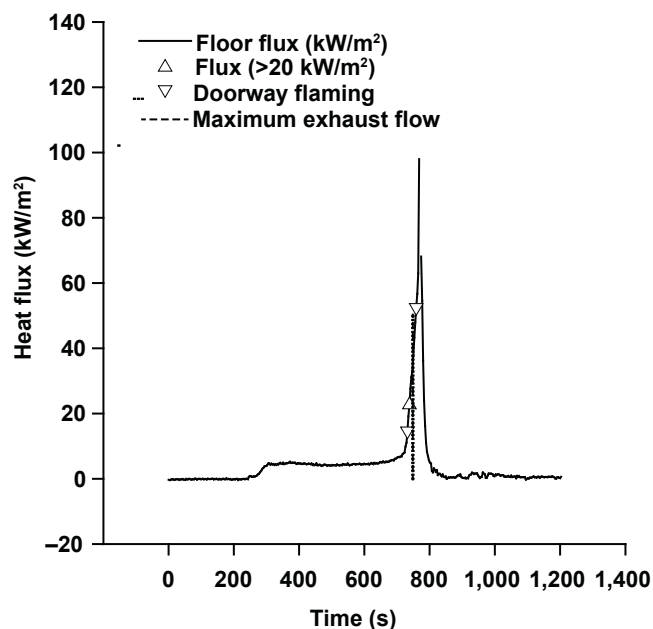


Figure 38. Heat flux to floor for redwood lumber—room/corner test 14.

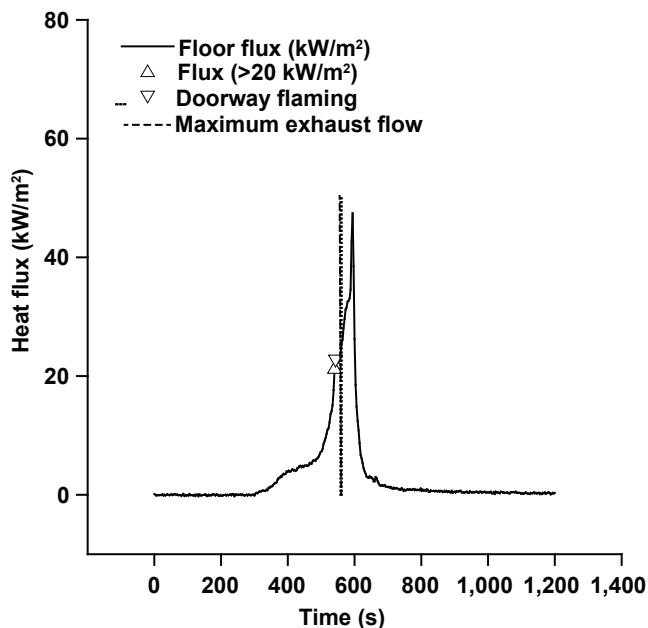


Figure 40. Heat flux to floor for Southern Yellow Pine flooring lumber—room/corner test 17.

The CO mass flow rate data are shown in Figures 62 to 77, and the soot mass flow rate is shown in Figures 78 to 93 for the 16 different wall linings. The data deviate from the oxygen consumption profiles after flashover is reached, presumably due to the water sprinkler activation. By fitting Equation (D2) for CO and soot to the data prior to flashover, the typical correlation coefficients are $r^2 = 0.95$ and $r^2 = 0.9$, respectively. No consistent flashover values for CO and soot mass flow could be determined.

Discussion

Relative Flammability of Materials

One of the main goals of this project was to propose the testing protocol to assess reaction-to-fire of materials with highest sensitivity for materials with normal reaction-to-fire (such as wood-based products). With the 100 kW/300 kW burner program and unlined ceiling used in this project,

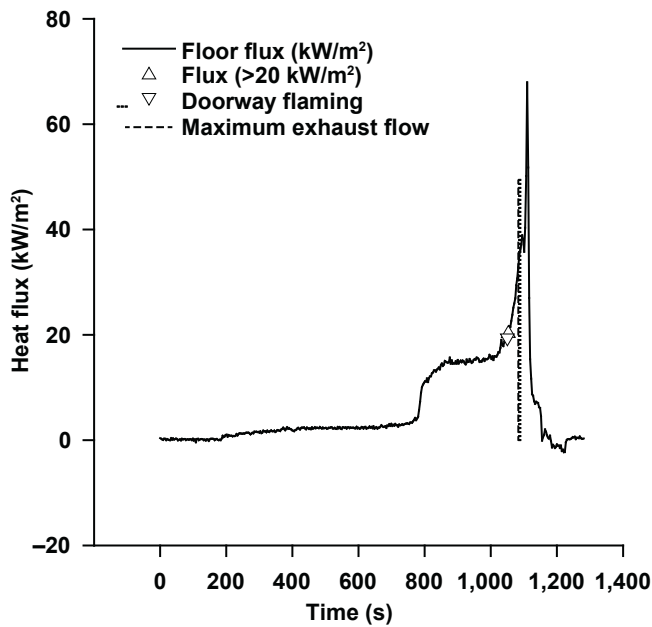


Figure 41. Heat flux to floor for FRT plywood from Forintek—room/corner test 4.

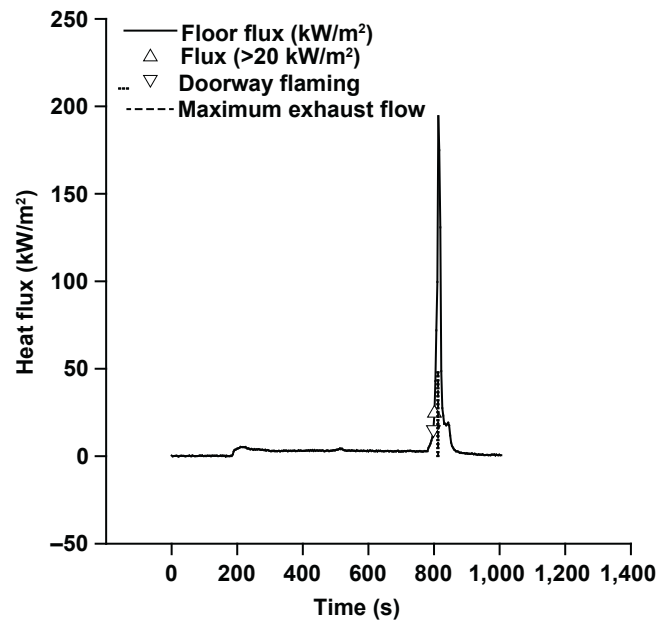


Figure 43. Heat flux to floor for FRT rigid polyurethane foam—room/corner test 6.

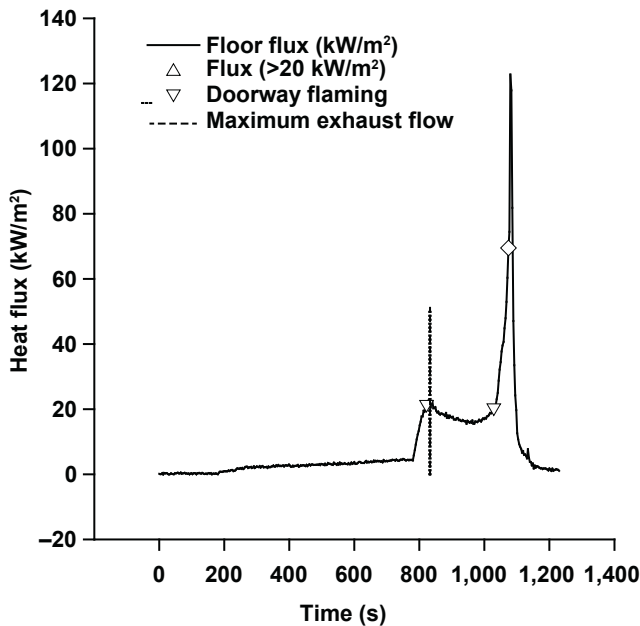


Figure 42. Heat flux to floor for FRT Douglas Fir plywood (ASTM round robin)—room/corner test 2.

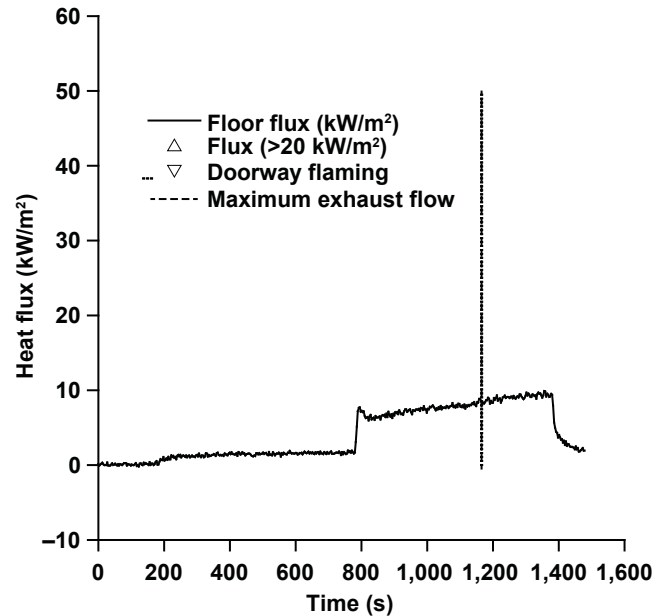


Figure 44. Heat flux to floor for Type X gypsum wallboard (test 7).

flashover times were distributed over the entire 600 s range of 100 kW burner exposure for untreated wood-based products (Fig. 94). Six of the untreated wood products resulted in flashover in a narrow range of 171 to 258 s (1 MW). Waferboard had the shortest overall time to flashover. Time to heat flux of 20 kW/m² to the floor for waferboard provided the shortest time to flashover of 141 s, which corresponds well with the time to reach a total heat release of 600 kW

at 144 s. The time to flashover defined as 1 MW was measured for waferboard as 174 s. Five untreated wood products (plywood materials and lumbers) had flashover times that ranged from 330 to 606 s (1 MW) or 321 s to 594 s based on a floor heat flux of 20 kW/m². Flashover occurred for all untreated wood products before the step increase of the burner to 300 kW. With the treated plywood and treated polyurethane foam plastic, flashover occurred after change

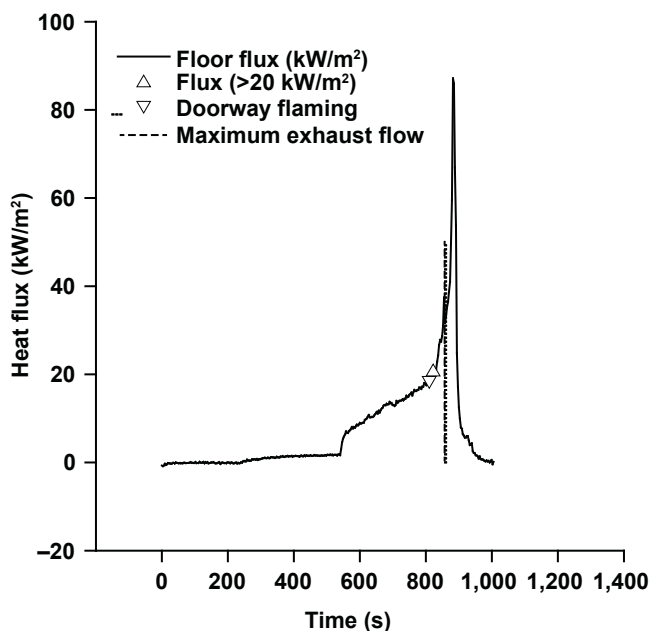


Figure 45. Heat flux to floor for FRT Southern Pine plywood (test 8).

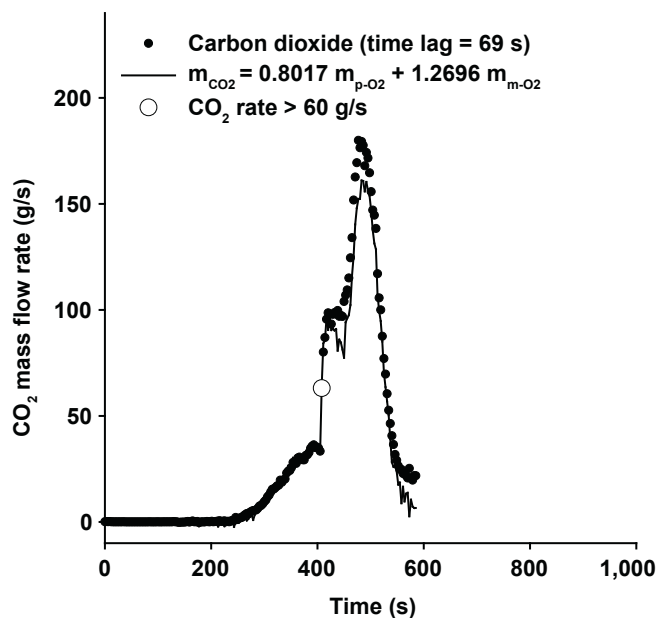


Figure 47. CO₂ mass flow rate of OSB—room/corner test 12.

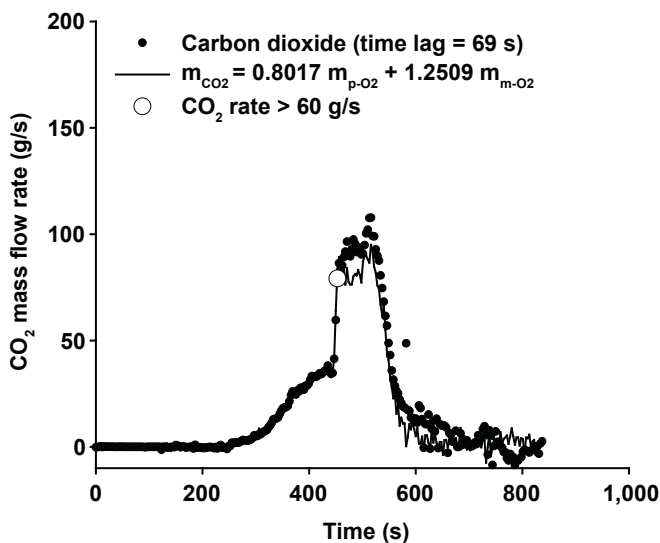


Figure 46. CO₂ mass flow rate of particleboard—room/corner test 11.

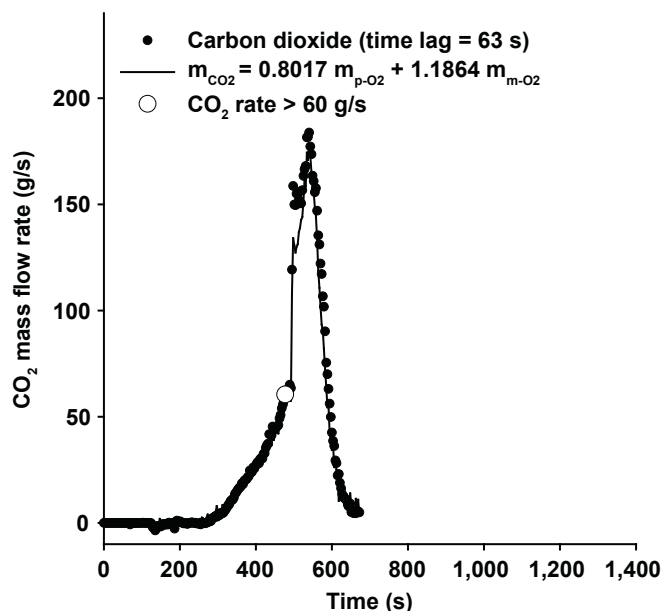


Figure 48. CO₂ mass flow rate of hardboard—room/corner test 13.

to the 300 kW burner output. In three tests with gypsum wallboard, no flashover (NFO) occurred before termination of the test.

Comparison of Flashover Times to ASTM E 84 Classification

The proposed protocol (with the 100 kW/300 kW burner program and the ceiling unlined) produced results that were consistent with expected performance in the ASTM E 84 flame spread test (ASTM 2000, or most recent edition)

currently used to regulate surface flammability in North America. The flame spread index values (Table 4) used in Figure 95 are mostly estimates based on the published literature for the generic wood products. The very flammable wood products with FSI of 150 or higher have time to flashover at 240 s or less. The remaining group of Class III untreated materials having $75 < \text{FSI} < 150$ has times to flashover between 321 and 474 s. The third group is Class II wood products that have times to flashover between 498 and 598 s. We note that borderline Class I FRT polyurethane

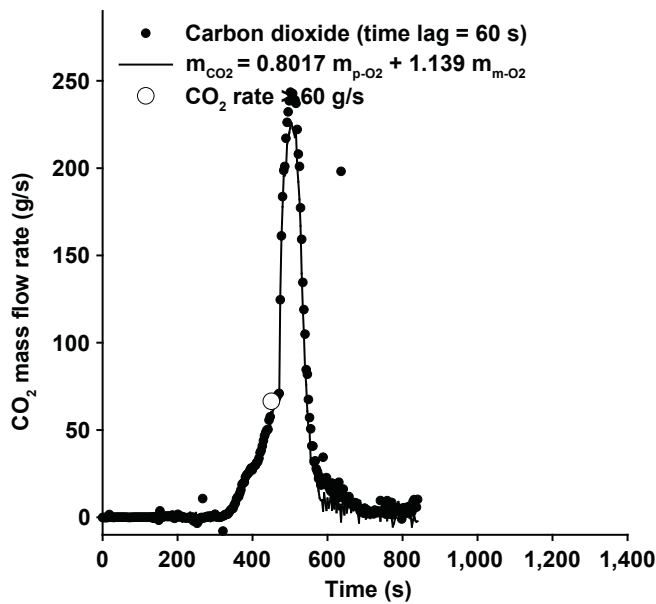


Figure 49. CO₂ mass flow rate for waferboard—room/corner test 18.

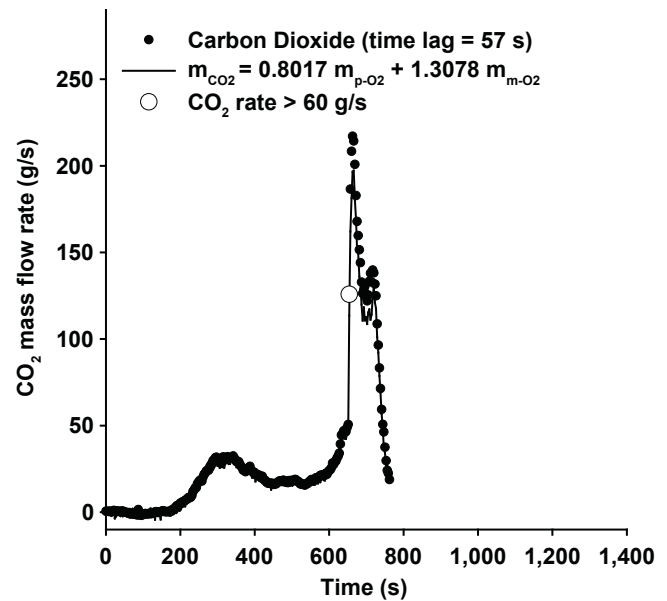


Figure 51. CO₂ mass flow rate of Douglas Fir plywood (ASTM round robin)—room/corner test 5.

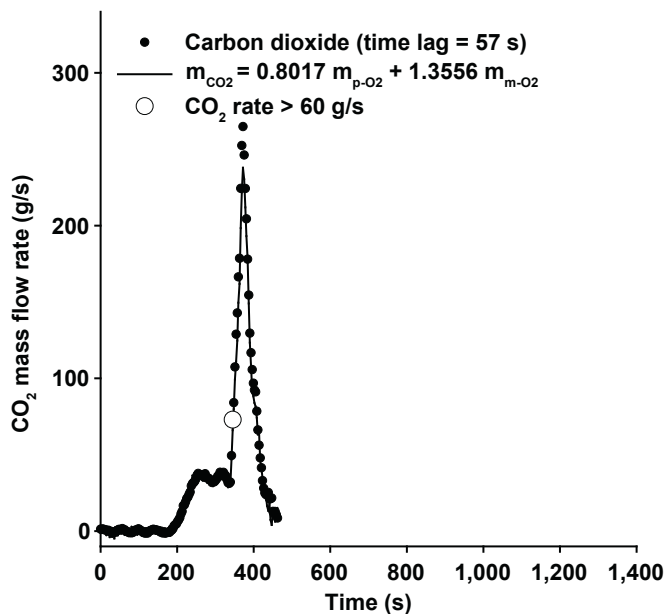


Figure 50. CO₂ mass flow rate of oak veneer plywood—room/corner test 3.

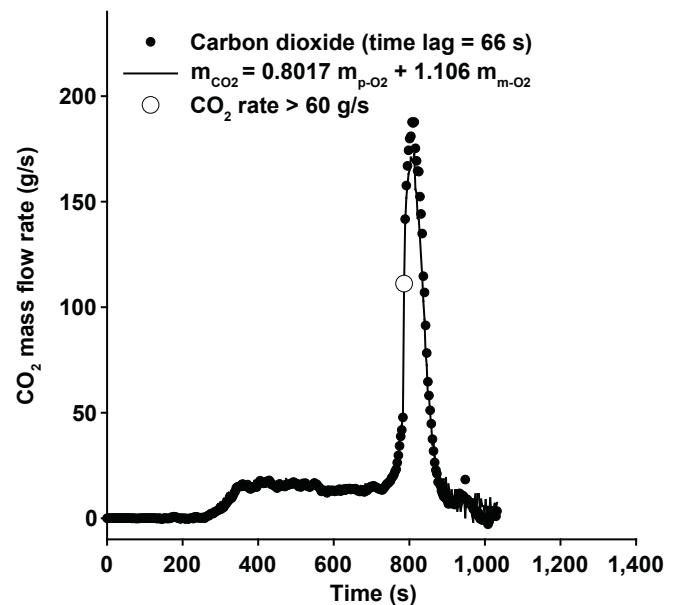


Figure 52. CO₂ mass flow rate of Douglas-fir plywood (material bank)—room/corner test 9.

foam (FSI 24) has a flashover time of 621 s. All Class I materials, except for Type X gypsum wallboard, have times to flashover between 620 and 1,200 s, with FRT plywood being in the middle at around 900 s. Thus, at least two sub-categories of both Class III and Class I can be identified. None of the 16 materials, which represent a broad range of flammability, is misplaced in this scheme. There are two potential regions of misplacement as more materials are tested: the time to flashovers of 474 to 498 s and 598 to 621

s, which straddles the boundaries of the current Class II materials to within 23 s.

Comparison of Flashover Times to Slovak Flammability Classification

In Slovakia, the flammability classes of building materials are defined in the STN 730862—Flammability of Building Materials. The five categories are used to define the flammability based on the index Q (see Table 5).

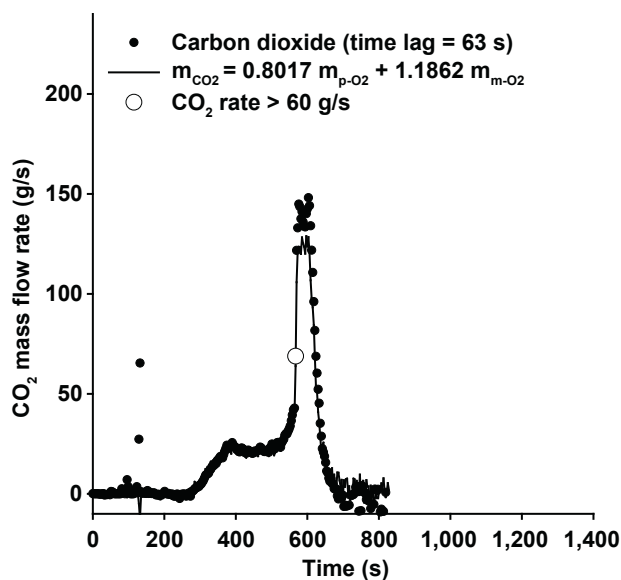


Figure 53. CO₂ mass flow rate of Southern Pine plywood—room/corner test 10.

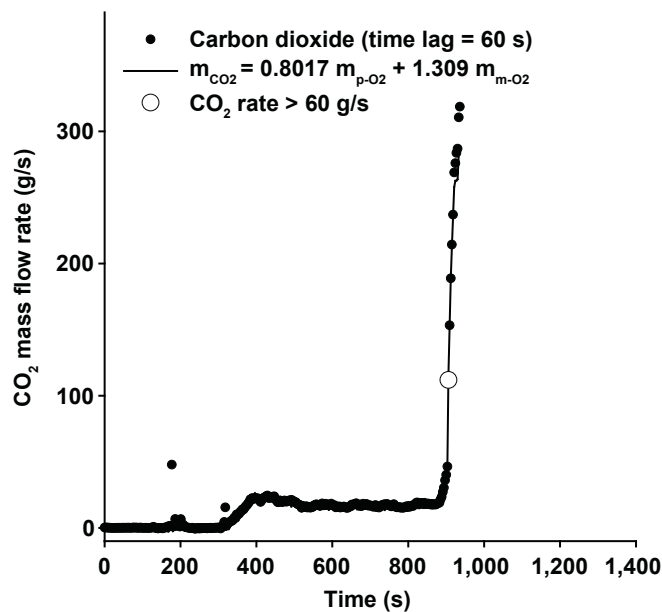


Figure 55. CO₂ mass flow rate of white spruce lumber—room/corner test 16.

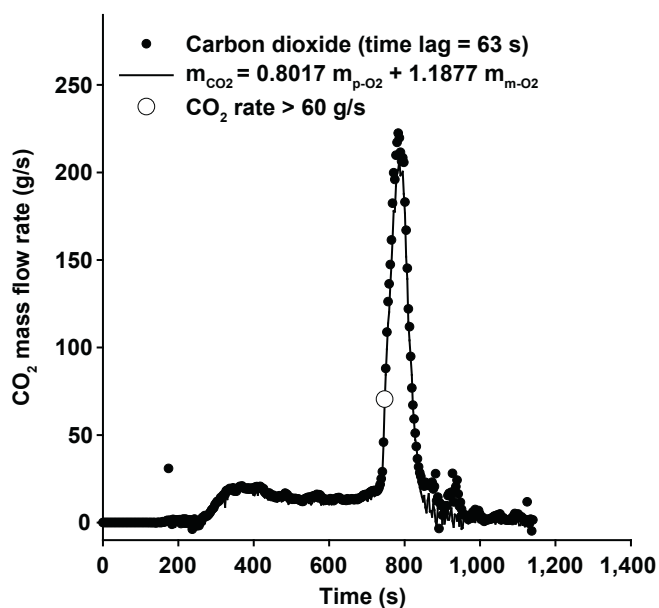


Figure 54. CO₂ mass flow rate of redwood lumber—room/corner test 14.

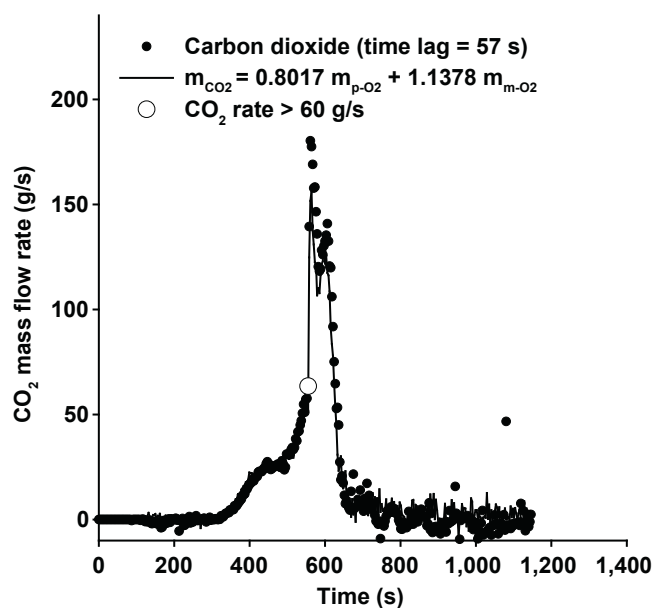


Figure 56. CO₂ mass flow rate of Southern Yellow Pine flooring lumber—room/corner test 17.

In the Slovak system, flammable materials are divided into three more detailed groups (C1–C3). All untreated wood-based products fall into one of the flammable categories. The hardwood lumbars (beech, oak) belong to class C1. Softwoods usually fall into class C2. Plywood materials belong to class C1 or C2. Particleboards are typically in class C2 or C3, and hardboard is in class C3. With the flame retardant treatment, class B can be reached. Comparison of time to flashover measured in the room/corner test with the index Q for some materials is shown in Table 6 and Figure 96.

Values for Q according to the STN 730862 are for similar materials previously tested at SDVU.

It can be seen from Figure 96 and Table 6 that reasonable consistency between time to flashover and index Q was found. Therefore, the protocol for the room/corner test 100 kW/300 kW burner output and ceiling unlined was able to differentiate the materials with the various indexes Q used in the Slovak five-class flammability system.

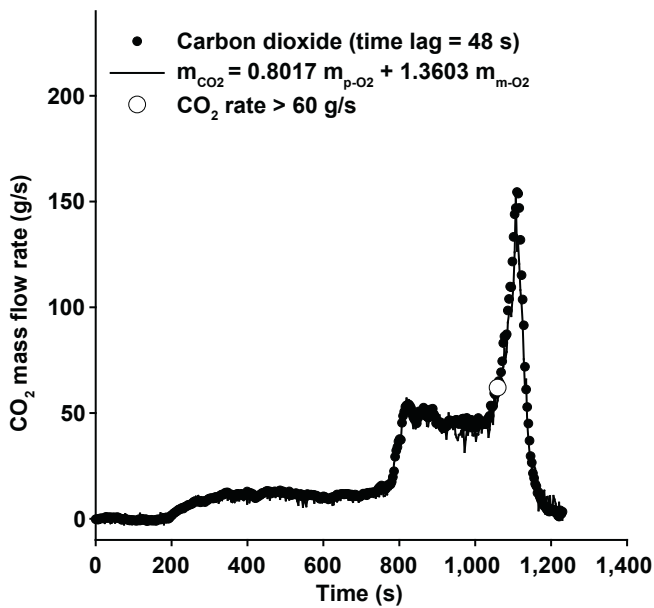


Figure 57. CO₂ mass flow rate of FRT plywood (from Forintek)—room/corner test 4.

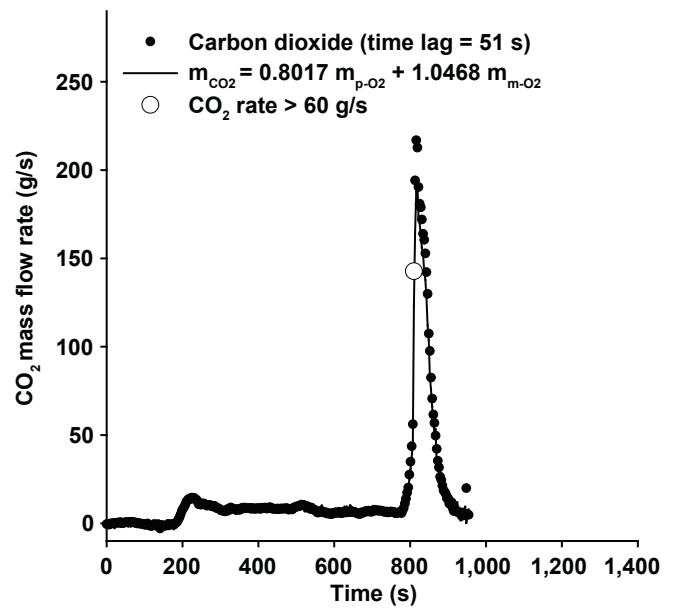


Figure 59. CO₂ mass flow rate of FRT rigid polyurethane foam—room/corner test 6.

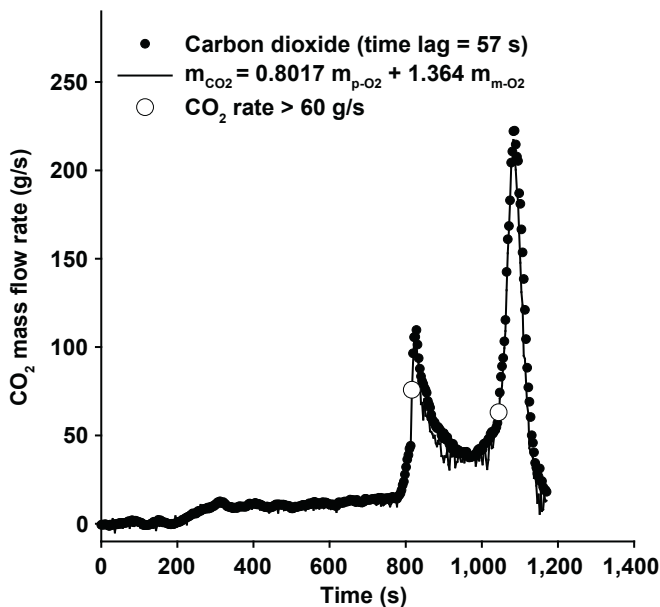


Figure 58. CO₂ mass flow rate of FRT Douglas Fir plywood (ASTM round robin)—room/corner test 2.

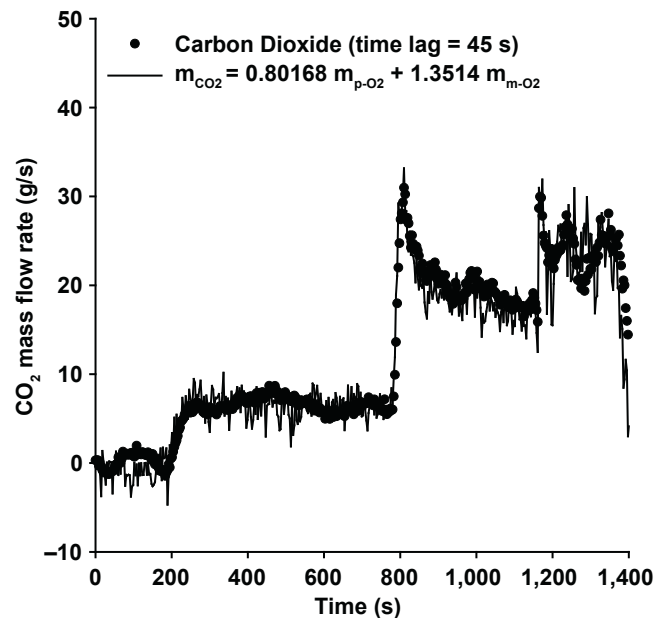


Figure 60. Prediction to CO₂ mass flow rate of gypsum wallboard—room/corner test 7.

Comparison to Flashover Times with other Room/Corner Test Protocols

By considering the two burners setting (40 kW/160 kW and 100 kW/300 kW) and the option of putting the test material on the ceiling as well as the walls, there are four possible alternatives for conducting the room/corner test. Using the data of this report and data from the National Research Council of Canada (Sumathipala and others 1993, 1994),

a more complete comparison of these four alternatives has been conducted (White and others 1999).

The selection of which protocol to use depends on the intended purpose. The protocol of 40 kW/160 kW burner and ceiling unlined resulted in little differences between the different untreated wood products and a clear distinction for treated products in that there was no flashover for those products. In previous studies, the 40 kW/160 kW burner

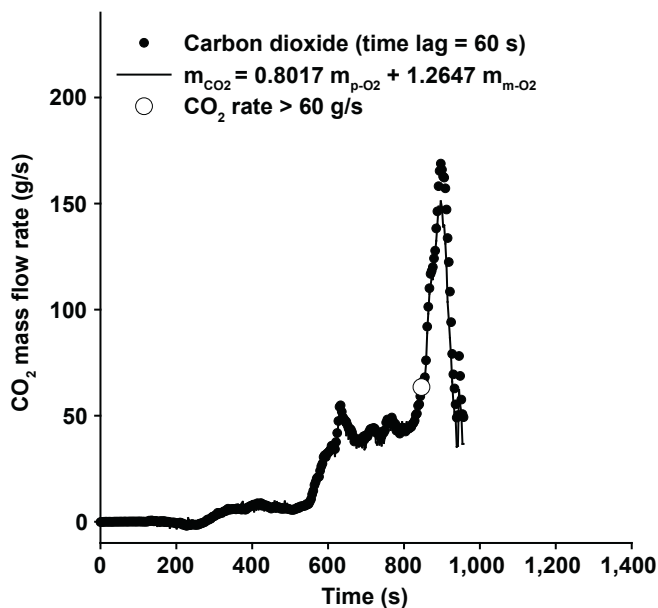


Figure 61. CO₂ mass flow rate of FRT Southern Pine plywood—room/corner test 8.

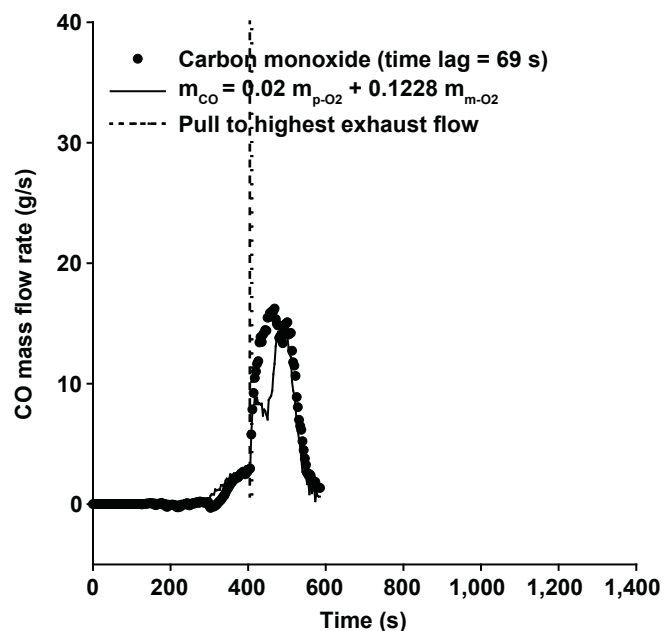


Figure 63. CO mass flow rate of OSB—room/corner test 12.

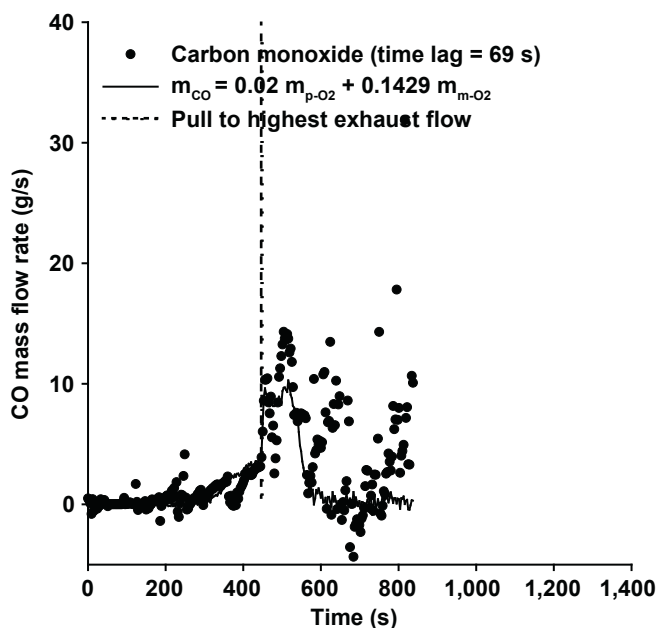


Figure 62. CO mass flow rate of particleboard—room/corner test 11.

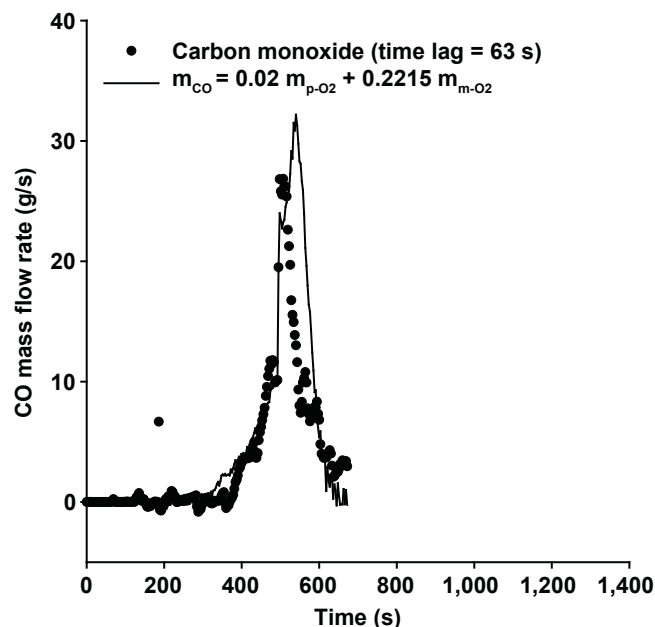


Figure 64. CO mass flow rate of hardboard—room/corner test 13.

program and the ceiling unlined protocol was used at FPL. With the 40 kW/160 kW burner program and the ceiling unlined protocol, flashover occurred shortly after the increase to 160 kW for almost all the untreated wood products. Only one untreated wood product resulted in flashover during the initial 300 s of 40 kW burner output. Using the ISR protocol, Gardner and Thomson (1988) found that even sawn Blackbutt, which has a FSI = 48, had a flashover time of

only 432 s. It appears that flashover times with this protocol cannot be used to distinguish materials that are Class II (FSI = 26 to 75) from Class III (FSI = 75 to 300) in the ASTM E 84 test. There was no flashover with gypsum wallboard, the FRT plywood products, or one of the treated polyurethane foam plastics. These materials have flame spread indexes of 25 or less. In tests in Canada (Sumathipala and others 1993, 1994), adding the test material to the

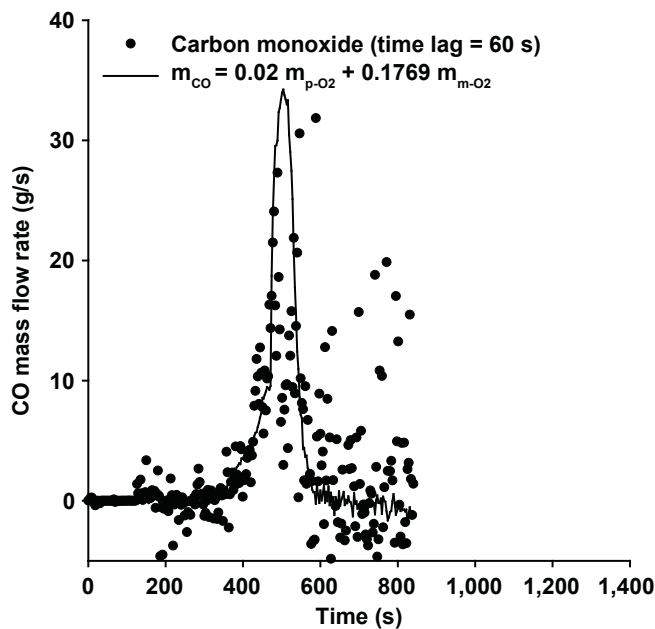


Figure 65. CO mass flow rate of waferboard—room/corner test 18.

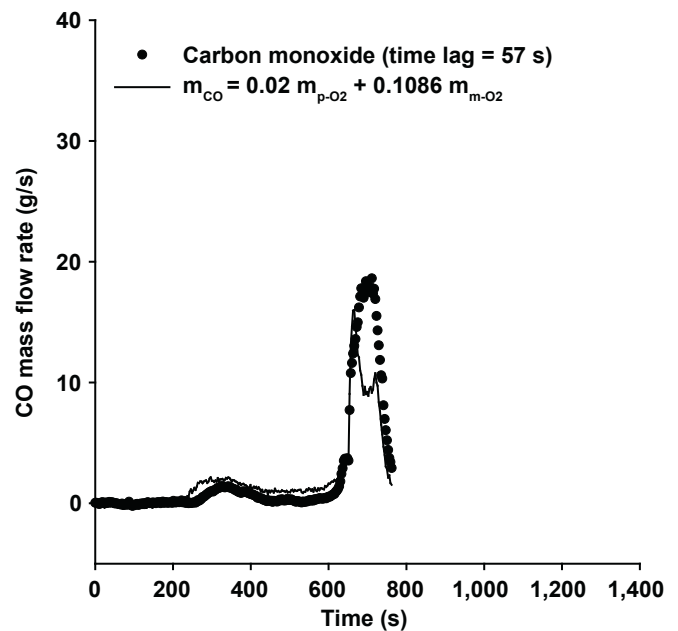


Figure 67. CO mass flow rate of Douglas Fir plywood (ASTM round robin)—room/corner test 5.

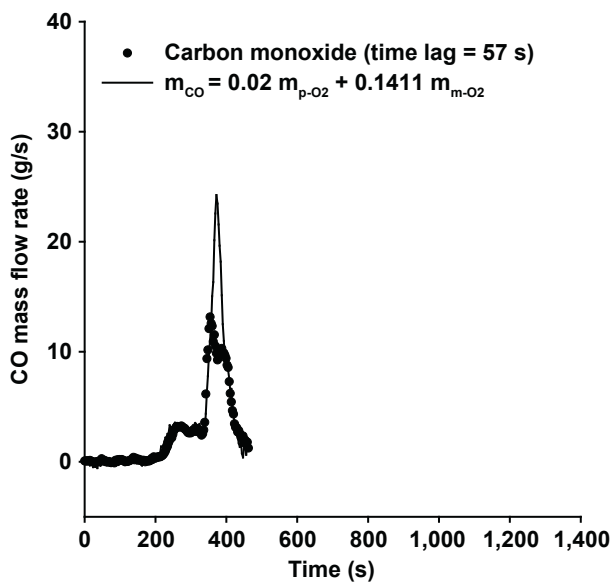


Figure 66. CO mass flow rate of oak veneer plywood—room/corner test 3.

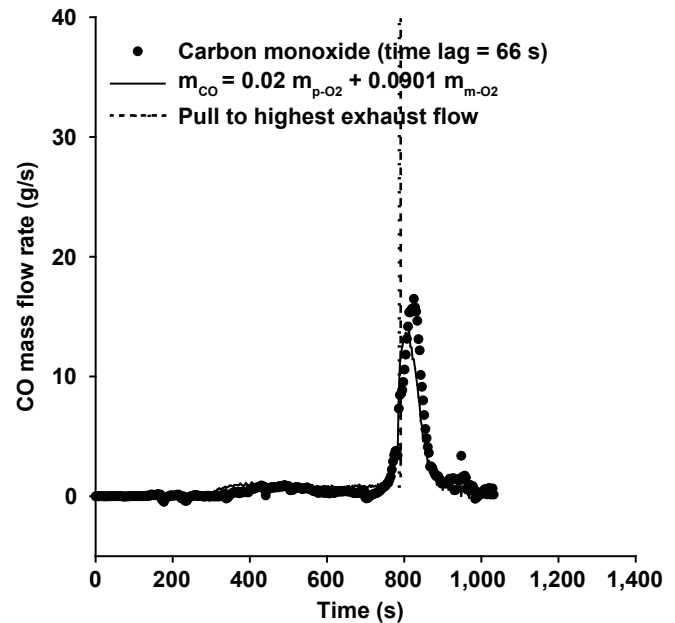


Figure 68. CO mass flow rate of Douglas Fir plywood (material bank)—room/corner test 9.

ceiling resulted in both the FRT plywood and the polyurethane foam plastic reaching flashover before the end of the test. It is also more likely that materials with low ignition characteristics will flashover during the initial exposure to 40 kW with the test material also on the ceiling.

In contrast with the 40 kW/160 kW scenarios, the 100 kW/300 kW scenario with the ceiling unlined (Fig. 94) used in this project allowed differentiation of wood products into five discernable flammability regions (Fig. 95), as discussed earlier. There is a need to test

additional materials, particularly those of Class II, to further refine the flammability categories for time to flashover, but this is a trivial problem compared to not being able to distinguish between Classes II and III or even Classes II and I for the other ignition burner scenarios. Finally, the ability to have five or more categories of flammability should give this protocol the greatest potential for correlating with the different flammability (reaction-to-fire) classifications used worldwide.

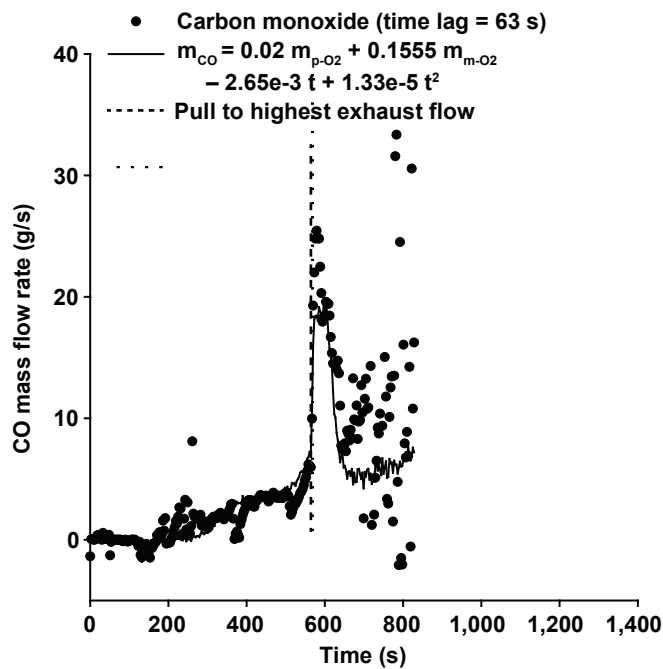


Figure 69. CO mass flow rate of Southern Pine plywood—room/corner test 10.

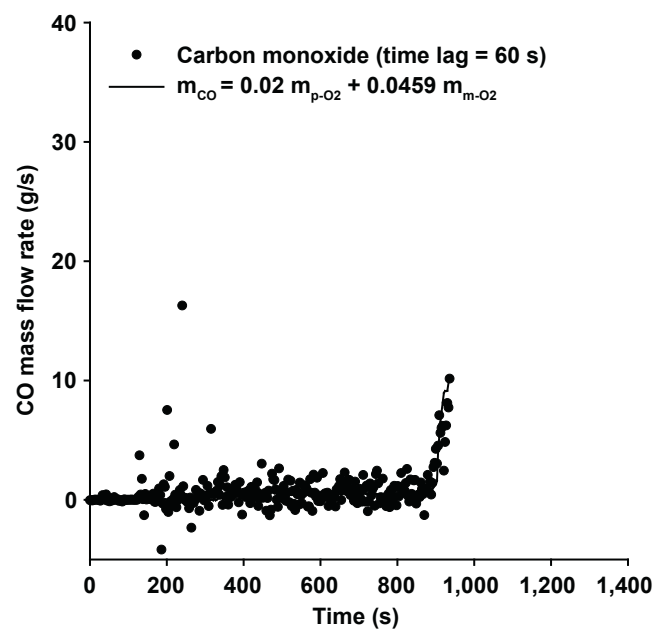


Figure 71. CO mass flow rate of white spruce lumber—room/corner test 16.

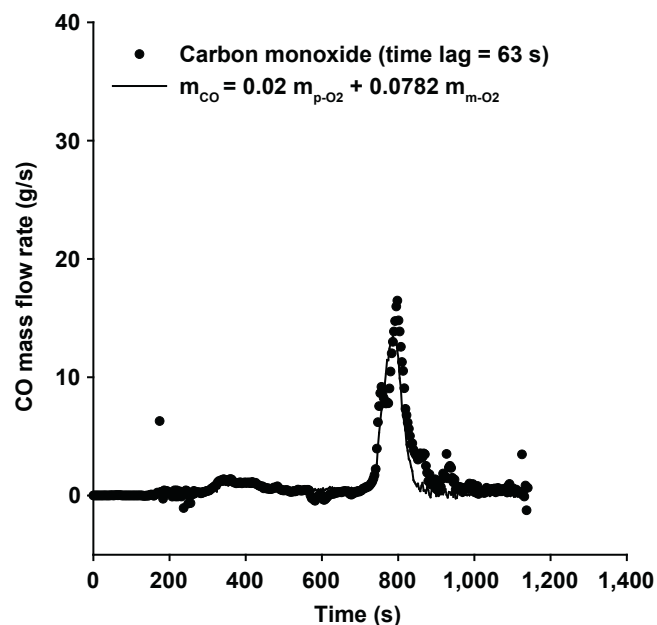


Figure 70. CO mass flow rate of redwood lumber—room/corner test 14.

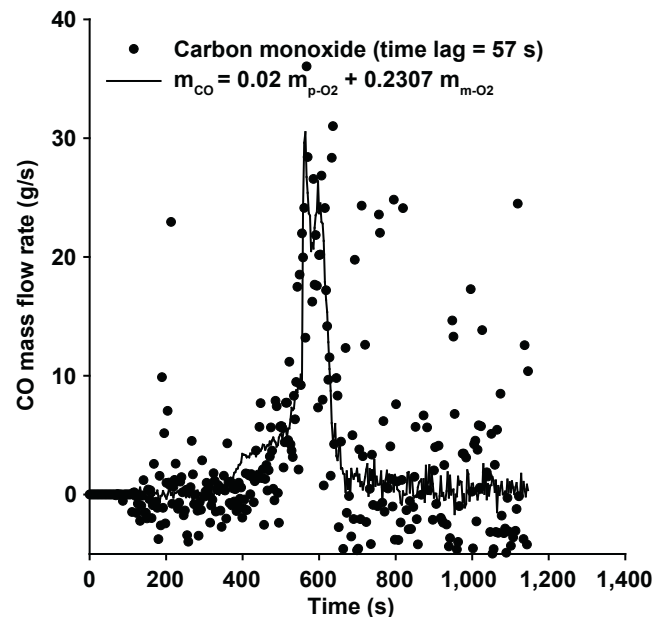


Figure 72. CO mass flow rate of southern yellow pine flooring lumber—room/corner test 17.

For the 100 kW/300 kW test with the materials on the ceiling as well as the walls, the flashover times are much shorter (Tsantaridis 1996; White and others 1999). In this protocol, Class II materials are indistinguishable from Class III materials because the flashover times occurred over a very narrow range at just under 200 s. European results for FRT wood products were either no flashover or flashover shortly

after the change to the 300-kW burner level (Östman 1993; Östman and Tsantaridis 1994). In a report on 28 different materials (Östman and Tsantaridis 1994), only one material resulted in flashover between 200 s and the change to the 300-kW burner level at 600 s. This protocol then effectively has only three discernable, yet sharply defined, flammability regions. It does best at discerning materials with very low

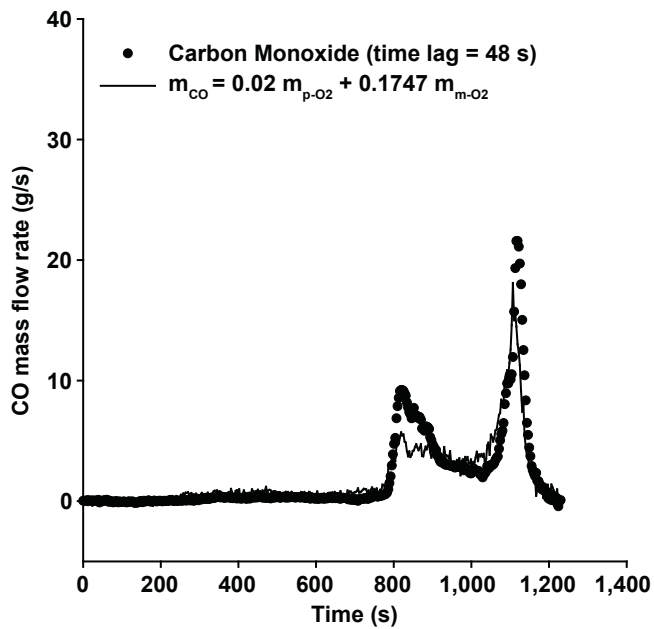


Figure 73. CO mass flow rate of FRT plywood (from Forintek)—room/corner test 4.

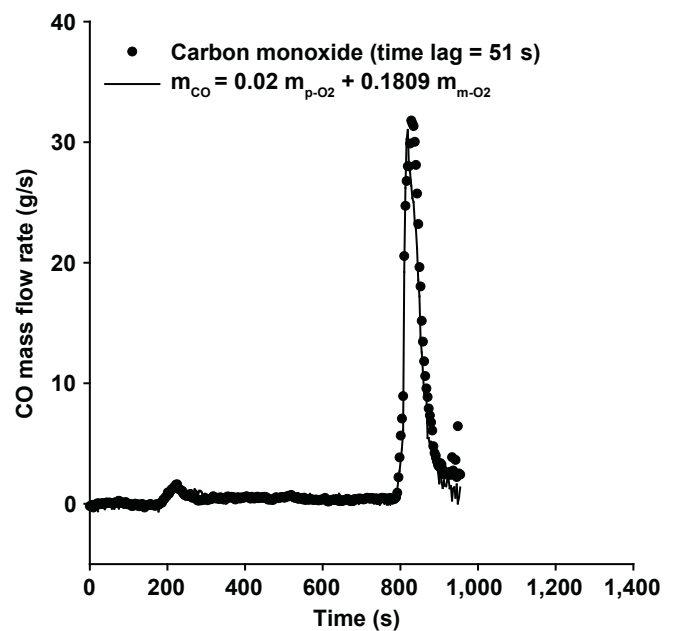


Figure 75. CO mass flow rate of FRT rigid polyurethane foam—room/corner test 6.

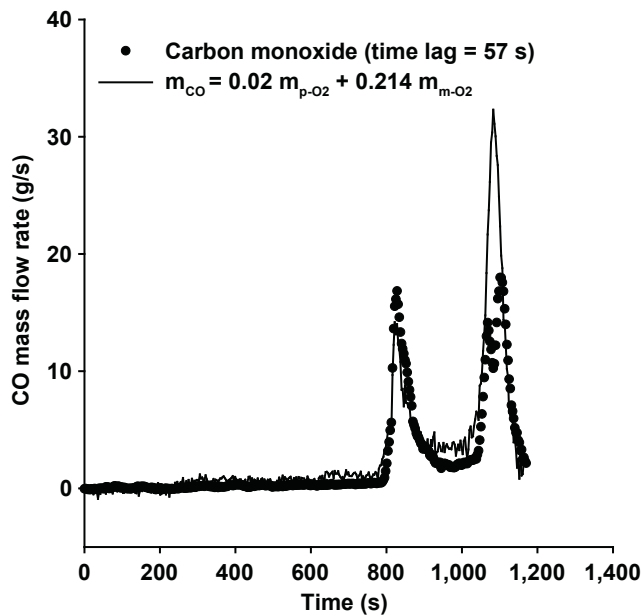


Figure 74. CO mass flow rate of FRT Douglas Fir plywood (ASTM round robin)—room/corner test 2.

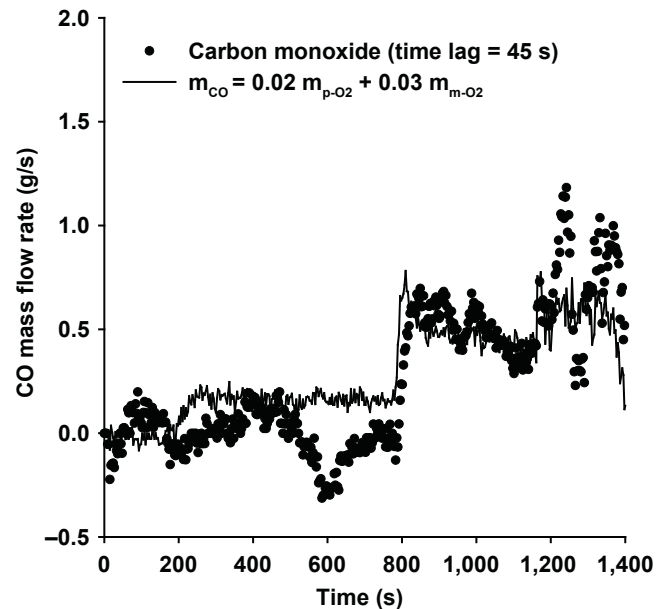


Figure 76. CO mass flow rate of gypsum board—room/corner test 7.

flammability but may correlate poorly with the various flammability classifications used worldwide.

Conclusions

The primary objective of this project was to develop a system to assess the reaction-to-fire of building materials based on the EUREFIC approach developed in the Nordic countries but also to be better able to distinguish between

common materials. By using the burner protocol of 100 kW for 10 min, followed by 300 kW for 10 min and placing the test materials only on the walls in the full-scale room/corner test (ISO 9705) (ISO 1993a), we obtained effective indications of the fire performance for 11 different untreated wood products, three different fire-retardant-treated plywood products, gypsum wallboard, and a fire-retardant-treated polyurethane foam. In contrast, the protocol option of ISO

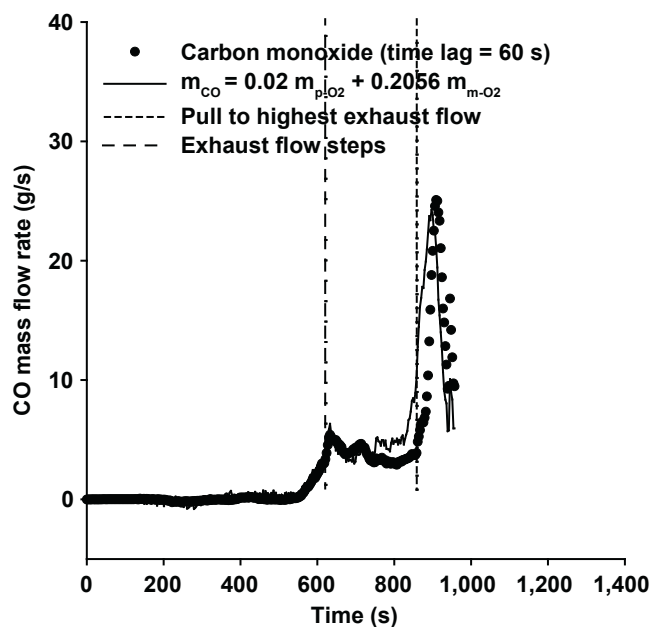


Figure 77. CO mass flow rate of FRT Southern Pine plywood—room/corner test 8.

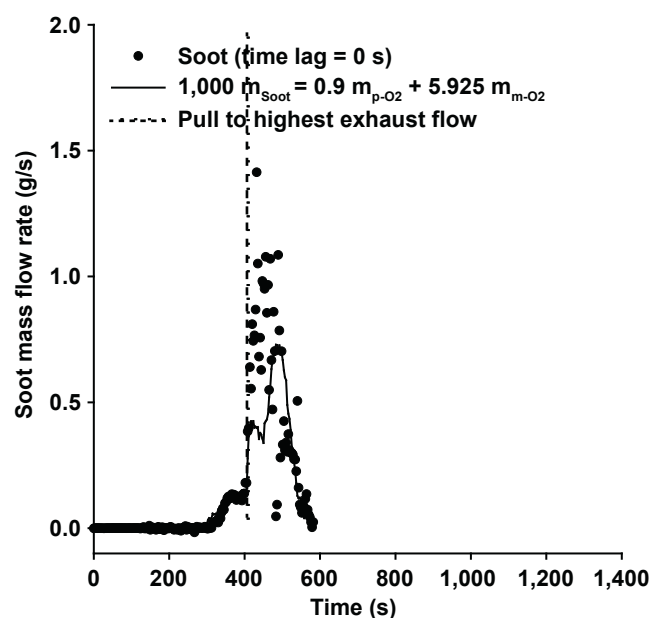


Figure 79. Soot mass flow rate of OSB—room/corner test 12.

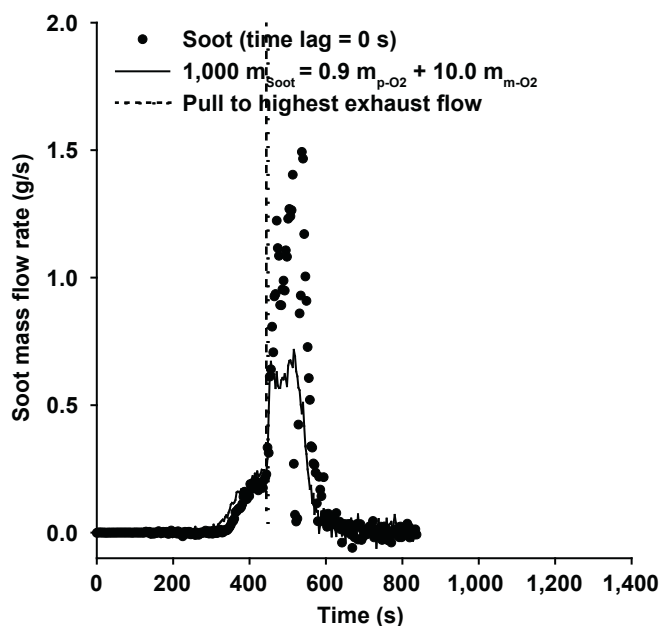


Figure 78. Soot mass flow rate of particleboard—room/corner test 11.

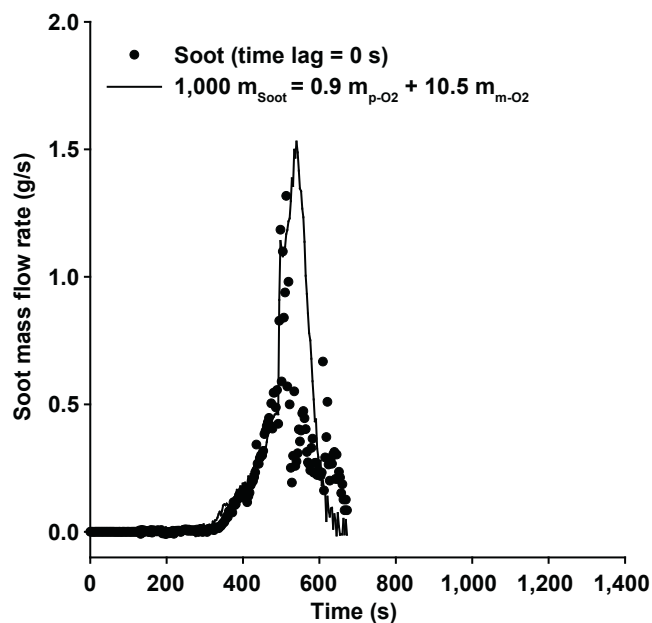


Figure 80. Soot mass flow rate of hardboard—room/corner test 13.

9705 (ISO 1993a) normally used in Europe and the option normally used in North America both resulted in flashover times for the different untreated wood products within fairly narrow time intervals. The relative performances of the different products were consistent with their expected performance in the current North America and Slovak regulatory tests for reaction-to-fire.

The auxiliary objectives in support of the primary objective were to convert the ISR room to the ISO room, implement the measurement protocols of ISO 9705 (ISO 1993a) along with the needed deviations, and provide data relevant for reaction-to-fire evaluations, particularly for fire growth modeling validations. The assessment methodology proposed in this project provides a more technically sound method that can be tied back to more fundamental fire properties that are

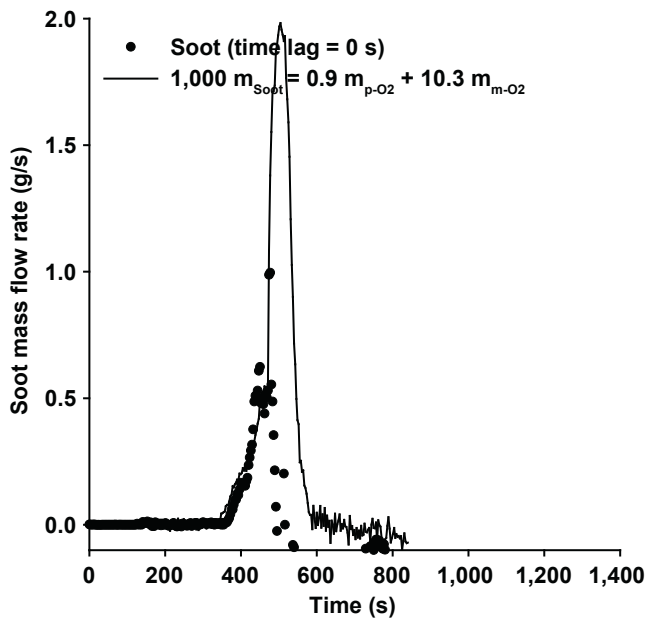


Figure 81. Soot mass flow rate for waferboard—room/corner test 18.

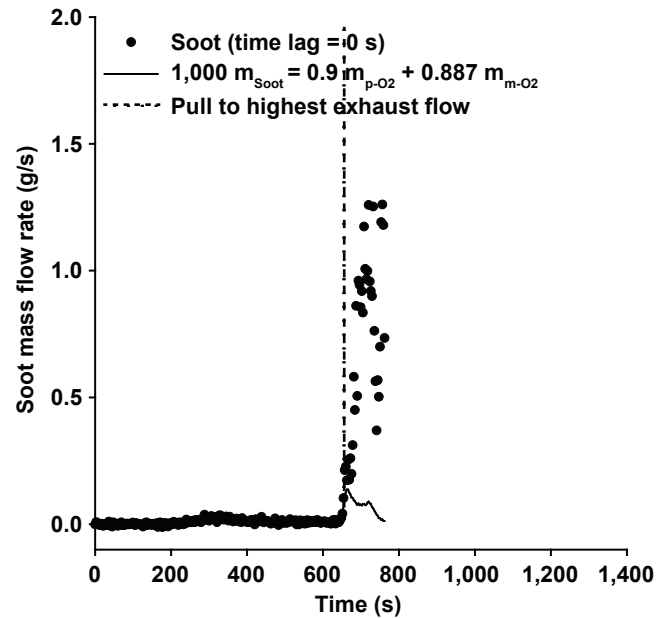


Figure 83. Soot mass flow rate of Douglas Fir plywood (ASTM round robin)—room/corner test 5.

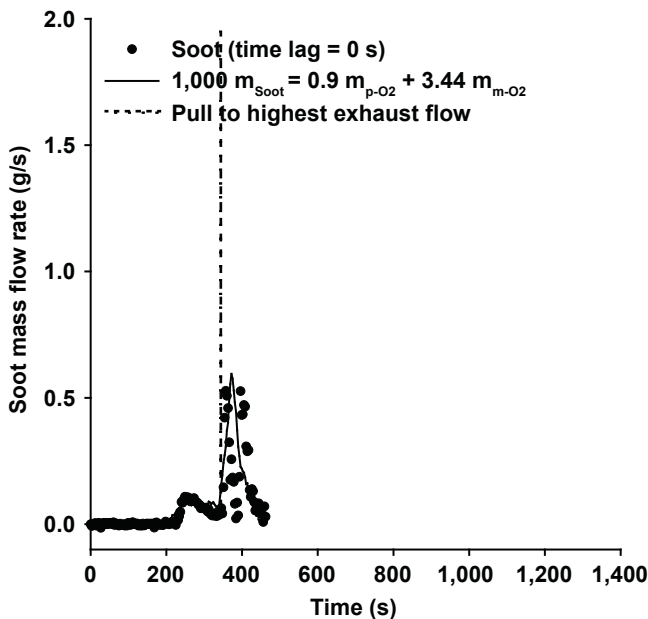


Figure 82. Soot mass flow rate of oak veneer plywood—room/corner test 3.

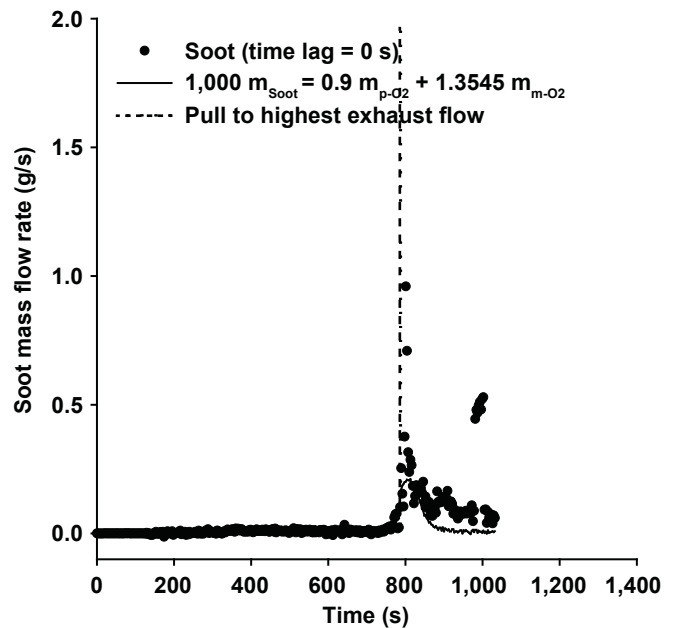


Figure 84. Soot mass flow rate of Douglas Fir plywood (material bank)—room/corner test 9.

determined in the bench-scale cone calorimeter test (ISO 5660) (ISO 1993b). Combustion information has been obtained on production of carbon dioxide, carbon monoxide, and soot during the room/corner tests and on fuel properties, so that for a future work their relative hazard can be assessed and data provided for computational fluid dynamics (CFD) modeling comparison. The effect of flow mixings in various control volumes was shown to greatly affect HRR

calculations and thereby make comparisons between various test facilities on the basis of HRR profiles to be a problem. Furthermore, direct comparisons between fire growth model predictions and processed data based on standard protocols (1993 versions) can lead to misinterpretations. For example, a low-pass exponential digital filter (with 10-s time constant) should be applied to a CFD model's predictions of existing HRR and combustion products profile to

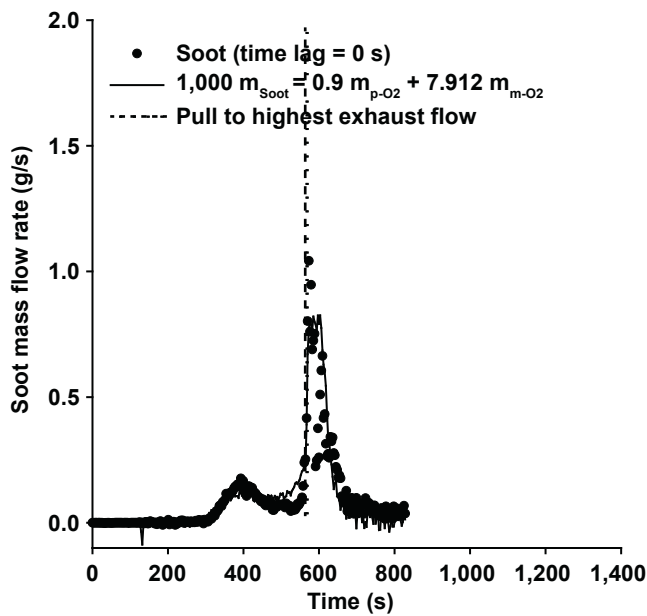


Figure 85. Soot mass flow rate of Southern Pine plywood—room/corner test 10.

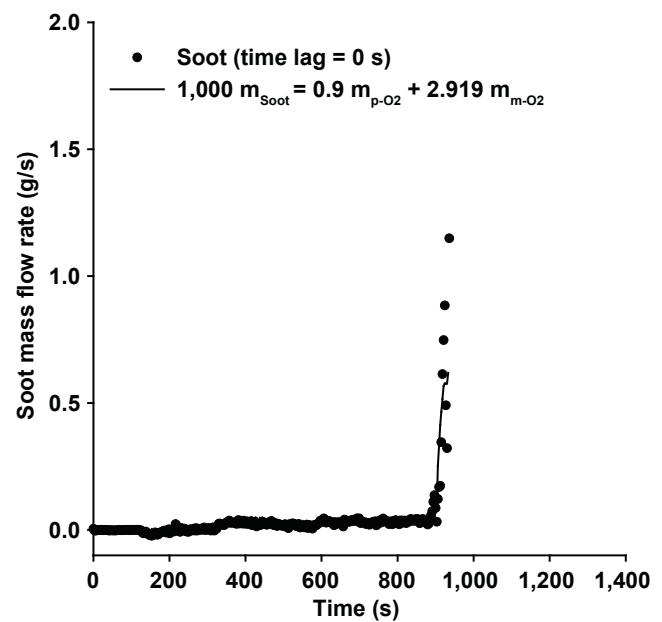


Figure 87. Soot mass flow rate of white spruce lumber—room/corner test 16.

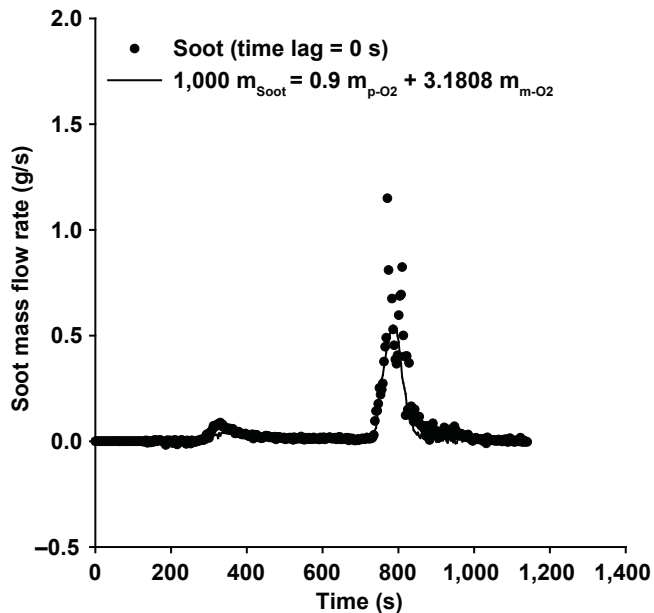


Figure 86. Soot mass flow rate of redwood lumber—room/corner test 14.

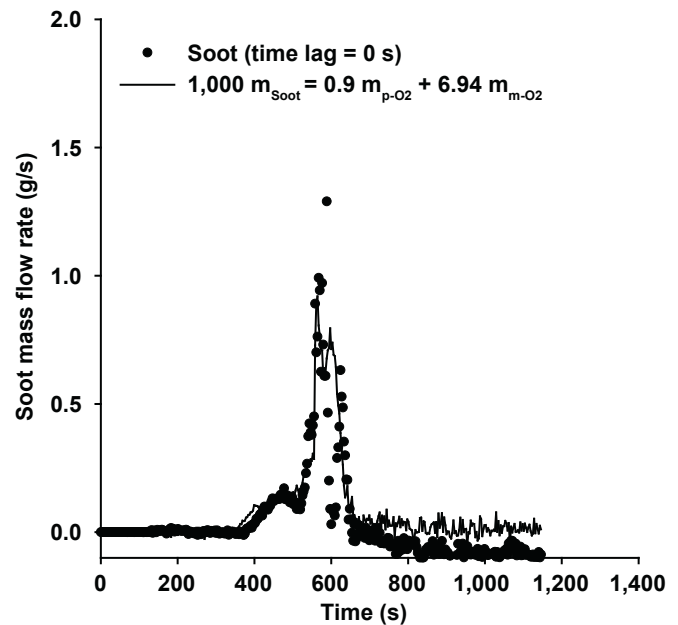


Figure 88. Soot mass flow rate of southern yellow pine flooring lumber—room/corner test 17.

compare directly to our room/corner test results. Our optimized data reduction resulted in consistent HRR and combustion profiles, such that spurious peaks in HRR are avoided when major changes occur and the data are then effectively digitally smoothed. As a result, the processed data is more nimble in detecting real changes, more effective in avoiding false indications of flashovers, and suitable for comparisons with fire growth models.

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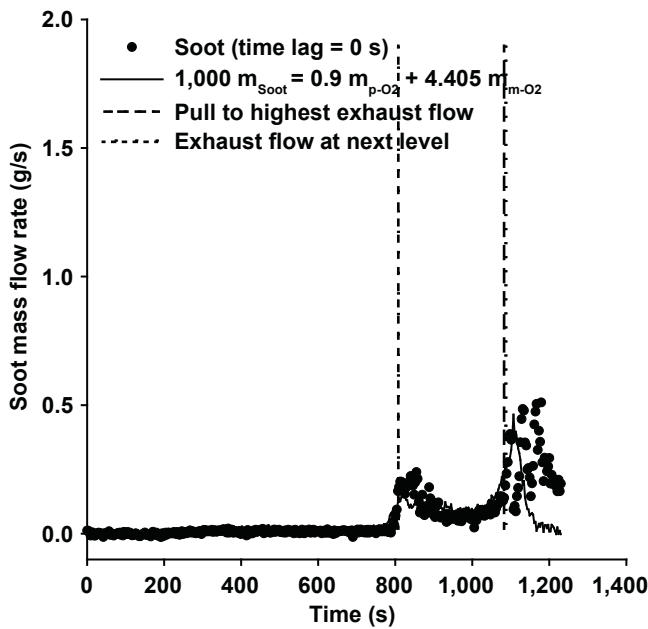


Figure 89. Soot mass flow rate of FRT plywood (from Forintek)—room/corner test 4.

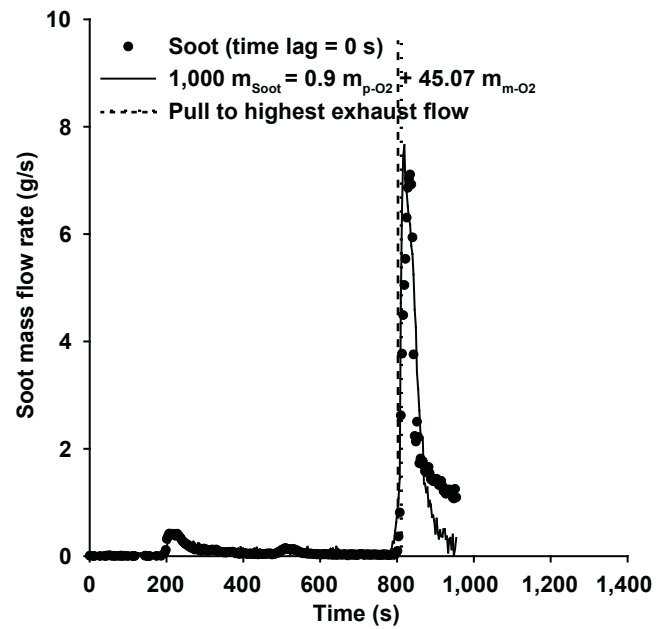


Figure 91. Soot mass flow rate of FRT rigid polyurethane foam—room/corner test 6.

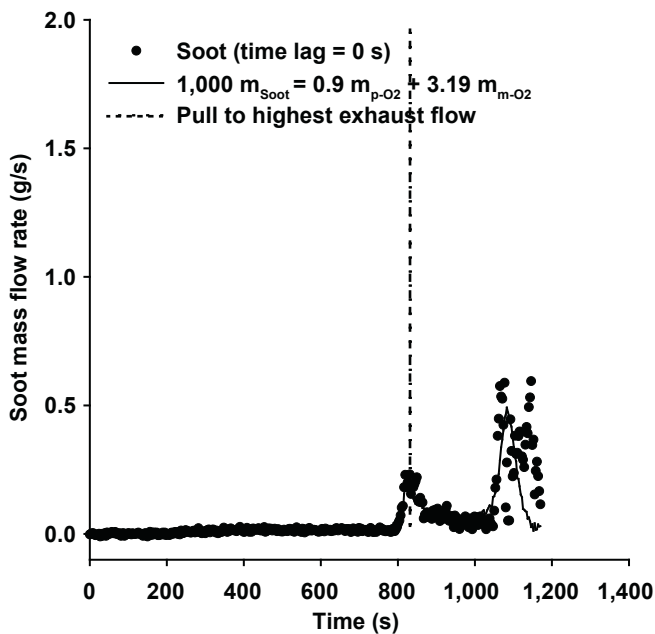


Figure 90. Soot mass flow rate of FRT Douglas Fir plywood (ASTM round robin)—room/corner test 2.

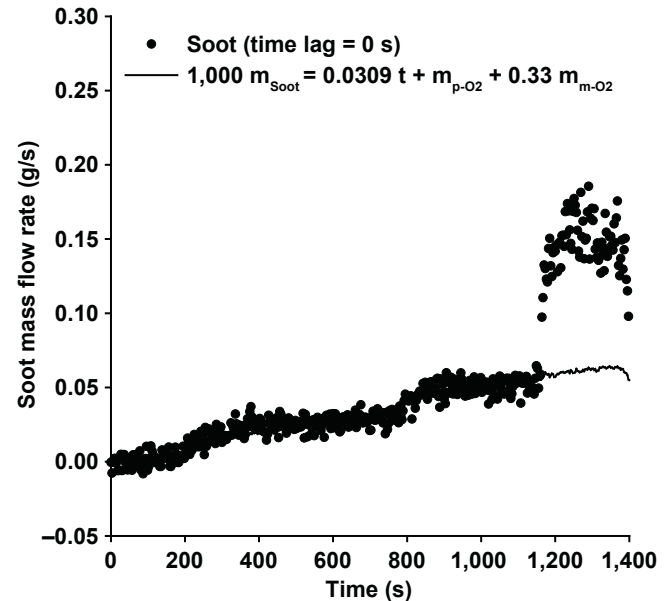


Figure 92. Soot mass flow rate of gypsum board—room/corner test 7.

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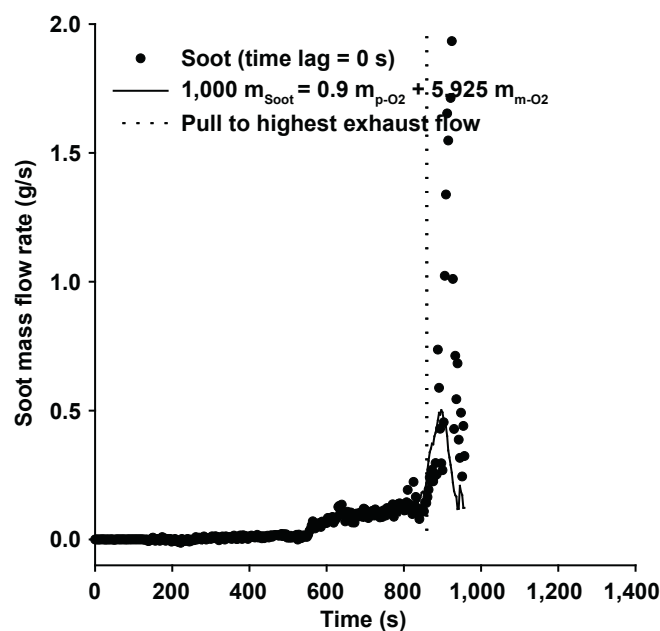


Figure 93. Soot mass flow rate of FRT Southern Pine plywood—room/corner test 8.

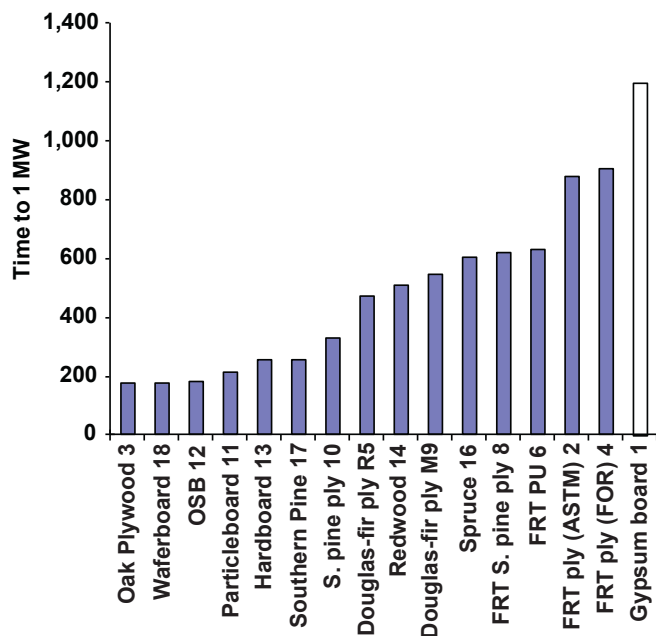


Figure 94. Flashover times for the different materials tested with the 100 kW/300 kW burner program and no test material on the ceiling. Material ID numbers are listed in Tables 1 and 2. Gypsum wallboard did not flashover during 20-min test time.

Borosan, M.L.; Howard, J.B.; Longwell, J.P.; Peters, W.A. 1989. Product yields and kinetics from the vapor phase cracking of wood pyrolysis tars. *AIChE Journal*. 35(1): 120–128.

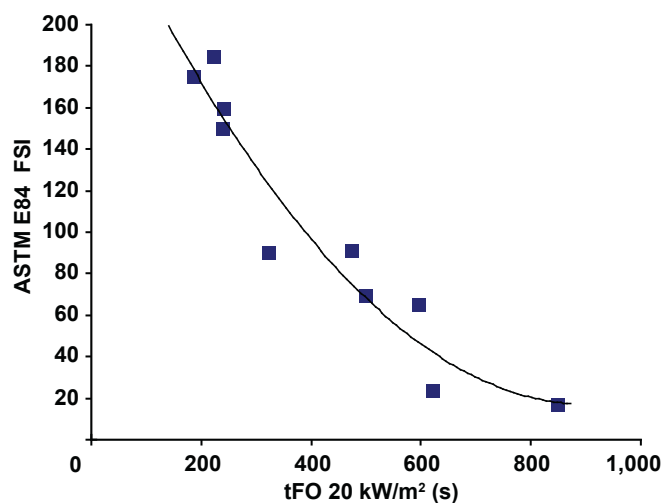


Figure 95. Comparison of the ASTM E 84 flame spread index with the time to flashover measured in room/corner test, 100 kW/300 kW burner output, ceiling unlined.

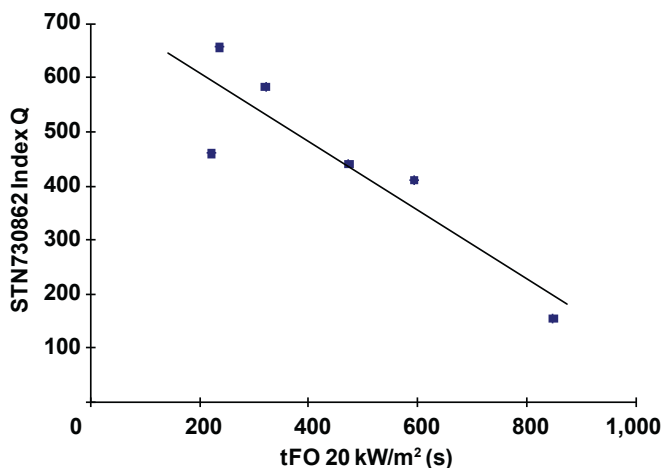


Figure 96. Comparison of the STN 730862 Index Q with the time to flashover measured in room/corner test, 100 kW/300 kW burner output, ceiling unlined.

Dembsey, N.A.; Pagni, P.J.; Williamson, R.B. 1995. Compartment fire near field entrainment measurements. *Fire Safety Journal*. 24: 383–419.

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Table 4—Flashover times in room/corner tests and estimated ASTM E 84 flame spread

Material	Test no.	1 MW flashover time (s)	Flux to floor >20 kW/m ² time (s)	Estimated ASTM E 84 flame spread index
Gypsum wallboard, Type X	1	NFO ^a	NFO	10
FRT Douglas Fir plywood	2	876	849	17
Oak veneer plywood	3	171	174	—
FRT plywood (Forintek)	4	906	873	—
Douglas Fir plywood (ASTM)	5	474	474	91
FRT polyurethane foam	6	630	621	24
Gypsum wallboard, Type X	7	NFO	NFO	10
FRT Southern Pine plywood	8	621	582	—
Douglas Fir plywood (MB)	9	546	531	—
Southern Pine plywood	10	330	321	90
Particleboard	11	216	237	150
Oriented strandboard	12	177	186	175
Hardboard	13	255	222	185
Redwood lumber	14	510	498	70
Gypsum wallboard, Type X	15	NFO	NFO	—
White spruce lumber	16	606	594	65
Southern Pine boards	17	258	240	160
Waferboard	18	174	141	—

^aNFO signifies no flashover.

Table 5—Classes of flammability according to Slovak fire code system

Flammability class	Flammability type	Index Q
A	Non-flammable	$Q \leq 50$
B	Not easy flammable	$50 < Q \leq 150$
C1	Hard-flammable	$150 < Q \leq 300$
C2	Medium-flammable	$300 < Q \leq 600$
C3	Easy-flammable	$600 < Q$

publications/specific_pub.php?posting_id=14012.
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Table 6—Flashover times in room/corner tests and estimated Q index (STN 730862)

Material	Test no.	1 MW flashover time (s)	Flux to floor >20 kW/m ² time (s)	Estimated index <i>Q</i> STN 730862
Gypsum wallboard, Type X	1	NFO ^a	NFO	100
FRT Douglas Fir plywood	2	876	849	155
Oak veneer plywood	3	171	174	—
FRT plywood (Forintek)	4	906	873	—
Douglas Fir plywood (ASTM)	5	474	474	441
FRT polyurethane foam	6	630	621	—
Gypsum wallboard, Type X	7	NFO	NFO	100
FRT Southern Pine plywood	8	621	582	—
Douglas Fir plywood (MB)	9	546	531	—
Southern Pine plywood	10	330	321	583
Particleboard	11	216	237	656
Oriented strandboard	12	177	186	—
Hardboard	13	255	222	460
Redwood lumber	14	510	498	—
Gypsum wallboard, Type X	15	NFO	NFO	—
White spruce lumber	16	606	594	411
Southern Pine boards	17	258	240	—
Waferboard	18	174	141	—

^aNFO signifies no flashover.

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Nomenclature for Appendixes

c	Stoichiometric carbon mass fraction of fuel mass
f	Mass ratio of thermally cracked products to excess fuel
F	Beam splitting/mirror factor
H	Heaviside function
I	Laser luminance
$\dot{m}$	Mass flow rate (g/s)
OD	Optical density
P	Pressure (mbar)
$\dot{q}$	Heat release rate (kW)
r_O	Stoichiometric oxygen mass consumption fraction of fuel mass
S	Any measurement signal
t	Time (s)
T	Temperature (Celsius)
V	Voltage signal (V)
V_i	Volume of zone i (m ³)
Y_l	Species product mass per fuel mass
ρ_i	Air density of zone i (kg/m ³)
β_l	Species product mass per oxygen depletion mass
τ	Time constant (s)
Φ	Global equivalent ratio (GER) for GER > 1, otherwise unity
χ	Concentration of oxygen gas

Subscripts

a	Ambient conditions
b	Ignition burner fuel—propane
c	Compensating photodiode
CO	Carbon monoxide
CO ₂	Carbon dioxide
f	Material fuel mixture, C _{χ} H _{γ} O _{z}
H ₂ O	Water vapor
m	Main photodiode
O ₂	Oxygen gas
r	Response value
s	Smoke—soot
st	Stoichiometric condition
t	True value
THC	Total hydrocarbons, CHW
W	Number of hydrogen atoms in the THC's empirical formula
X	Number of carbon atoms in empirical fuel
Y	Number of hydrogen atoms in empirical fuel
Z	Number of oxygen atoms in empirical fuel

Appendix A—Calibration and Data Processing of Laser Smoke System

One method of processing signals from the photodiodes is to use a closed-circuit design for measuring the electrical current and converting to a voltage signal using a logarithmic amplifier unit. Since the current is proportional to the incident laser beam intensity, the difference in voltages derived from the main and compensate photodiodes are linearly related to optical density along the laser beam. The advantage of this approach is that noises due to ambient temperature variations and extraneous EM sources are low. The standard, ISO 5660-1, has more details on this method. If, however, one does not have an appropriate logarithmic amplifier unit and has instead a DAS board with very high internal impedance, then measuring the voltage of the photodiode open circuit is also an acceptable approach. Extra effort is required to reduce noises in the direct voltage signal from the photodiodes. Grounding of the lead wires reduces noise associated with very low electrical current. During testing with the pilot burner, the increase in air temperature above the test room has caused a gradual decrease of up to 0.3 volts from a nominal 2 volts level in the photodiode direct voltage. The high sensitivity to ambient temperatures is indicated in the manual for the Hamamatsu silicon photodiodes (model S1336-44BQ) (Bridgewater, New Jersey) when measuring the open circuit voltage. Our solution to this problem is to thermally insulate the optical components by loose wrappings with insulation cloth and aluminum foil. This removed the voltage bias from transient half-hour changes in air temperature, but the measurement is still affected by day-to-day changes in ambient temperature. A more permanent approach would be to cover the optical bench in a controlled environmental box.

After achieving a low-noise and low-bias measurement of open-circuit voltages, we investigated the effect of optical filters (or smoke opacity) on the photodiodes response. The Hamamatsu manual indicates the open-circuit voltage is linearly related to the logarithm of the laser luminance and to the ambient temperature as

$$V_{oc,T} = a + b \log(I) - c T_{amb} \quad (A-1)$$

With optical filters used at the laser source (or at the main photodiode), the light intensity to the compensating photodiode is given by

$$I_c = I_o (10^{-OD}) \quad (A-2)$$

Then the light intensity to the main photodiode is given by

$$I_m = F_m I_c \quad (A-3)$$

and where F_m is the beam splitting/mirror factor. Substitution of Equations (A-2) and (A-3) into Equation (A-1) result in the optical density (OD) as function of open-circuit voltages at the main and compensate photodiode given by

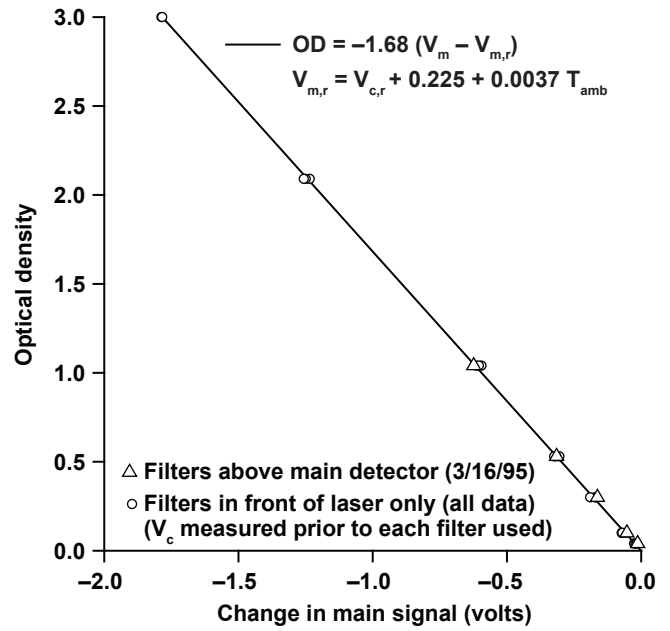


Figure A-1. Correlating optical density with photo detector voltage difference.

$$b_m OD_m = V_{m,r} - V_m \quad (A-4)$$

$$b_c OD_c = V_{c,r} - V_c \quad (A-5)$$

where

$$V_{m,r} = a_m + b_m \log(F_m) + b_m \log(I_o) - c_m T_{amb} \quad (A-6)$$

$$V_{c,r} = a_c + b_c \log(I_o) - c_c T_{amb} \quad (A-7)$$

Note that V_m and V_c are measured with optical filters inserted and $V_{m,r}$ and $V_{c,r}$ are measured just before inserting optical filters. Generally we have found that for any given optical filter (that is, $OD_m = OD_c$ for a filter inserted at the laser source), Equation (A-4) is equal to Equation (A-5) to within <5% error. This means both photodiodes have the same response to changes in laser luminance (that is, $b_m = b_c$) and serves as a quality check on the laser smoke system. Figure A-1 shows a plot of optical density being proportional to the decrease in photodiode voltage or, $1/b_m = 1.68$ for use with Equations (A-4) and (A-5). With the optical filter placed instead within the exhaust duct or more conveniently above the main photodiode (so that $OD_c = 0$), Figure A-1 also shows the same proportionality constant. The usefulness of the compensate photodiode is that as the laser power output varies over time (and even as the baseline voltage of the data acquisition system drifts during the day), we can subtract Equation (A-7) from Equation (A-6) to derive the reference voltage of the main photodiode as

$$V_{m,r} - V_{c,r} = a_{eff} + (c_c - c_m) T_{amb} \quad (A-8)$$

where $V_{c,r} = V_c$ (from $OD_c = 0$ in Eq. (A-5)) at any given time during a burning and

$$a_{\text{eff}} = a_m - a_c + b_m \log(F_m) \quad (\text{A-9})$$

Because we allow at least a few minutes of recording time before activating the burner, the voltage difference, $V_m - V_c$, is essentially a constant over this pre-burner phase. This voltage difference is used to calibrate the value for the right side of Equation (A-8) and serves as another quality check on the laser smoke system. Over a series of tests, where the ambient temperature varies, we calibrated the coefficients in Equation (A-8) as $a_{\text{eff}} = 0.225$ and $c_c - c_m = 0.0037$. This correlation also showed the absolute error in the optical density is equal to or less than 0.01 ($r^2 = 0.9997$) and can be used if for some reason the laser smoke system is not calibrated with optical filters on the day of a test.

Appendix B—Design of Digital Filter Optimized for HRR Calculations

The convolution of the true signal S_t with an exponential system response, such as the gas analysis system (Evans and Breden 1978), is

$$S_r(t) = \int_0^t \frac{1}{\tau} \exp\left(-\frac{(t-\varepsilon)}{\tau}\right) S_t(\varepsilon) d\varepsilon \quad (\text{B-1})$$

If the true signal occurs in step changes as in

$$S_t(t) = \sum [S_t(t_{i+1}) - S_t(t_i)] H(t - t_i) \quad (\text{B-2})$$

where $H(t)$ is the Heaviside function, then the exact solution for the convoluted signal is

$$S_r(t_n) = S_t(t_n) - \sum_{i=-\infty}^n [S_t(t_i) - S_t(t_{i-1})] \exp\left(-\frac{(t_n - t_{i-1})}{\tau}\right) \quad (\text{B-3})$$

For computational purposes, this equation is converted to the recursive formula

$$S_r(t_n) = S_t(t_n) - [S_t(t_n) - S_r(t_{n-1})] \exp\left(-\frac{(t_n - t_{n-1})}{\tau}\right) \quad (\text{B-4})$$

which mimics a first-order low-pass recursive filter. Thus, the noisy data from the bi-directional pressure probe and duct thermocouples are smoothed with Equation (B-4) using $\tau = 10$ s to match the Equation (B-1) convolution by the gas analysis system on the gas analyzer signals. This also means that step changes in pressure and temperature (such as from increasing exhaust flow) as modified by Equation (B-4) would synchronize with “step” changes to the gas concentrations. Mathematically this is easily proven as follows. Examination of the HRR formula shows that it varies as square root of differential pressure, as inverse square root of temperature, and approximately directly with depletion of oxygen concentration. Time differentiation of this HRR relationship result in

$$\frac{d\dot{q}}{dt} = \dot{q} \left(\frac{dP/dt}{2P} - \frac{dT/dt}{2T} - \frac{d\chi/dt}{\chi_\infty - \chi} \right) \quad (\text{B-5})$$

If a step change is imposed by a change in the burner output, or in the exhaust fan speed, then the exponential system response of each measurement is given by the equations

$$\frac{dP}{dt} = \frac{\Delta P}{\tau_p} \exp(-t/\tau_p) \quad (\text{B-6})$$

$$\frac{dT}{dt} = \frac{\Delta T}{\tau_T} \exp(-t/\tau_T) \quad (\text{B-7})$$

$$\frac{d\chi}{dt} = \frac{\Delta \chi}{\tau_\chi} \exp(-t/\tau_\chi) \quad (\text{B-8})$$

If final sizes of a step change in measurements are relatively small compared to their pre-stepping values, then approximate integration of Equation (B-5) for $t > t_i$ is given by

$$\begin{aligned} \dot{q} \approx \dot{q}_i & \left[1 + \frac{\Delta P}{2P_i} - \frac{\Delta T}{2T_i} - \frac{\Delta \chi}{\chi_\infty - \chi_i} - \frac{\Delta P}{2P_i} \exp\left(-\frac{t_i - t}{\tau_p}\right) \right. \\ & \left. + \frac{\Delta T}{2T_i} \exp\left(-\frac{t_i - t}{\tau_T}\right) + \frac{\Delta \chi}{\chi_\infty - \chi_i} \exp\left(-\frac{t_i - t}{\tau_\chi}\right) \right] \end{aligned} \quad (\text{B-9})$$

In most facilities, the time response of the gas analysis system, τ_χ , is typically much larger than time responses of differential pressure and temperature, τ_p and τ_T . Suppose with the mass flow controllers we impose a step change from 100 kW to 300 kW. It is obvious the change in oxygen concentration, $\Delta \chi$, is negative and relatively slow responding because of its relatively large value of τ_χ . What is not so obvious is that the FPL exhaust flow system also has a decrease in differential pressure and increase in exhaust temperature to result in a significant decrease of exhaust volume flow from 0.9 to 0.6 m³/s. With small time responses τ_p and τ_T , Equation (B-9) predicts a spurious negative spike in the HRR profile until the time response of the oxygen depletion finally removes the HRR spike. In a second example, suppose the exhaust flow is manually increased to ensure the capture of all product gases and smoke. The almost instantaneous increase in differential pressure and decrease in temperature coupled with a slow responding increase in oxygen concentration results in a spurious positive HRR spike instead. If we also apply the ISO 9705 procedure of time shifting the gas concentration data (69 s for ISO test 7), then a corresponding modification of Equation (B-9) predicts reversing of the signs of the spurious HRR spikes. These very examples can be seen in Figure B-1 for the Type X gypsum wallboard in ISO test 7.

Our remedy to this “spurious spike” bias problem is to cause all measurement systems to have the same time response, τ . This means the differential pressure and temperatures should be digitally filtered with Equation (B-4) with a time constant of 10 s. Because the signals from the gas analyzers already have a time constant of 10 s, their signals are not digitally filtered. One also obtains a simplification of Equation (B-9) as

$$\begin{aligned} \dot{q} & \approx \dot{q}_i + \Delta \dot{q} (1 - \exp[-(t - t_i)/\tau]) \\ \Delta \dot{q} & = \dot{q}_i \left(\frac{\Delta P}{2P_i} - \frac{\Delta T}{2T_i} - \frac{\Delta \chi}{\chi_\infty - \chi_i} \right) \end{aligned} \quad (\text{B-10})$$

With the change in the burner output given to a good approximation by the term $\Delta \dot{q}$, the HRR calculated using the signals from the mass flow controllers is also digitally filtered with Equation (B-4) using a time constant of 10 s. This should ensure agreement between two different calculations of HRR during step changes in the burner output during the calibration of the ignition burner (see Fig. 5 in the text).

Recalling predictions (Yeager 1986) concerning inaccuracies of the gas analyzers at high volumetric flows, the burner calibration for ISO test 8 included gradual increases in the exhaust flow up to the maximum flow. The result is shown

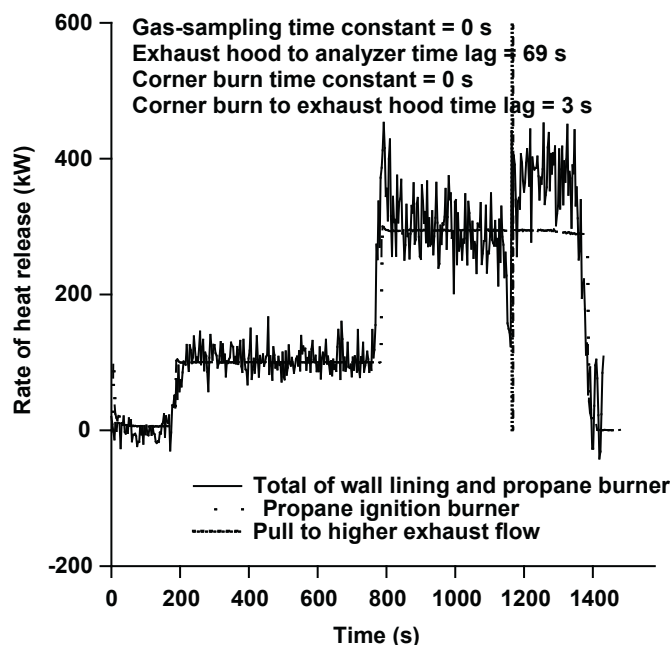


Figure B-1. Results with Type X gypsum wallboard using ISO 9705 procedure.

in Figure B-2, which confirms the increased HRR noise levels as the exhaust flow increases. Merely increasing the time constant to as high as 30 s in the digital filtering of differential pressure and temperature data could not reduce this noise level at all as it could for the low exhaust flows. Being mindful of causing all measurement systems to have the same overall time constant, a second digital filter pass on previously filtered differential pressure, temperature, and mass flow controller data along with a single digital filter pass of the gas analyzers data all with the time constant of 15 s provided the result in Figure B-3. Not only is the HRR profile much smoother, there is no introduction of spurious spikes in the HRR profile. Thus we have confirmed the noises in gas analyzers signals caused the increased level of HRR noise at high exhaust flow rates. This is also where the discrete noises caused by the 12-bit resolution of the DAS board become a limiting factor. These particular noises can be smoothed only with digital filtering techniques, as opposed to electronic signal filtering. Indeed, given the simplicity and superiority of digital filtering, we avoid electronic filtering of any signals (except to remove the very high frequency noise, such as from a 60 Hz power source). The user-defined program in Sigma Plot 2001 (Ashburn, Virginia) spreadsheet software that produced the Figure B-3 results is shown in Table B-1. A similar program using an Excel spreadsheet (Microsoft Corp., Redmond, Washington) can be easily constructed.

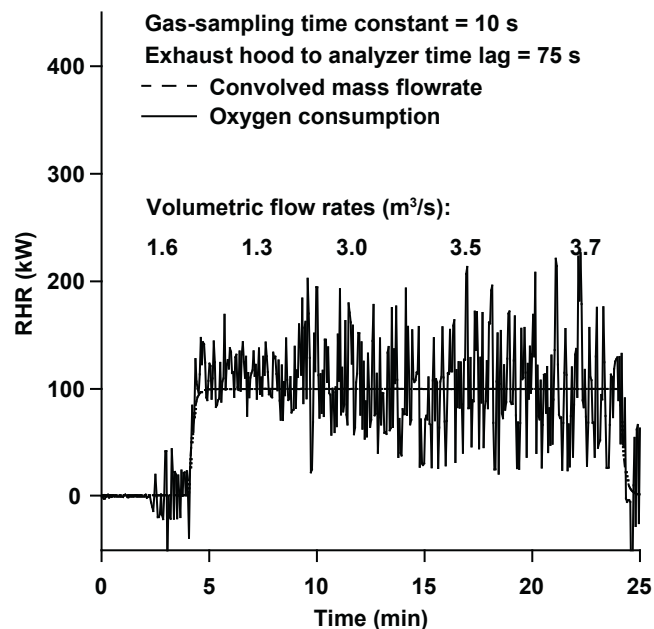


Figure B-2. Effects of increasing exhaust flow on burner's heat release rate (HRR) in test 8.

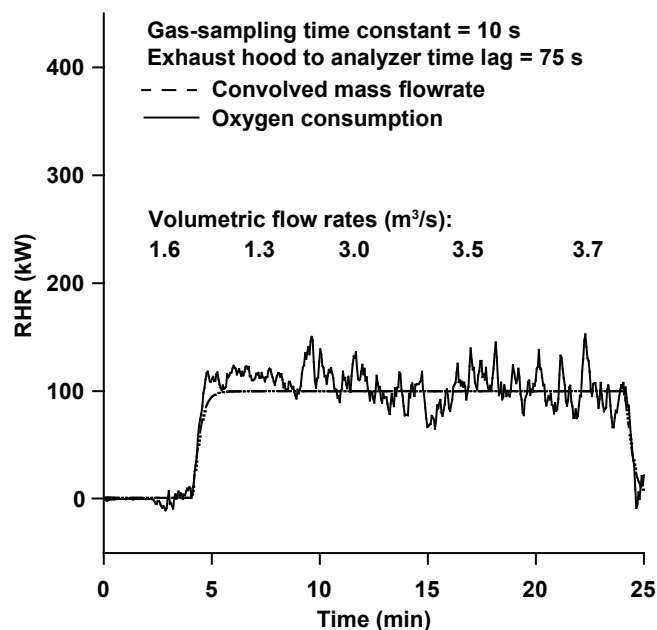


Figure B-3. Second digital filter pass of Figure B-2 data with a 15-s time constant.

Appendix C—Mathematical Model of Creating, Mixing, and Flowing Combustion Products and Soot

A theoretical calculation for mixing in the different gas layers is to consider the conservation of species mass fraction, $Y_{l,i}$, in a well-stirred control volume, V_i , given by

$$\rho_i V_i \dot{Y}_{l,i} = \sum_{j < i} (Y_{l,j} - Y_{l,i}) \dot{m}_{j,i} + Y_{l,b} \dot{m}_{b,i} + Y_{l,f} \dot{m}_{f,i} \quad (C-1)$$

To simplify analysis without loss of generality, assume the ignition burner output at 100 kW or 300 kW establishes the different flow control volumes within the room and the hood. The exiting flows of each control volume also do not circulate back to earlier control volumes. This means the control volume mass, $\rho_i V_i$, and the inflow/outflow mass rate, $\dot{m}_{j,i}$, will be approximately constant, at least while new species are introduced when the room lining is ignited and the fire begins to spread. Let us further assume the species mass production rate from combustion of propane and material fuel, $Y_{l,b} \dot{m}_{b,i} + Y_{l,f} \dot{m}_{f,i}$, and entrainment rate of ambient species, $Y_{l,a} \dot{m}_{a,i}$, are constants within a control volume over some time interval.

The mathematical integration of Equation (C-1) corresponding to (1) fire plume, (2) upper gas layer, and (3) hood mixing zone (with all zones receiving entrainment from the ambient air) as shown in Figure C-1 is given by

$$Y_{l,1}(t) = Y_{l,1}(t_0) \exp\left(\frac{t_0 - t}{\tau_1}\right) + \frac{Y_{l,a} \dot{m}_{a,1} + Y_{l,b} \dot{m}_{b,1} H(t - t_b) + Y_{l,f} \dot{m}_{f,1} H(t - t_f)}{\dot{m}_{1,2}} \left[1 - \exp\left(\frac{t_0 - t}{\tau_1}\right)\right] \quad (C-2)$$

$$Y_{l,2}(t) = Y_{l,1}(t_0) \left(\frac{\rho_1 V_1}{\rho_2 V_2} \left[\frac{\exp((t_0 - t)/\tau_1)}{\tau_1/\tau_2 - 1} + \frac{\exp((t_0 - t)/\tau_2)}{1 - \tau_1/\tau_2} \right] + Y_{l,2}(t_0) \exp\left(\frac{t_0 - t}{\tau_2}\right) + \frac{Y_{l,a} \dot{m}_{a,1} + Y_{l,b} \dot{m}_{b,1} H(t - t_b) + Y_{l,f} \dot{m}_{f,1} H(t - t_f)}{\dot{m}_{2,3}} \right) \times \left[\frac{1 - \exp((t_0 - t)/\tau_1)}{1 - \tau_2/\tau_1} + \frac{1 - \exp((t_0 - t)/\tau_2)}{1 - \tau_1/\tau_2} \right] + \frac{Y_{l,a} \dot{m}_{a,2} + Y_{l,b} \dot{m}_{b,2} H(t - t_b) + Y_{l,f} \dot{m}_{f,2} H(t - t_f)}{\dot{m}_{2,3}} \left[1 - \exp\left(\frac{t_0 - t}{\tau_2}\right)\right] \quad (C-3)$$

$$Y_{l,3}(t) = Y_{l,1}(t_0) \left(\frac{\rho_1 V_1}{\rho_3 V_3} \left[\frac{\exp((t_0 - t)/\tau_1)}{(\tau_2/\tau_1 - 1)(1 - \tau_1/\tau_3)} + \frac{\exp((t_0 - t)/\tau_2)}{(\tau_1/\tau_2 - 1)(1 - \tau_2/\tau_3)} + \frac{\exp((t_0 - t)/\tau_3)}{(\tau_1/\tau_3 - 1)(\tau_2/\tau_3 - 1)} \right] + Y_{l,2}(t_0) \left(\frac{\rho_2 V_2}{\rho_3 V_3} \left[\frac{\exp((t_0 - t)/\tau_2)}{\tau_2/\tau_3 - 1} + \frac{\exp((t_0 - t)/\tau_3)}{1 - \tau_2/\tau_3} \right] + Y_{l,3}(t_0) \exp\left(\frac{t_0 - t}{\tau_3}\right) + \frac{Y_{l,a} \dot{m}_{a,1} + Y_{l,b} \dot{m}_{b,1} H(t - t_b) + Y_{l,f} \dot{m}_{f,1} H(t - t_f)}{\dot{m}_{3,4}} \right) \times \left[\frac{1 - \exp((t_0 - t)/\tau_1)}{\left(\frac{\tau_2}{\tau_1} - 1\right)\left(\frac{\tau_3}{\tau_1} - 1\right)} + \frac{1 - \exp((t_0 - t)/\tau_2)}{\left(\frac{\tau_1}{\tau_2} - 1\right)\left(\frac{\tau_3}{\tau_2} - 1\right)} + \frac{1 - \exp((t_0 - t)/\tau_3)}{\left(\frac{\tau_1}{\tau_3} - 1\right)\left(\frac{\tau_2}{\tau_3} - 1\right)} \right] + \frac{Y_{l,a} \dot{m}_{a,2} + Y_{l,b} \dot{m}_{b,2} H(t - t_b) + Y_{l,f} \dot{m}_{f,2} H(t - t_f)}{\dot{m}_{3,4}} \times \left[\frac{1 - \exp((t_0 - t)/\tau_2)}{1 - \tau_3/\tau_2} + \frac{1 - \exp((t_0 - t)/\tau_3)}{1 - \tau_2/\tau_3} \right] + \frac{Y_{l,a} \dot{m}_{a,3} + Y_{l,b} \dot{m}_{b,3} H(t - t_b) + Y_{l,f} \dot{m}_{f,3} H(t - t_f)}{\dot{m}_{3,4}} \left[1 - \exp\left(\frac{t_0 - t}{\tau_3}\right)\right] \quad (C-4)$$

$$\tau_i \equiv \rho_i V_i / \dot{m}_{i,i+1} \quad (C-5)$$

$$\dot{m}_{i,i+1} = \dot{m}_{i-1,i} + \dot{m}_{a,i} + \dot{m}_{b,i} H(t - t_b) + \dot{m}_{f,i} H(t - t_f) \quad (C-6)$$

We note that these equations have the solution restart capability with the use of the Heaviside function, $H(t)$ that allows the restart time, t_0 , to have any value of interest. The simplest implementation is placing the ignition burner under the hood only. This makes product species concentration in zones 1 and 2 within the room and in the ambient air equal to zero. Equation (C-4) is simplified to the expression

$$Y_{l,3}(t) = \frac{Y_{l,b} \dot{m}_{b,1} H(t - t_0)}{\dot{m}_{3,4}} \left[1 - \exp\left(\frac{t_0 - t}{\tau_3}\right)\right] \quad (C-7)$$

Because the exhaust flow is around 1 m³/s and the mixing volume within the hood is 1 or 2 m³, the time constant of mixing product gases with drawn air via Equation (C-5) is 1 to 2 s. In addition, the mixing reduces all product gases concentrations by the mass ratio of the burner flow rate divided by the exhaust flow rate. We note that oxygen depletion concentration amount is also reduced by the same mass ratio. Even if the exhaust flow varies between 0.5 and 5 m³/s in a test, the time constant for hood mixing remains small compared to other mixing volumes. If we now place the ignition burner within the room, then Equation (C-4) is still simplified, but not as much as Equation (C-7). The time constant of zone 2, the room's upper gas layer, is its mass divided by the mass flow rate exiting the doorway. This exiting mass

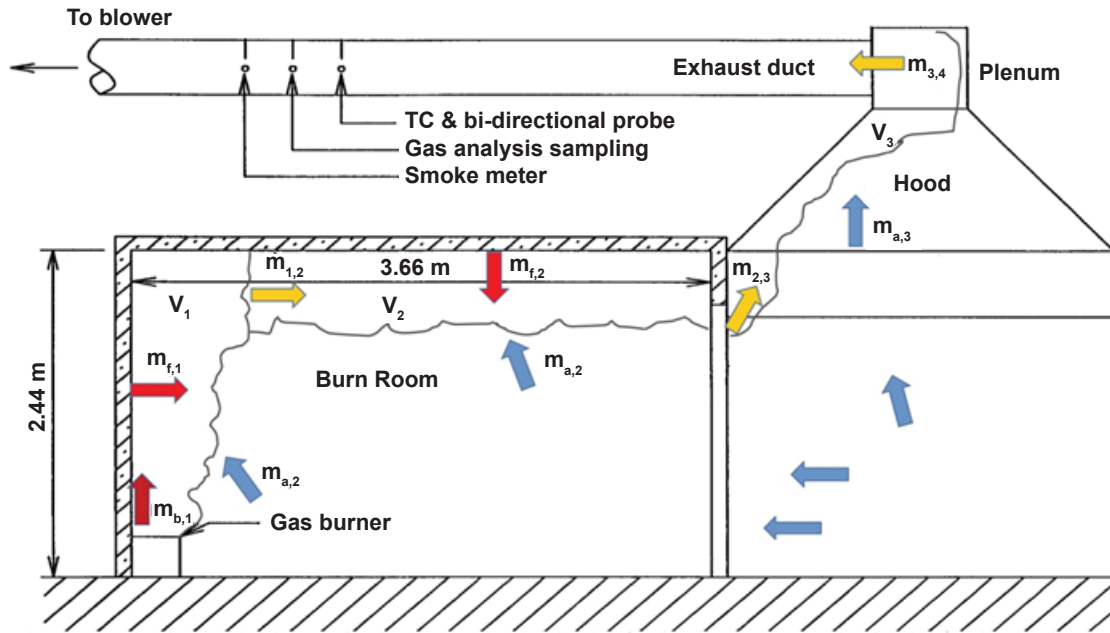


Figure C-1. Schematic for mixing volumes of fire plume, upper gas layer, and hood.

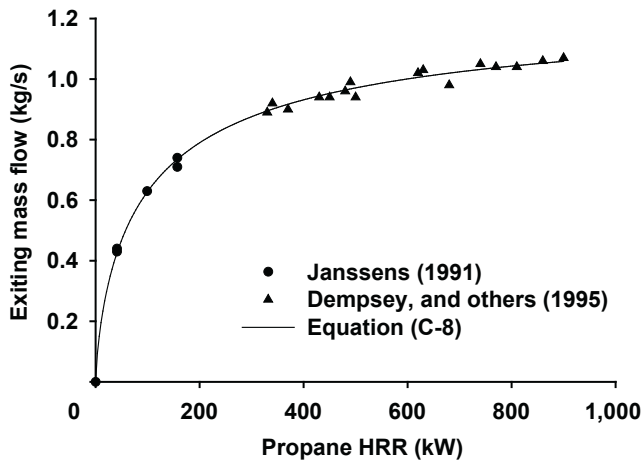


Figure C-2. Correlation of exiting mass flow rate from doorway.

flow rate is a function of HRR and limited by the ventilation factor within the source room, correlated in this paper to the data of Janssens (1991) and Dempsey and others (1995) (shown in Fig. C-2) as the formula

$$\dot{m}_{2,3} = \frac{0.588 \dot{q}^{3/4} A_d \sqrt{H_d}}{14.88 A_d \sqrt{H_d} + \dot{q}^{3/4}} \quad (\text{C-8})$$

Thus, for a door width of 0.76 m and height of 2.0 m, the maximum flow rate is 1.26 kg/s. The mass flow rates corresponding to HRR of 100, 300, and 1,000 kW are 0.63, 0.88, and 1.07 kg/s. We note that our data for the 100-kW burner has the upper gas layer temperature at around 334 K within the heights of 1.02 to 1.55 m and around 583 K within the heights of 1.55 to 2.44 m. The average density of the upper

gas layer is then calculated as 0.77 kg/m^3 , and its volume as $2.44 \times 3.66 \times (2.44 - 1.02) = 12.7 \text{ m}^3$. The time constant of the upper gas layer via Equation (C-5) is $0.77 \text{ kg/m}^3 \times 12.7 \text{ m}^3 / 0.63 \text{ kg/s} = 15.5 \text{ s}$. Combining this with the 2-s mixing time in the hood, one can easily justify the value of 18 s for overall mixing time constant of the three regions.

A similar effect of flow mixing was noted in the gas analysis system. Although air infiltration along the gas lines was eliminated, the processes of removing water in the cold-water trap and the desiccant canister and of removing carbon dioxide/carbon monoxide in yet another canister resulted in three mixing regions where all gas concentrations are incrementally changed before their arrival at the oxygen analyzer. These necessary treatments of the sampled gases are the main contributor to the effective time constant of 10 s for the gas analysis system. With the physical basis for flow-mixing responses established with Equation (C-4), we included these flow-mixing response functions into the analytical modeling of fire growth in the room/corner test in Part II (Dietenberger and others, in press) as well as in the repeated digital filtering of instrumental signals used in our data reduction procedure.

During quasi-steady motions, the fresh mass rate entering the room is about the same as the exiting mass flow rate because the propane mass rate contribution was found to be relatively quite small (Dembsey and others 1995). The maximum possible rate of heat release obtainable in the room, assuming the oxygen consumption principle for an average fuel, is simply given by,

$$\dot{q}_{\max} = 13100 * Y_{\text{a,O}_2} (\dot{m}_{\text{a},1} + \dot{m}_{\text{a},2}) \approx 13100 \times 0.231 \times \dot{m}_{2,3} \quad (\text{C-9})$$

Combining this equation with Equation (C-8), the practical maximum flow rate is 1.18 kg/s, with a corresponding maximum HRR from ambient air within the room of 3.5 MW. At this level of HRR, excess thermally cracked fuel is just spilling out the door and being combusted with the hood's ambient air entrainment. If the fuel is just enough to generate the HRR of 3.5 MW and the hood exhaust flow is no greater than 1.18 kg/s, then the global equivalency ratio (GER) is unity for the room/hood as a whole, although there are local variations. Initial flaming outside the doorway at around 1 MW, however, appears because the exiting fuel/air mixture from the upper gas layer is finishing its combustion, as opposed to the process of the excess fuel being combusted with the hood's fresh drawn air, $\dot{m}_{a,3}$. This also means that $GER = \dot{q}/\dot{q}_{max} = 1 \text{ MW}/3.17 \text{ MW} = 0.32$, making flashover an overventilated combustion event. When the total HRR corresponds to just the burner at 100 or 300 kW, the combustion of propane defines the fire plume as the first zone. Zones 2 and 3 are then just mixing regions that include air entrainments, which simplifies Equation (C-4) somewhat. Therefore, as the test progresses to flashover and beyond, the full complexity of Equation (C-4) is involved in the overall time constant of gas mixings. This raises the serious question of how to separate the propane combustion product gases from the material combustion gases in our analysis for material properties. That is, the propane product gases are mixed in all three zones (thereby the time constant of about 18 s is appropriate for propane), whereas the material combustion product gases have a shorter overall time constant for mixing. This dilemma is resolved by noting that production of combustion gases is accompanied by oxygen depletion, so that the equivalent expression to Equations (C-2) to (C-4) is

$$\dot{m}_{l,i} = \Delta Y_{l,i}(t) \dot{m}_{l,i+1} = \left(\frac{Y_{l,b}}{r_{O_2,b}} \right) \sum_{j \leq i} \Delta \dot{m}_{O_2,b,j}(t) + \left(\frac{Y_{l,f}}{r_{O_2,f}} \right) \sum_{j \leq i} \Delta \dot{m}_{O_2,f,j}(t) \quad (C-10)$$

All combustion yields and the oxygen consumption per fuel mass are assumed to be unchanged in going from one zone to the next. Expressed in this form, the total mass production rate of any combustion product is separately proportional to total oxygen mass consumption rates of the ignition burner and material. The flow mixing effect in various zones is a "built-in" factor of Equation (C-10), allowing the experimenter to overlook various mixing times. It would be worthwhile to check the validity of Equation (C-10) over a wide range of HRRs, including the post-flashover regime where one can expect the GER to go as high as unity and beyond. To show the importance of Equation (C-10), we next examine stoichiometric values of carbon dioxide, water vapor, and oxygen consumption for propane (C_3H_8) and paper (cellulose, $C_6H_{10}O_5$) as follows. For complete combustion of propane, we have

$$\beta_{H_2O,b} = \left(\frac{Y_{H_2O,b}}{r_{O_2,b}} \right) = \left(\frac{18/11}{40/11} \right) = 0.45 \quad (C-11)$$

and

$$\beta_{CO_2,b} = \left(\frac{Y_{CO_2,b}}{r_{O_2,b}} \right) = \left(\frac{33/11}{40/11} \right) = 0.825 \quad (C-12)$$

For complete combustion of paper, we have

$$\beta_{H_2O,f} = \left(\frac{Y_{H_2O,f}}{r_{O_2,f}} \right) = \left(\frac{15/27}{32/27} \right) = 0.46875 \quad (C-13)$$

and

$$\beta_{CO_2,f} = \left(\frac{Y_{CO_2,f}}{r_{O_2,f}} \right) = \left(\frac{44/27}{32/27} \right) = 1.1852 \quad (C-14)$$

On the basis of water vapor production per oxygen consumption, there is not much difference between propane and paper. Besides that, the interpretation of water vapor data is complicated by the presence of moisture content in the specimen and from the use of the water sprinkler after flashover. On the basis of carbon dioxide production per oxygen consumption, there is a significant measurable difference between propane and paper values. In the case of incomplete combustion, carbon monoxide and smoke will be observed and compared on the basis of Equation (C-10), although the presence of moisture has some effects. Thus, for data presentation, each combustion product will be plotted as its mass production rate versus time. Their mass flow rate measurements are described by Janssens and Parker (1992) and are adopted for this work. The global combustion properties will be derived from the fit of Equation (C-10) to the data for each species, including the soot. The soot concentration is derived from the coefficient of light extinction in the control volume i using the fundamental relationship of additivity of extinction coefficients from multiple sources as

$$k_i = \sum_{j \leq i} k_{j,i} = \sum_{j \leq i} \sigma_{s,j} \rho_{s,j,i} = \sum_{j \leq i} \sigma_{s,j} Y_{s,j,i} \rho_i \quad (C-15)$$

Investigation of smoke by Babrauskas and Mulholland (1987) with the cone calorimeter showed that the specific extinction area, σ_s , as an intrinsic property of flaming smoke was essentially a constant for a given material regardless of flux and orientation. Using a more precise measurement apparatus, Mulholland and Choi (1998) demonstrated the nearly universal value for specific extinction area as 8.3 m²/g for the post-flame smoke produced from overventilated fires and measured with a laser using a red wavelength of 632.8 nm. Adjustment for other light wavelengths, including equivalent values for white light or the dominant wavelength of a radiating body, is to multiply the value of specific extinction area by the term $(632.8/\lambda)$. In a classic study with composite materials (formed with different mass proportions of homogeneous materials), Ou and Seader (1978) obtained specific extinction area values of 7.6 m²/g for flaming conditions and 4.4 m²/g for smoldering

conditions. (Note that the conversion factor of $\ln(10)$ was applied to Ou and Seader data as well as to the OD values of our room-test laser measurement system.) They were also perhaps the first to show the additivity relationship of Equation (C-15) through the variation in the contents of the composite materials. That smoldering conditions require oxidizing flow through a charring material means that the room-test fire scenario can be considered as flaming, whereas that of pre-ignition and after-glow in the cone calorimeter test are considered as smoldering conditions. The simplification to Equation (C-15) for each control volume is obtained (for room tests and where initial and ambient smoke concentrations are zero) as

$$k_i = \sigma_s \rho_i \Delta Y_{s,i}(t) \quad (\text{C-16})$$

The mass flow rate of soot exiting each control volume (corresponding to the left side of Equation (C-10)) is therefore simply derived from Equation (C-16) as

$$\Delta Y_{s,i}(t) \dot{m}_{i,i+1} = (k_i \dot{m}_{i,i+1} / \rho_i) / \sigma_s = k_i \dot{V}_i / \sigma_s = \text{SPR}_i / \sigma_s \quad (\text{C-17})$$

where SPR is smoke production rate. Calculating the soot mass flow rate in this form allows the use of Equation (C-10) and thus obtains beta coefficients separately for soot production of propane and the specimen. This approach is more fundamental and less error prone than deriving values for the “smoke” specific extinction area calculated as the ratio SPR/MLR. This is because the mass loss rate measurement, MLR, is generally not available for wall linings, and one would have to use the heat of combustion data from the cone calorimeter tests corresponding to specific room test conditions (Tran and Janssens 1991). Suppose the specific extinction area for certain materials has values different than $8.3 \text{ m}^2/\text{g}$. Then Equation (C-17) would not be appropriate to use, and instead Equation (C-15) would be multiplied by the volumetric flow rate, $\dot{V}_i = \dot{m}_{i,i+1} / \rho_i$, which would permit use of just the SPR data. We will also realize the simplification offered by Equation (C-10) would not be permitted and instead use each of the soot mass flow rate components due to various sources as determined in Equations (C-2) to (C-4). To better sort out the soot sources in this situation, laser extinction measurements ought to be measured at positions corresponding to the exiting mass flow rates, $\dot{m}_{i,i+1}$ of each control volume. Suppose in a different situation the soot beta coefficient for the material lining varies with time or with some other time-changing condition. Then by subtracting out the pre-calibrated propane contributions, we can plot this time dependency for the material lining and perhaps correlate with some combustion condition, such as the global equivalent ratio.

We should note that the volumetric flow rate computed for the smoke production rate as given in annex F of ISO 9705 requires a correction. According to Janssens and Parker

(1992), mass flow rate at the bi-directional probe is correctly calculated with the formula

$$\dot{m}_{\text{ex}} = 26.54 (A k_t / k_p) (\Delta p_{\text{ex}} / T_{\text{ex}})^{1/2} = \rho_{298} \dot{V}_{298} \quad (\text{C-18})$$

Because the air density at 298 K at atmospheric pressure has the value 1.184 kg/m^3 , Equation (C-18) is essentially equation F.2 in the annex F of ISO 9705. Indeed, Equation (C-18) provides the needed link to show equivalent formulations of HRR between that of ISO 9705 and that of Janssens and Parker (1992). With inner diameter of the circular exhaust pipe measured at 0.4059 m, its cross section area, A , is 0.1294 m^2 . Along with $k_t = 0.915$ and $k_p = 1.08$, Equation (C-18) is simplified to $\dot{V}_{298} = 2.457 (\Delta p_{\text{ex}} / T_{\text{ex}})^{1/2}$. The laser extinction measurement is located just a short distance (0.6 m) downstream from the bi-directional probe, which means the smoke volumetric flow is to a very good approximation given by

$$\begin{aligned} \dot{V}_s &\cong \dot{V}_{\text{ex}} \equiv \dot{m}_{\text{ex}} / \rho_{\text{ex}} \equiv (\rho_{298} / \rho_{\text{ex}}) \dot{V}_{298} \\ &\equiv (1013.25 / p_{\text{ex}}) (T_{\text{ex}} / 298) \dot{V}_{298} \end{aligned} \quad (\text{C-19})$$

The small correction to ISO 9705 for smoke volumetric flow is to include actual ambient pressure along with the exhaust temperature in the manner given by Equation (C-19). One other factor that should not be overlooked is the principle of causing all measurement systems to have the same time constant, τ . So if the oxygen depletion measurement has a time constant of 10 s, then all measurement components for computing SPR_i in Equation (C-17) should be made to have a time constant of 10 s. The response of the photodiode voltages as a function of time after quick insertion of various optical filters indicates a time response of approximately 10 s (or 20 s to reach 90% of steady value). Therefore the extinction coefficient data is not digitally filtered, whereas the differential pressure and temperature data are digitally filtered with a time constant of 10 s.

In Table C-1 is shown our Sigma Plot spreadsheet program (Ashburn, Virginia) for analysis of ISO test 7 data as described in the text, including the two pass digital filtering of the ignition burner signal with time constants of 10 s and 18 s. A similar program can be easily written for other spreadsheets, such as Excel. Actual data and spreadsheet programs for all 18 tests are available from the authors.

Table C-1—Sigma Plot spreadsheet program for ISO 9705 room/corner no. 7 test data

```

jsv5D.,
Pamb=981 ;ambient pressure
tau1=10 ;time constant for the sample gas train
tau2=18 ;(small value for burner under hood, 18 sec for most room tests))
mn=51 ;conversion ratio from new MFC voltage to propane HRR
mno=105 ; conversion ratio from combined MFC voltage to propane HRR
is=17 ;gas analyzer time shift = 3*is seconds, smaller value in earlier tests)
ishift=1 ;corner burn time lag = 3*ishift (set to zero for burner under hood)
El=17200. ;heat release per volume of oxygen consumed (16800 for propane)
Hcomb=cell(6,3) ;heat of combustion for volatiles (kJ/g), for propane it's 46.4 kJ/g
mflux2 = 48.5 ;conversion from mV to kW/m^2 for fluxmeter 1 (serial # = 87892)
mflux1 = 57.6 ;conversion from mV to kW/m^2 for fluxmeter 2 (serial # = 87891)
cell(7,2)=mean(col(3,is,35+is)) ;reference voltage for ambient o2 (exhaust fan is on)
cell(8,2)=mean(col(6,is,35+is)) ;reference voltage for ambient co2 (exhaust fan is on)
cell(9,2)=mean(col(5,is,35+is)) ;reference voltage for ambient co (exhaust fan is on)
cell(10,2)=cell(8,6) ;reference for "zero" differential pressure (exhaust fan is off)
mo2=(0.20946-0.1022)/(cell(7,1)-cell(7,3)) ; o2 soft spanning ambient-reference
mco2=(0.00033-0.1014)/(cell(8,1)-cell(8,3)) ; co2 soft spanning ambient-reference
mco=(0.0-0.0489)/(cell(9,1)-cell(9,3)) ; co soft spanning ambient-reference
cell(15,2)=mean(col(15,7,47))-mean(col(14,7,47)) ;reference difference for "zero" smoke
cell(31,7)=0.5*(cell(20,7)+cell(22,7)) ;average temperature at bidirectional probe, C
cell(32,7)=0.20946+mo2*(cell(3,7+is)-cell(7,2)) ;o2 concentration
cell(33,7)=0.00033+mco2*(cell(6,7+is)-cell(8,2)) ;co2 concentration
cell(34,7)=mco*(cell(5,7+is)-cell(9,2)) ;co concentration
cell(35,7) = 248.84*(cell(8,7)-cell(10,2)) ;differential pressure
for iii=8+is to size(col(24)) do ;filter with time constant tau1 and time shift (3*is)
ii=iii-is
term1=exp((cell(24,ii-1)-cell(24,ii))/tau1)
cell(31,ii)=0.5*(cell(20,ii)+cell(22,ii))*(1-term1)+cell(31,ii-1)*term1 ;temp smoothing
cell(32,ii)=0.20946+mo2*(cell(3,ii+is)-cell(7,2)) ; time shifting of o2 concentration
cell(33,ii)=0.00033+mco2*(cell(6,ii+is)-cell(8,2)) ;time shifting of co2 concentration
cell(34,ii)=mco*(cell(5,ii+is)-cell(9,2)) ; time shifting of co concentration
cell(35,ii)=248.84*(cell(8,ii)-cell(10,2))*(1-term1)+cell(35,ii-1)*term1 ;presssmoothing
cell(35,ii-1)=max({cell(35,ii-1),0.0}) ;ensure non-negative pressure differential
end for
col(36)=2.4569*sqrt(col(35)/(col(31)+273.15)) ;Volume rate formula
col(37)=(0.20946*(1-col(33))-col(32)*(1-0.00033))/(0.20946*(1-col(33)-col(32))) ;phi
col(37)=16800*col(36)*0.20946*(1-0.00495)*col(37)/(0.105*col(37)+1);HRR(propane constant)
col(39)=(-1.692*(col(15)-col(14))-
cell(15,2))*ln(10)/0.406)*col(36)*((col(31)+273.15)/298)*(1013.25/Pamb) ;k*Vdots m^2/s)
col(42)=(col(37)/12.76)*(44/32)*(col(33)*(1-0.20946)-0.00033*(1-col(32)-col(34)))/(0.20946*(1-
col(33)-col(34))-col(32)*(1-0.00033)) ;CO2 mass rate
col(43)=(col(37)/12.76)*(28/32)*(col(34)*(1-0.20946-0.00033)-0.0)/(0.20946*(1-col(33)-col(34))-
col(32)*(1-0.00033)) ;CO mass rate
col(44)=col(39)/8.3 ;post-flame soot mass rate
cell(38,7+ishift)=(mno-mn)*cell(17,7)+mn*cell(19,7) ;HRR of mass flow controller
for k = 8+ishift to size(col(24)) do ;filter with time constant tau2 & shift by ishift*3
i=k-ishift
term2=exp((cell(24,i-1)-cell(24,i))/tau2)
cell(38,i+ishift)=(mno-mn)*cell(17,i)+mn*cell(19,i)*(1-term2)+cell(38,i+ishift-1)*term2
end for
for jj = 8+ishift to size(col(24)) do ;convolute again with time constant tau1
j=jj-ishift
term3=exp((cell(24,j-1)-cell(24,j))/tau1)
cell(38,jj)=cell(38,jj)*(1-term3)+cell(38,jj-1)*term3
qdiff=cell(37,jj)-cell(38,jj)
cell(45,jj)=cell(38,jj)/12.76 ;filtered propane oxygen mass consumption rate
cell(46,jj)=qdiff/12.76 ;filtered material oxygen mass consumption rate (recall we used propane
constant to get HRR)
cell(37,jj)=if(qdiff>0,(El/16800)*qdiff+cell(38,jj),cell(37,jj)) ;adjust total HRR for volatile
and propane portions
end for
for jjj = 7 to size(col(24)) do
cell(27, jjj)=0.5*(mflux1*cell(1, jjj)+mflux2*cell(2, jjj)) ;radiant flux to floor (kW/m^2)
cell(28, jjj)=(mno-mn)*cell(17, jjj)+mn*cell(19, jjj))/46.4 ;propane mass flow rate (g/s)
cell(29, jjj)=(cell(37, jjj+ishift)-cell(38, jjj+ishift))/Hcomb ;volatile mass flowrate(g/s)
cell(30, jjj)=cell(24, jjj) ;time (seconds)
end for

```

Appendix D—Combustion Products Development

As the hydrocarbon or wood volatile fuel is oxidized, the combustion products are water vapor and carbon dioxide in a complete reaction. For an incomplete reaction, the additional combustion products are primarily carbon monoxide and soot. Although light hydrocarbons may be prominent as part of the fuel, especially during the thermally cracked stage, they are negligible after the incomplete combustion reaction. In the current room/corner tests, we have only available the measurements of oxygen consumption, carbon dioxide, carbon monoxide, and smoke concentrations in the exhaust flow. The water vapor concentration was not measured in the current test series, whereas it was measured in the previous FPL work (Tran and Janssens 1991).

In this work, we introduce the calculation of fuel hydration value (Eq. (D-3)), which is molar fuel carbon amount per molar stoichiometric combustion oxygen, to ensure that the carbon content of wood volatiles in the room/corner test is replicated at the bench scale, such as in the cone calorimeter (ISO 5660). That is, the boundary conditions in the bench tests, such as heat flux levels or material backings, need to be adequate to provide fuel hydration values that are similar to that calculated in the room/corner tests (to be shown in Part II (Dietenberger and others, in press)) and independent of the level of combustion achieved at different scales. An important problem is that the combustion in room/corner tests is usually incomplete compared to the nearly complete combustion in the cone calorimeter test. Therefore it is useful to derive the molar fractions of the fuel's carbon that end up in soot, carbon monoxide, and carbon dioxide at the scale of the room/corner tests. This information is preferred over that of providing yields of soot, CO, and CO₂ (defined as ratios of their mass to the volatile mass) because the mass of volatiles varies considerably with the mass of water vapor component as a result of drying and charring of the specimen. Indeed, in Appendix C we provide the argument that to overcome the flow mixing complications, the properties should be obtained initially on the basis of species product mass per oxygen depletion mass, β_i , rather than on the basis of product mass per fuel mass, Y_i . We begin this analysis by noting that for any incomplete hot combustion, the dynamic mass flow rate of a fuel mixture with empirical formula $C_xH_yO_zN_vS_w$ has six equivalent calculations (which can be directly compared with measured fuel mass rates) as

$$\begin{aligned}\dot{m}_{\text{fuel}} &= \left(\frac{12X + Y + 16Z + 14U + 38V}{32(X + V) + 8Y - 16Z} \right) \\ &\quad \times \left(\Delta\dot{m}_{\text{O}_2} + \frac{32\dot{m}_s}{12} + \frac{16\dot{m}_{\text{CO}}}{28} + \frac{(32 + 8W)\dot{m}_{\text{CHW}}}{12 + W} \right) \quad (\text{D-1}) \\ &= \left(\frac{12X + Y + 16Z + 14U + 38V}{44X} \right) \\ &\quad \times \left(\dot{m}_{\text{CO}_2} + \frac{44\dot{m}_s}{12} + \frac{44\dot{m}_{\text{CO}}}{28} + \frac{44\dot{m}_{\text{CHW}}}{12 + W} \right)\end{aligned}$$

$$\begin{aligned}&= \frac{12X + Y + 16Z + 14U + 38V}{9Y} \left(\Delta\dot{m}_{\text{H}_2\text{O}} + \frac{9W\dot{m}_{\text{CHW}}}{12 + W} \right) \\ &= \frac{12X + Y + 16Z + 14U + 38V}{14U} \Delta\dot{m}_{\text{N}_2} \\ &= \frac{12X + Y + 16Z + 14U + 38V}{70V} \dot{m}_{\text{SO}_2} \\ &= \dot{m}_{\text{CO}_2} + \dot{m}_s + \dot{m}_{\text{CO}} + \Delta\dot{m}_{\text{H}_2\text{O}} + \dot{m}_{\text{CHW}} + \Delta\dot{m}_{\text{N}_2} + \dot{m}_{\text{SO}_2} - \Delta\dot{m}_{\text{O}_2}\end{aligned}$$

This mass balance for incomplete combustion assumes all of (1) fuel's carbon is accounted for in the carbon dioxide, carbon monoxide, soot, and THC measurements, (2) fuel's hydrogen is accounted for in water vapor and THC measurements, and (3) fuel's oxygen is converted to become part of carbon dioxide, carbon monoxide, water vapor, and sulfur dioxide. It is seen that with a known fuel any one of the six calculations can be used and one merely selects one with the least amount of experimental measurement errors or inert gas contaminations from non-fuel sources. The validity of Equation (D-1) for the room tests is determined as follows. Analysis of three tests with only Type X gypsum wallboard as wall lining provides calibrated propane coefficients from fitting the following equation (see Eq. (C-10) in App. C),

$$\dot{m}_{i,3}(t) = \beta_{i,b} \sum_{j \leq 3} \Delta\dot{m}_{\text{O}_2,b,j}(t) + \beta_{i,f} \sum_{j \leq 3} \Delta\dot{m}_{\text{O}_2,f,j}(t) \quad (\text{D-2})$$

to soot and CO mass flow rate data as the values, $\beta_{s,b} = 0.0009$ and $\beta_{\text{CO},b} = 0.02$. In overventilated conditions (HRR < 3.5 MW, as derived in App. C), the THCs are miniscule, thereby making the THC betas equal to zero herein for all tests. Note the second half of Equation (D-2) pertains to the paper facing of the gypsum wallboard. The use of Equation (D-1) (convert to corresponding betas by dividing each mass rate term by the oxygen depletion mass rate) for the combusting propane fuel C₃H₈ provides the beta coefficients for carbon dioxide, water vapor, and fuel as $\beta_{\text{CO}_2,b} = 0.8017$, $\beta_{\text{H}_2\text{O},b} = 0.4562$, and $\beta_{\text{fuel},b} = 0.2788$. These values are slightly different than the complete combustion values provided in Appendix C. Using these incomplete combustion values for propane, it is simple to show a change of net heat of combustion of -0.16 kJ/g (Dietenberger 2002a), which is -1.3% of the stoichiometric value of 12.76 kJ/g. A loss of only 1.3% of the heat of combustion for propane's incomplete combustion would confirm its use as a calibration fuel in the room tests. There is sufficient sensitivity in our data processing of ISO tests 1, 7, and 15 to measure for the thin paper C₆H₁₀O₅ covering on gypsum wallboard the values of coefficients as, $\beta_{s,f} = 0.00034$, and $\beta_{\text{CO},f} = 0.03$, which upon using Equation (D-1) we derived the coefficients $\beta_{\text{CO}_2,f} = 1.351$, $\beta_{\text{H}_2\text{O},f} = 0.4772$, and $\beta_{\text{fuel},f} = 0.859$. These values correspond to decreasing net heat of combustion by 0.1 kJ/g, which is -0.7% of the stoichiometric value of 15.4 kJ/g. Because the betas of carbon dioxide for both propane and paper are "predictions," their values are inserted into Equation (D-2) to predict CO₂ mass flow rate data from tests 1, 7,

and 15. Close agreement was obtained ($r^2 = 0.99$). Equation (D-1) is validated as a result, at least between oxygen depletion and carbon dioxide production during incomplete combustion in the room/corner test. Note that the mass loss rate calculated is that of the paper only, although the gypsum wallboard does provide considerable mass production rate of water vapor to dilute the paper volatiles and considerably lower the heat of combustion for the wall lining.

The other material linings cannot be analyzed to this level of detail because elemental compositions of their volatiles are not generally known. Consider a volatile composition of fuel (tar), water vapor, and carbon dioxide, $C_XH_YO_ZN_U S_V + mH_2O + nCO_2$. The non-condensable volatile gases such as CO_2 , CO , H_2 , CH_4 , C_2H_2 , C_2H_4 , and C_2H_6 are the byproducts of thermal cracking of primary tar at high temperatures around, 450 °C or higher (Boroson and others 1989). Gases with higher molecular weight are considered part of the tar that can be initially trapped in a tube packed with Teflon wool and secondarily trapped in a tube packed with activated carbon to collect the highly volatile tars. Although there is evidence that CO_2 is also formed in the earliest stage of primary wood pyrolysis (Boroson and others 1989), it is a relatively small amount. From Equation (D-1) the ratio of molar carbon content of the fuel mixture to its stoichiometric molar consumption of oxygen gas is derived as

$$\frac{v_{C, \text{fuel}}}{\Delta v_{O_2}} = \frac{X' + n}{V + X' + Y'/4 - Z'/2} \quad (D-3)$$

$$\equiv \frac{\frac{\beta_{CO_2}}{44} + \frac{\beta_s}{12} + \frac{\beta_{CO}}{28} + \frac{\beta_{CHW}}{12+W}}{\frac{\beta_{O_2}}{32} + \frac{\beta_s}{12} + \frac{1}{2} \frac{\beta_{CO}}{28} + \frac{(1+W/4)\beta_{CHW}}{12+W}} = \frac{8\beta_{CO_2, st}}{11}$$

We note that by definition $\beta_{O_2} = 1$ and the production of soot, carbon monoxide, and THC are usually small compared to oxygen consumption and carbon dioxide production. Also the value of n and V are quite small compared to X' for wood volatiles. This means the carbon dioxide production per oxygen consumption largely determines the fuel hydration level defined by Equation (D-3). We also note the fuel hydration level is independent of water content in any form—whether as part of volatiles, part of sprinkler activation, or as moisture content in the wall linings—because the parameter m is factored out of Equation (D-3). In our room/corner tests we found only evidence for water sprinkler scrubbing of soot and carbon monoxide, while that of carbon dioxide production per oxygen consumption was unaffected by any level of moisture or HRR. Therefore, the betas for soot and carbon monoxide are only derived for the period of time prior to suppression of the flashover fire. The use of Equation (D-3) will ensure proper fuel evaluation when combustion becomes incomplete, as might happen during post-flashover or in the difference between small-scale and large-scale fires. We note that if propane and wood volatiles are simultaneously burning, then the propane contribution needs to be calibrated and subtracted out of

Equation (D-2) in order to derive the betas of the wall linings for use in Equation (D-3). Using Equation (D-3), the pure fuel hydration values of hydrogen gas, methane, propane, carbohydrates, and carbon monoxide are respectively 0, 1/2, 3/5, 1, and 2. They also remain exactly at these values if any amount of water vapor is added to the mixture (such as from charring or non-scrubbing water sprinkling).

Since the monomers of holocellulose, lignin, and extractives have fuel hydration values of 1.0, 0.91, and 0.71, respectively, the wood volatiles should have fuel hydration values somewhat less than unity. On the average, hydration values for forest fuel and bio-waste/coal are 0.94 and 0.85, respectively (Dietenberger 2002a). However, variations with the heating regimen and/or fire-retardant treatment are expected. For example a low internal temperature or very low rate of overall temperature rise will permit more of the monomers to dehydrate, rather than evaporate (Dietenberger 2002a) so that the volatile fuel hydration value will be closer to the carbohydrate value of unity as a result of removing low-hydration-value monomers from the volatiles. This would also mean some sensitivity to the boundary conditions, such as different imposed heat fluxes, different surface emissivities with specialized paint, or different backing conditions of the specimen. Another kind of heating regimen is the practice of subjecting wood to elevated temperatures (up to 200 °C) in constructing wood-based composites. In these processes, the wood extractives are usually driven out, particularly if steam is used. The ensuing primary wood volatiles from composites would be devoid of extractives in a fire, thereby moving the fuel hydration value toward unity. Because fire-retardant treatment can cause greater primary emissions of carbon dioxide and carbon monoxide along with a proportionate increase of primary water vapor, the fuel hydration value of volatiles from NaOH-treated cellulose, for example, is slightly greater than unity (Dietenberger 2002a).

Suppose that during a test period, the measured water vapor, excess nitrogen gas, sulfur dioxide, and THCs are attributed only to material pyrolysis. Using Equations (D-1) and (D-3), further fuel properties are derived as

$$\frac{Y}{X} = \frac{Y' + 2m}{X' + n} = \frac{[\dot{m}_{H_2O}/9 + W\dot{m}_{CHW}/(12+W)]}{\frac{\dot{m}_{CO_2}}{44} + \frac{\dot{m}_s}{12} + \frac{\dot{m}_{CO}}{28} + \frac{\dot{m}_{CHW}}{12+W}} \quad (D-4)$$

$$\equiv \frac{[\beta_{H_2O}/9 + W\beta_{CHW}/(12+W)]}{\frac{\beta_{CO_2}}{44} + \frac{\beta_s}{12} + \frac{\beta_{CO}}{28} + \frac{\beta_{CHW}}{12+W}}$$

$$\frac{Z}{X} = \frac{Z' + m + 2n}{X' + n} = 2 + \frac{2V}{X} + \frac{Y}{2X} - \frac{11}{4\beta_{CO_2, st}} \quad (D-5)$$

$$\frac{U}{X} = \frac{\beta_{N_2}/14}{\frac{\beta_{CO_2}}{44} + \frac{\beta_s}{12} + \frac{\beta_{CO}}{28} + \frac{\beta_{CHW}}{12+W}} \quad (D-6)$$

$$\frac{V}{X} \cong \frac{\beta_{\text{SO}_2}/70}{\frac{\beta_{\text{CO}_2}}{44} + \frac{\beta_s}{12} + \frac{\beta_{\text{CO}}}{28} + \frac{\beta_{\text{CH}_2\text{O}}}{12+W}} \quad (\text{D-7})$$

These fuel properties can be used to determine the mixture's net heat of combustion using the refined formula by Dietenberger (2002a) applicable to wood volatiles, hydrocarbons, coals, and various other fuel types, which only requires as inputs the derived parameters $s = 38V / (12X + Y + 16Z + 14U + 38V)$, $c = 12X / (12X + Y + 16Z + 14U + 38V)$, and $r_O = (32X + 8Y - 16Z) / (12X + Y + 16Z + 14U + 38V)$. For hydrocarbon fuels, we have $Z = U = V = 0$, which we derive the expression $Y/X = 5.5/\beta_{\text{CO}_2, \text{st}} - 4$ from Equation (D-5). Likewise, in the special case of carbon-oxides fuel, no water vapor is produced because there is no hydrogen in the fuel, $Y = 0$. Therefore, Equation (D-4) would not be needed and the measurement of water vapor can be avoided or ignored for these particular fuels. In an interesting application, suppose we know that a "clean" fuel, $C_XH_YO_Z$, is contaminated with carbon dioxide and water vapor in a mixture, then Equations (D-4) and (D-5) can be used to solve for m and n in $C_XH_YO_ZN_U S_V + mH_2O + nCO_2$ as

$$n = \frac{X' \left(\frac{2Z}{X} - \frac{Y}{X} \right) + Y' - 2Z'}{4 + \frac{Y}{X} - \frac{2Z}{X}} \quad (\text{D-8})$$

$$m = (X' + n)Z / X - Z' - 2n \quad (\text{D-9})$$

As a result, the fuel mixture mass flow rate (from Eq. (D-1)) can be decomposed into clean fuel, water vapor, and carbon dioxide mass flow rates as a function of time. This would be useful in determining the effectiveness of fire suppressions with water sprinklers and/or carbon dioxide flooding of the test room lined with clean fuel. In the case of wood volatiles, the tar fuel composition is unknown and can also vary with time and heating regimen. This complication requires specialized modeling techniques as demonstrated by Dietenberger (2002a) for very thin wood lining. The absence of water vapor and THC measurements, however, limits the available derived fuel properties to just the fuel hydration level given by Equation (D-3) and the soot, CO, and CO₂ beta values.

The analysis for underventilated combustion is made simple by applying the constants for the betas of combustion products to the oxidized fuel portion. Excess fuel portion at "combustion" temperature is fully thermally cracked into simpler gas components (Borison and others 1989), including THCs, given as mass fractions, $f_i = \dot{m}_{i, \text{ex}} / \dot{m}_{f, \text{ex}}$. As applicable to this combustion, Equation (D-1) is conveniently decomposed into oxidized and excess fuel mass flow rates. Overall yield of combustion products is

$$Y_i = \frac{(\beta_i / \beta_f) \dot{m}_{f, \text{ox}} + f_i \dot{m}_{f, \text{ex}}}{\dot{m}_{f, \text{ox}} + \dot{m}_{f, \text{ex}}} = \frac{\beta_i}{\beta_f} \frac{1}{\Phi} + f_i \left(1 - \frac{1}{\Phi} \right) \quad (\text{D-10})$$

$$\Phi = 1 + (\text{GER} - 1)H(\text{GER} - 1) \quad (\text{D-11})$$

The parameter, H , is the Heaviside function. We note by definition, $\beta_{\text{O}_2} = 1$ and $f_{\text{O}_2} = 0$, so the "oxygen depletion" yield is equal to $1/\beta_f$ for $\text{GER} < 1$ and inversely proportional to GER for $\text{GER} > 1$, even under the conditions of incomplete combustion. With specially designed compartment fires, Gottuk (1992) obtained a very good agreement of this oxygen yield prediction with the data for the fuel sources hexane, polymethyl-methacrylate (PMMA), spruce, and polyurethane. Using a burner under a 1-m, insulated collection hood, Beyler (1986) varied burner rate and height in order to vary the GER. For his fuels, which are propane, low-density polyethylene (LDPE), PMMA, and ponderosa pine, we find close agreement of Equation (D-10) to the O₂ and H₂O data. Examination of Guttok's and Beyler's CO₂ yield data also shows a fair agreement with Equation (D-10), which is our generalization to their complete combustion/uncracked fuel formulas. Guttok also provided CO, soot, and THC while Beyler provided CO, THC, and H₂ data, but they have considerable noise levels, such that Equation (D-10) provides just approximations for these combustion products. Indeed, better agreement with CO₂/CO data would be obtained if oxidized portions of Equation (D-10) were corrected for the two-step sequence of oxidation, which converts fuel first to H₂O and CO and then to CO₂ from CO. This means CO begins "lingering" at GER = 0.6 and increases to a fully "linger" yield value of around 0.2 at GER = 1.4. The formula for the "linger" yield value of CO as a function of GER is given in the *SFPE Handbook of Fire Protection Engineering*, 3rd edition, on pages 2–78. This additional CO yield in turn reduces CO₂ yield, so correction to CO₂ beta via Equation (D-1) is $\beta_{\text{CO}_2, \text{cor}} = \beta_{\text{CO}_2} - (44/28)(\beta_f Y_{\text{CO, linger}} - \beta_{\text{CO}})$. or our room tests, Equation (D-10) is cumbersome to use because of the difficulty of linking fuel rate with combustion product rates, particularly if both the propane and specimen are burning. Taking advantage of the very good prediction of oxygen yield regardless of the fuel source, we divided Equation (D-10) by oxygen yield formula to a more suitable form

$$\frac{Y_i}{Y_{\text{O}_2}} = \beta_i + f_i \beta_f (\Phi - 1) \quad (\text{D-12})$$

This means Equation (C-10) in Appendix C can include the underventilation correction term shown in Equation (D-12). Also in Appendix C is a convenient procedure to calculate the room's GER. It is noted that the combustion products and oxygen depletion concentrations for use in Equation (D-12) must be measured within the hot air jetting out of the room's doorway. This is because the excess fuel generated during the room's underventilation has gone outside the room to combust with the hood's entrained air. With the

propane fuel being highly flammable, along with the ignition burner located on the floor putting out at most 0.3 MW, there would be negligible amount of excess propane fuel, which would simplify calculations. The importance of underventilation for room tests is shown from the results of Boroson and others (1989) on thermal cracking of volatiles at 800 °C for sweetgum hardwood charred at 450 °C (char fraction = 0.18) as $f_{\text{CO}_2} = 0.16$, $f_{\text{CO}} = 0.43$, $f_{\text{H}_2\text{O}} = 0.18$, $f_{\text{THC}} = 0.16$ and $f_{\text{soot}} = 0.07$. As an excess fuel, it has threateningly high CO concentrations (up to half of fuel's carbon converted to CO) if it is not combusted after leaving the doorway. Therefore, the results in Table 3 (shown previously in this report) only apply to overventilated combustion, whereas more data are needed for underventilated combustion.