Fire Technology, Vol. 34, No. 4, 1998

Carbon Monoxide Levels in Structure Fires: Effects of Wood in the Upper Layer of a Post-Flashover Compartment Fire

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Abstract

This experimental study was performed to determine the effects of wood pyrolyzing in a high-temperature, vitiated compartment upper layer on the environment inside the compartment and an adjacent hallway. This was done by comparing species concentrations and temperature measurements from tests with and without wood in the compartment upper layer. Experiments were performed with a window-type opening and a door-type opening between the compartment and the hallway. In these tests, the wood in the compartment upper layer caused CO concentrations inside the compartment to increase, on average, to 10.1% dry, which is approximately 3 times higher than levels measured without wood in the upper layer. Down the hallway 3.6 m from the compartment with wood in the upper layer, CO concentrations were measured to be as high as 2.5% dry. The use of the global equivalence ratio concept to predict species formation in a compartment was explored for situations where wood or other fuels pyrolyze in a vitiated upper layer at a high temperature.

Introduction

Researchers have been investigating the effect of wood in the upper portion of the burn room on CO levels in structure fires since the tragic townhouse fire in Sharon, Pennsylvania, in which three people died from CO poisoning. One victim had a carboxyhemoglobin (COHb) level of 91%. Levine and Nelson[1] conducted a full-scale test from which they determined that a large load of wood in the upper portion of the kitchen, the room of fire origin, was the source of high CO levels in the structure. To develop a more detailed understanding of how CO is formed in a room with wood in the upper layer that has reached flashover, Pitts, *et al.*[2] conducted tests using a reduced-scale compartment with the ceiling and upper portion of the walls lined with wood. In these tests, CO levels were measured to be as high as 12%, which was 4 times greater than CO concentrations in room fires with no wood in the upper layer.[2]

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Keywords: carbon monoxide, wood, structures, fires

The goals of the research presented in this paper were to confirm that wood in the compartment upper layer increases the CO levels produced in the room; to determine whether the compartment global equivalence ratio could be used to predict species levels produced by a post-flashover compartment fire with wood in the upper layer; to determine the effect of wood in the compartment upper layer on the species levels in an adjacent hallway; and to examine the effect of the type of opening—a window or door opening—on the species levels in the hallway outside the compartment. To quantify the effect of wood in the compartment upper layer on CO levels, results from tests with wood in the upper layer were compared to results without wood in the upper layer. The series of tests were performed first with a window opening and then with a door opening from the compartment into the hallway.

Experimental Methods

Facility

Experiments were conducted in the reduced-scale fire facility shown in Figure 1, consisting of a compartment, a hallway, and an exhaust system. The compartment was 1.52 m wide, 1.22 m high, and 1.22 m deep and was constructed of 25.4 mm thick UL-rated Fire Master fire-insulation wallboard, supported externally by a steel frame. To allow an upper layer in the compartment to form, a soffit measuring 0.20 m—the distance between the top of the opening and the ceiling—was created.

The source fire inside the compartment was an *n*-hexane pool fire located on the floor in the middle of the compartment. The source fire alone was of sufficient size to cause the compartment to reach flashover. In tests with wood in the compartment upper layer, a truss system on top of the compartment was used to hang Douglas fir plywood approximately 0.05 m below the ceiling. The plywood was 6.35 mm thick and had overall dimensions of 1.22 m long and 0.90 m wide. These dimensions were chosen to provide the maximum amount of plywood in the upper layer while leaving an area large enough to allow the plywood to fall to the floor without damaging the sample probes and the temperature rake. The position of the wood inside the compartment is shown in Figure 2, which is a plan view of the facility. During the fire, both sides of the wood, with a total surface area of 2.20 m^2, were exposed to the hot upper-layer gases and were allowed to pyrolyze. At 1.92 m^2, the total surface area of the wood was slightly larger than the area of the ceiling.

A variable-size opening led from the compartment to the adjacent hallway. Tests were performed with a 0.12 m^2 (0.50 m wide, 0.24 m high) window-type opening and a 0.375 m^2 (0.50 m wide, 0.75 m high) door-type opening. In tests with a window opening, the fire entrained air from the plenum below the compartment and exhausted hot fire gases out through the opening. With a door opening, the plenum was blocked, and air was entrained through the door. Hot fire

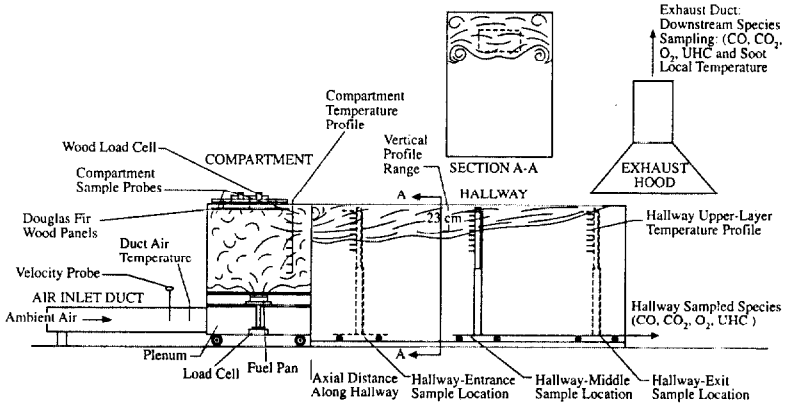

Figure 1. Side view of the facility used in this study.

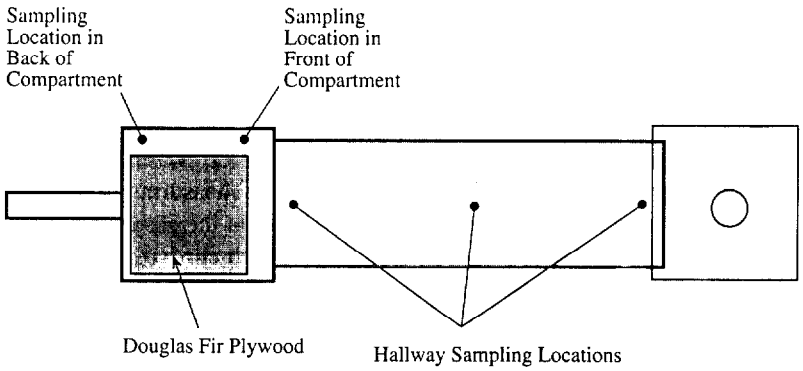

Figure 2. Plan view of the facility showing the orientation of the wood in the upper layer of the compartment and the gas sampling locations.

gases were exhausted from the compartment through the top of the door opening. The bottom of the door opening was level with the top of the fuel pan inside the room, but the door was elevated approximately 0.74 m above the hallway floor.

The adjacent hallway was 1.22 m wide, 1.67 m high, and 3.66 m long. Hallway walls were constructed of 6.35 mm thick fire-resistant gypsum board lined with 1.5 mm thick Fiberfax fire-proof paper. The ceiling was constructed of 25.4 mm thick UL-rated Fire Master fire-insulation board. Both the walls and the ceiling of the hallway were externally supported by a steel frame. On the hallway side of the opening, there was a 0.20 m soffit, called the "inlet soffit."

The fire gases leaving the hallway were collected in a 1.5 m square hood situated above the hallway exit. A blower was connected to the exhaust ducting to remove the products of combustion from the facility.

Sampling and Measurement Techniques

Gas sampling was performed in the facility at the five locations shown in Figure 2. Gases were sampled at two positions inside the compartment and at three positions along the hallway. Sampling was conducted at one of these five locations for the duration of an experiment.

The in-compartment sampling was done 0.10 m from the front wall of the compartment—the wall with the opening—and 0.10 m from the compartment rear wall, opposite the opening. At both of these in-compartment locations, gas sampling was performed 0.10 m below the ceiling and 0.23 m from the side wall.

The in-hallway sampling was done along the center of the corridor, 0.05 m below the ceiling. The hallway sampling probe was connected to a cart whose location could be varied along the length of the hallway. For the in-hallway sampling experiments, the cart was positioned 0.45 m, 1.83 m, and 3.20 m from the compartment.

Gas samples were drawn from these locations through a heated (110°C) line into a data acquisition room for species analysis. Inside the data acquisition room, sampled gases were divided into two streams for measuring O_2, CO_2, CO, and unburned hydrocarbon (UHC) concentrations within the gases. A portion of the sampled gases was dried using a water trap in a bath at –10°C and was analyzed for O_2, CO_2, and CO concentrations. The O_2 concentration was measured with a Siemens paramagnetic Oxymat 5E analyzer, while the CO_2 and CO concentrations were measured using two separate Rosemont Analytical 880 NDIR analyzers. The other portion of sampled gases was kept at 110°C and analyzed while wet. With the wet sample gases, the UHC concentration, taken to be ethylene (C_2H_4), was measured using a Gow-Mac flame ionization detector (FID).

Inside the compartment with wood in the upper layer, CO concentrations were in excess of 10%, which was the maximum range of the CO analyzer available for this study. To measure the CO concentrations, the gas stream flowing to the CO, CO_2, and O_2 was diluted by 50% with nitrogen. Several tests were conduct-

ed to verify the performance of the dilution process.

Vertical temperature profiles were measured in the compartment and the hallway using two separate aspirated temperature rakes. In the compartment, the temperature rake was always located in the front corner, as shown in Figure 1. The compartment thermocouple rake consisted of eight Type-K 30- gauge thermocouples placed 0.10 m apart, with the top thermocouple located 0.10 m from the ceiling. Inside the hallway, the other aspirated temperature rake was mounted on the mobile sampling cart. The hallway rake consisted of eight Type-K 30-gauge thermocouples. Due to the steep temperature gradients in the hallway's upper layer, the thermocouples were placed 0.05 m apart, with the top thermocouple located 0.05 m from the ceiling.

The mass of the *n*-hexane pool fire and the mass of the wood were monitored using two separate A&D load cells with 1 gram resolution. The *n*-hexane mass was measured using a load cell located in the plenum beneath the compartment. To measure the wood mass, a load cell was placed beneath the truss assembly supporting the wood on top of the compartment. The mass loss rate of the *n*-hexane and of the wood was determined by taking the temporal derivative of the mass data.

The method for determining air entrainment into the compartment varied, depending on the opening between the compartment and the hallway. In experiments with a window opening, air was entrained into the compartment through a duct connected to the plenum. The mass flow of air entrained into the compartment was determined by measuring the average velocity and the temperature of the air flowing through the duct. The average velocity was measured using a Kurz Model 415, 0–2 m/s hot film probe, and the temperature was measured using a Type-K thermocouple. For the door experiments, the plenum was blocked off from the ambient surroundings, thereby causing air to be entrained into the compartment only through the door opening. Methods for estimating air entrainment into the room are discussed in the next section.

Data Analysis

Post-processing of the raw data was performed to further characterize the test conditions and to determine the average post-flashover environment. Calculated test conditions included the ideal fire size, compartment air entrainment for the door case, the compartment-plume equivalence ratio (CPER), the wet species concentrations, and the steady-state time of the fire. Methods used to calculate these parameters are described here along with an explanation of the procedure followed when averaging the data.

The ideal fire size was determined by multiplying the fuel's mass-loss rate by the heat of combustion. Table 1 provides the heat of combustion for the fuels used in this study, in addition to other properties necessary for data analysis. The heat of combustion of the Douglas Fir plywood was taken to be the effective heat

TABLE 1
Properties of the Fuels Used in the Study

Fuel	Volatile Composition	Heat of Combustion ΔH_c, [kJ/kg]
n-Hexane	C_6H_{14}	44,735
Douglas Fir Plywood	$CH_{2.506}O_{1.071}$*	10,400

*Assumed 15% char

of combustion, determined using the cone calorimeter. In tests with wood in the upper layer, the ideal fire size was calculated by adding the *n*-hexane fire size to the wood fire size. The actual total size of the fire, which would include the heat released both inside the compartment and in the hallway, was not calculated, since the oxygen concentration was not measured in the exhaust duct during the test.

Air entrainment into the compartment with a door-type opening was estimated using the ventilation parameter,

$$\dot{m}_{air} = 0.50A\sqrt{H} \qquad (1)$$

where A is the opening area, measured in square meters, and H is the opening height, measured in meters.[3] The air entrainment calculated using Equation 1 assumes choked flow at the opening, which is nearly the case during post-flashover. McKay *et al.*[4] measured the mass flow rates through a door during the post-flashover time of the fire, using the temperature profile method developed by Janssen and Tran.[5] Air entrainment values measured by McKay *et al.*[4] were approximately 20% lower than values determined using Equation 1, which would be expected, since Equation 1 provides the maximum possible ventilation into the compartment. This data indicates that the error associated with using Equation 1 is approximately 20%.

The ventilation into the compartment relative to the size of the fire defines whether the compartment is well-ventilated or under-ventilated. In a well-ventilated compartment, the fire has enough air to burn all of the fuel produced and is said to be "fuel-controlled." In an under-ventilated compartment, fire does not have enough air to burn all of the fuel produced and is said to be "ventilation controlled." Stoichiometric burning occurs at the transition between a fuel-controlled and a ventilation-controlled fire. The ventilation state of the compartment can be quantified using the CPER, ϕ. The compartment plume equivalence ratio,

$$\phi = \frac{\left(\dot{m}_f / \dot{m}_{air}\right)}{\left(\dot{m}_f / \dot{m}_{air}\right)_{st}}, \tag{2}$$

is defined as the mass flow of air into the compartment, ($\dot{m}_{air}$), divided by the mass-loss rate of the fuel, ($\dot{m}_f$), all normalized by the stoichiometric fuel-to-air ratio. A CPER less than 1 (ϕ <1) denotes a fuel-controlled fire, while a CPER greater than 1 (ϕ >1) indicates a ventilation-controlled fire. Stoichiometric burning inside the compartment occurs when ϕ =1. Calculating the CPER is simple when one fuel is inside the compartment, but it is more complicated when multiple fuels are involved.

When calculating the CPER for fires with multiple fuel sources, the stoichiometric fuel-to-air ratio of the fire may change with time. The stoichiometric ratio is constant if the fraction of fuel from each source remains constant (e.g., the first fuel always has a mass loss rate twice that of the second fuel), but this is usually not the case. To determine the temporal stoichiometric fuel-to-air ratio, the stoichiometric equation is balanced using the appropriate molar contribution from each fuel source, which is calculated by dividing the molar loss rate of a fuel source by the total molar loss rate. After balancing the stoichiometric equation, the moles of air from each fuel type are used to calculate the stoichiometric fuel-to-air ratio. In experiments with *n*-hexane and wood as fuels, the ratio of the mass-loss rates of the fuels was not constant. Therefore, the stoichiometric fuel-to-air ratio was determined at each time step of the test.

For accuracy, the concentrations of CO, CO_2, and O_2 are reported on a dry-basis. For some calculations (i.e., species yields), wet species concentrations are necessary. Dry concentrations were converted to wet concentrations by assuming that CO_2 and H_2O were formed in stoichiometric proportions. This assumption was estimated to be accurate to within 20% at equivalence ratios greater than 3.0, and within 10% at equivalence ratios less than 3.0. The UHC concentrations were measured wet and reported on a wet-basis. Reported temperatures were the maximum temperatures in the vertical temperature profile at that location.

All of the temporal test data was averaged during the post-flashover period of the fire, where the fire was determined to be at a quasi-steady state. The quasi-steady state time of the fire was determined using the fire growth parameter,

$$G = t_{res,comp}\left(\frac{d\dot{m}_f / dt}{\dot{m}_f}\right), \tag{3}$$

where $t_{res,comp}$ is the residence time inside the compartment and $\dot{m}_f$ is the fuel's mass-loss rate. The fire was assumed to be in the quasi-steady state when the fire-growth parameter was approximately zero, which was always the case during the post-flashover period. The species concentrations and CPER were also relatively constant during the quasi-steady state period. Averaging was conducted over a 30-second time window during the quasi-steady state period.

Types of Experiments

The purpose of the experimental study was to determine: the effect of the wood pyrolyzing in the upper layer on species concentrations in the compartment and hallway; whether the global equivalence ratio concept could be used to predict species levels produced in a compartment with wood in the upper layer; and the effect of the type of compartment opening on species levels in the compartment and hallway. Four sets of conditions were tested to examine these issues. These were a compartment with:

- a window opening and no wood in the upper layer;
- a window opening and wood in the upper layer;
- a door opening and no wood in the upper layer; and
- a door opening and wood in the upper layer.

For each set of conditions, a series of five separate experiments were conducted to determine the species and temperature levels throughout the facility. In two of the five tests, gas sampling was performed inside the compartment, and in the other three tests, gas sampling was performed along the hallway. To assess the accuracy of the results, some tests were repeated. All of the fires considered in the study caused the compartment to reach flashover.

The effect of wood in the upper layer on species concentrations, particularly on CO, was determined by comparing results from tests with and without wood. This was done in both the window opening and the door opening tests. Effects of the opening type on the species levels in the compartment and the hallway were evaluated by comparing the window-opening results with the door-opening results. The two types of openings were tested because they produce different flow patterns in the compartment and hallway. Such flow patterns may affect the species levels, particularly that of CO, in the compartment and the hallway.

Tests with the window opening were used to establish whether the global equivalence ratio concept could determine species yields, particularly of CO, in the compartment. In tests with the window opening, the inflow and outflow of the compartment were measured directly. This made it possible to accurately determine CPER and the species yields during the test.

Results

Compartment with a Window Opening

A series of ten experiments were performed (five with wood and five without wood in the upper layer) to examine the impact of the wood on the facility's conditions when the compartment had a window opening. For tests without wood in the upper layer, the temporal CO concentrations at the various locations in the facility are shown in Figure 3. The temporal CO concentrations are shown in Figure 4 for tests with wood in the compartment upper layer. Levels of CO formed inside the compartment with wood are shown in Figure 4 to be approximately 10% on average, which is nearly three times greater than levels measured without wood. CO concentrations were measured to be as high as 14% inside the compartment with wood, which is slightly higher than the 12% CO concentration measured by Pitts *et al.*[2] In Figure 4, the sudden drop in the CO concentration inside the compartment near the end of the test was due to the wood falling from the upper layer to the floor of the compartment. The wood was allowed to burn and smolder until the fire went out. Virtually all of the wood was consumed

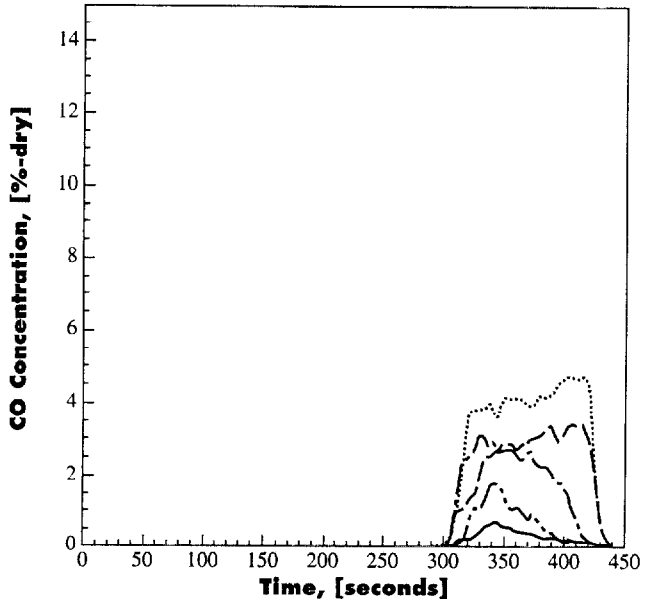

Figure 3. The CO concentration at the five sampling locations in experiments with a window opening and no wood in the compartment upper-layer. Sample locations in the compartment —-Rear and • • •Front; and down the hallway: • — 0.46 m, • •—1.83 m, —3.20 m.

by the time the smoldering ceased.

With wood in the upper layer, the CO concentration in the compartment was not only elevated but also more variable than the CO concentration in a compartment with no wood. This variability was attributed to the fact that the CO concentration depends on the total mass-loss rate in the compartment. The plot of the compartment CO concentration and the different mass-loss rates of fuel in the compartment shown in Figure 5 indicate that the CO concentration does track with the total mass-loss rate of the fuel. The variability in the total mass-loss rate of fuel is due to the mass-loss rate of the wood, which is shown in Figure 5 to have two characteristic peaks. The mass-loss rate curves shown in Figure 5 are typical of the mass-loss rate curves for fuels measured in all of the tests. In the tests with wood in the upper layer, the quasi-steady state time of the fire was determined to be during the second peak in the wood's mass-loss rate.

The temporal plots of CO concentration at the different locations show that as

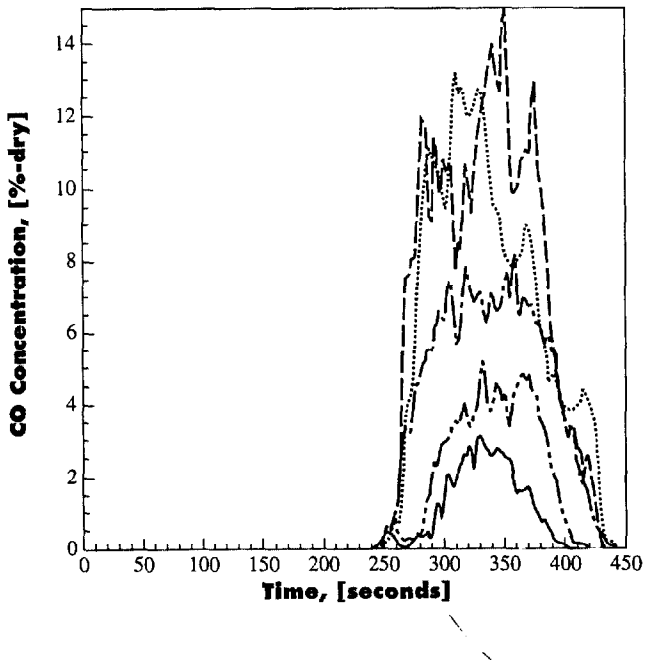

Figure 4. The CO concentration at the five sampling locations in the facility in experiments with a window opening and wood in the compartment upper-layer. Sample locations in the compartment —-Rear and • • •Front; and down the hallway: • — 0.46 m, • •—1.83 m, —3.20 m.

the gases were transported down the hallway, the CO concentration was reduced. By the end of the hallway, the CO concentration in tests with wood was different than the concentration in tests without wood. A more detailed understanding of CO oxidation, dilution, and transport in the hallway was determined by plotting the spatial variations of CO, CO_2, O_2, and UHC concentrations and temperatures from tests with and without wood in the upper layer. The reported species concentrations and temperatures at each spatial location are quasi-steady averages of the data.

The average species concentrations and temperatures in the compartment and hallway where there was no wood in the compartment upper layer are shown in Figure 6. After the gases left the compartment and convected 0.5 m down the hallway, the CO and UHC concentrations went down by approximately 30%. Since the CO_2 concentration had increased by 10% in the initial 0.5 m of the hallway, the decrease in CO and UHC concentration was attributed to oxidation.

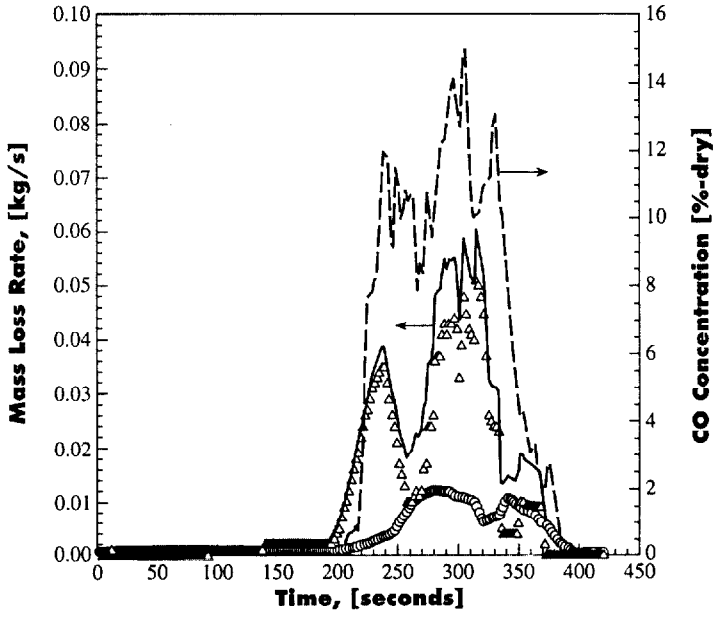

Figure 5. The mass loss rate of the liquid *n*-hexane pool fire (○), the wood (△), and the total fuel mass loss rate (—) in an experiment with wood in the compartment upper-layer. The dashed line represents the CO concentration in the compartment during this test.

TABLE 2
Percent Change in Species Concentrations from Compartment Levels

Opening Type [%][1]	Wood Present in Compartment Upper-Layer	O_2 Concentration at End of Hallway [%-dry]	Percent Reduction in Species Concentration from Compartment Levels	
			CO	UHC
Window	No	2.1	86	96
Window	Yes	0.3	79	86
Door	No	7.8	95	97
Door	Yes	1.5	88	94

1) 100% reduction corresponds with all of the species being oxidized.

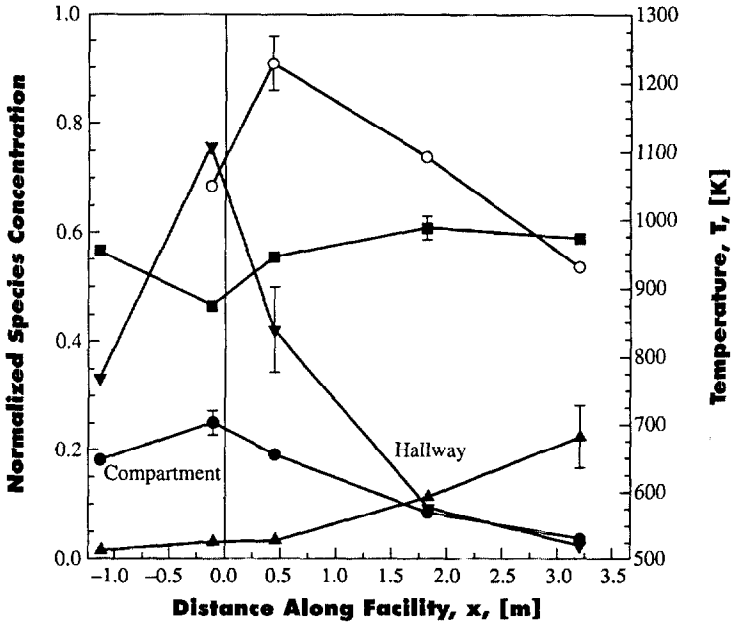

Figure 6. The normalized species concentrations and temperatures within the compartment and hallway for experiments with a window opening and no wood in the compartment upper-layer. Symbols and normalization values: ●-CO (15%), ▼-UHC (10%), ■-CO_2 (20%), ▲-O_2(10.5%), and ○-Temperature. The average fire size was 535 kW and the average compartment global equivalence ratio was 2.3.

After the gases had been convected 1.8 m down the hallway, the CO concentration in the gases was reduced to 70% of the in-compartment CO level. The UHC concentration at this position had been reduced by 85% of the in-compartment UHC level. At approximately 1.8 m down the hallway, the CO_2 concentrations began to decrease, indicating that the gases were being diluted instead of oxidized. The region where the gases began to be diluted is consistent with the location of the flame tip in the hallway, which was approximately 2.3 m in these tests. At the hallway exit, the in-compartment level of CO had been reduced by 86%, while the in-compartment UHC had been reduced by 96%, as shown in Table 2.

The average CO, CO_2, O_2, and UHC concentrations as well as the temperature are plotted with distance in the facility in Figure 7 for tests with wood in the compartment upper layer. Inside the compartment, the CO concentrations were measured to be 10.1% on average, which is approximately three times greater than

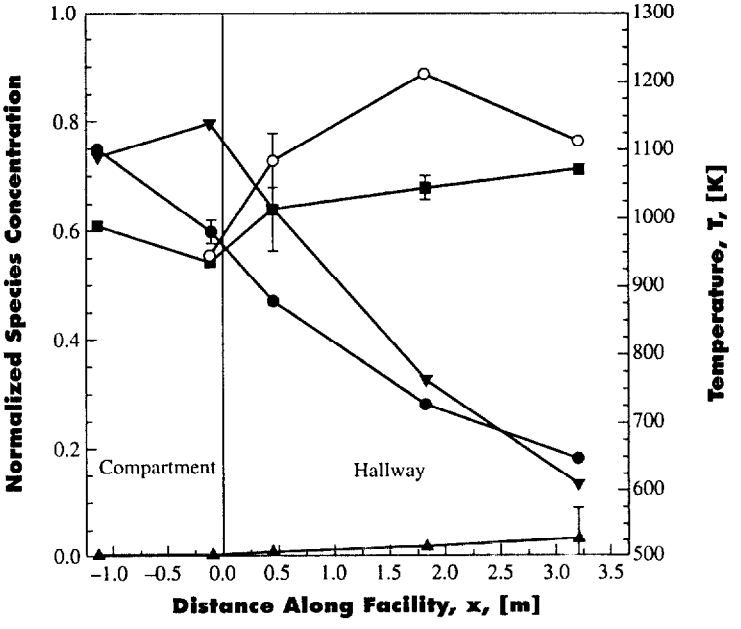

Figure 7. The normalized species concentrations and temperatures within the compartment and hallway for experiments with a window opening and wood in the compartment upper-layer. Symbols and normalization values: ●-CO (15%), ▼-UHC (10%), ■-CO_2 (20%), ▼-O_2(10.5%), and ○-Temperature. The average fire size was 721 kW and the average compartment global equivalence ratio was 5.4.

average concentrations measured in the compartment with no wood. Unburned hydrocarbon concentrations in the compartment with wood were, however, only 40% higher than the concentrations measured in experiments with no wood. Research has shown that the FID measurement of total UHC can be in error when certain types of hydrocarbons are in the sample. Colket *et al.*[6] determined that the response of the FID was reduced when measuring total UHC in a gas stream containing oxygenated, aromatic, and some unsaturated hydrocarbons. For example, the signals produced by C_2H_4O and C_2H_2 were 60% and 65% lower, respectively, than that of C_2H_6.[6] In full-scale fire tests using wood cribs, Fardell *et al.*[7] determined that approximately 50% of the UHCs produced by the wood crib fire were oxygenated and aromatic hydrocarbons. This indicates that in this study, the UHC measured in tests with wood in the upper layer may be lower than the actual UHC levels.

According to measurements in the first 0.5 m of the hallway, CO oxidized at a faster rate than did the UHC. This trend may not be correct, due to the inaccurate measurement of UHC concentration with wood inside the compartment.

The reduction in CO and UHC levels along the entire length of the hallway was primarily due to oxidation and not dilution. Evidence of this is the increase in the CO_2 concentration and the low O_2 concentration of less than 1% along the length of the hallway. Oxidation of CO and UHC were favored because of the high temperature environment of more than 1000 K created by burning fuel-rich gases in the hallway upper layer. In these tests, the flame extension from the compartment was observed to extend past the end of the hallway and was estimated to be 4.4 m long. By the end of the hallway, the in-compartment CO concentration had been reduced by 79%, while the in-compartment UHC concentration had been reduced by 86%. This indicates that the CO and UHC concentrations were reduced less efficiently by the time the gases reached the end of the hallway, compared to the results with no wood in the compartment upper layer, as shown in Table 2.

Compartment with a Door Opening

A series of ten experiments were performed (five with and five without wood in the upper layer) to examine the impact of wood in the compartment upper layer on conditions in the facility when the compartment had a door opening.

The spatial distribution of CO, CO_2, O_2, and UHC concentrations and temperature are plotted in Figure 8 for tests with a door opening and no wood in the upper layer. In the compartment, the CO concentration was measured, on average, to be 5.7% dry, while the UHC concentration was measured, on average, to be 4.5% wet. After the gases left the compartment and were convected 0.5 m down the hallway, CO had oxidized to a level 35% lower than that measured inside the compartment. The UHC concentration was measured at this position to be reduced by 60% of the UHC level in the compartment. The increase in CO_2

concentration within the first 0.5 m of the hallway was evidence that CO and UHC were being oxidized in this region. After the gases had convected 1.8 m down the hallway, both the CO and UHC concentrations were measured to be reduced by 90% of their respective compartment levels. The CO_2 concentration remained nearly constant, from 0.5 to 1.8 m, along the hallway, meaning that both oxidation and dilution of the fire gases were occurring in this region. The dilution of the gases was also evident by the O_2 concentration increasing to 2.7% dry. The slowing of oxidation in the hallway was consistent with the end of the flaming region, which was observed to be approximately 2.0 m down the hallway. At the end of the hallway, the CO concentration had been reduced by 95% of the in-compartment CO level, while the UHC concentration had been reduced by 97% of in-compartment UHC levels.

For door experiments with wood in the compartment upper layer, the variations in CO, CO_2, O_2, and UHC concentrations and temperatures are shown in

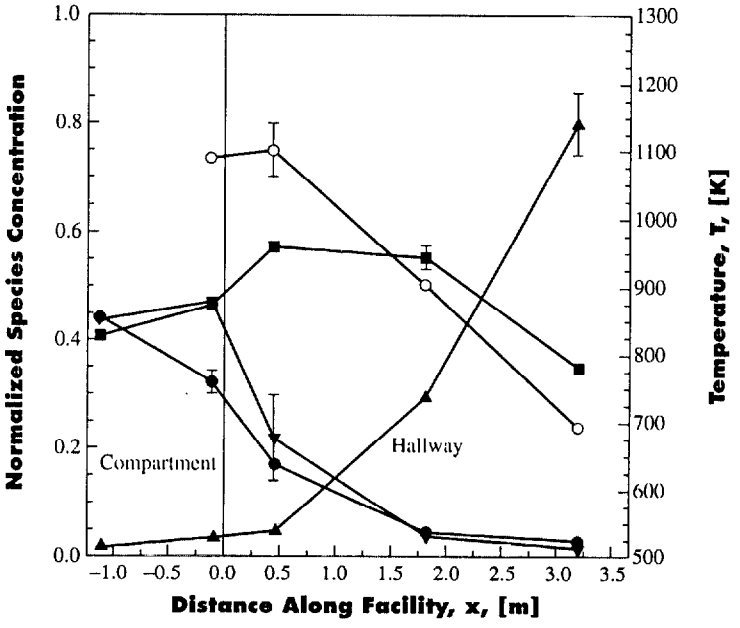

Figure 8. The normalized species concentrations and temperatures within the compartment and hallway for experiments with a door opening and no wood in the compartment upper-layer. Symbols and normalization values: ●-CO (15%), ▼-UHC (10%), ■-CO_2 (20%), ▼-O_2 (10.5%), and ○-Temperature. The average fire size was 545 kW.

Figure 9. CO concentrations in excess of 10.6% were measured in these tests, but quasi-steady state averages were 8.0%. These CO levels were, on average, approximately 40% higher than the concentrations in tests with a door opening and no wood in the compartment. The UHC concentrations were measured at an average of 8.1%, which represents a 75% increase in the UHC concentration measured in tests with no wood in the compartment upper layer.

CO and UHC concentrations were reduced in the gases being convected down the hallway. After the gases had flowed 1.8 m down the hallway, the CO concentrations were reduced by 50% of the compartment levels, while the UHC concentrations were reduced by 75%. The CO and UHC were being oxidized during the initial 1.8 m of the hallway, which is evident in Figure 9 by the increase in CO_2 concentrations. At the end of the hallway, the CO concentrations had been reduced by approximately 88% of in-compartment levels, while the UHC concentration at the end of the hallway had been reduced by approximately 94% of

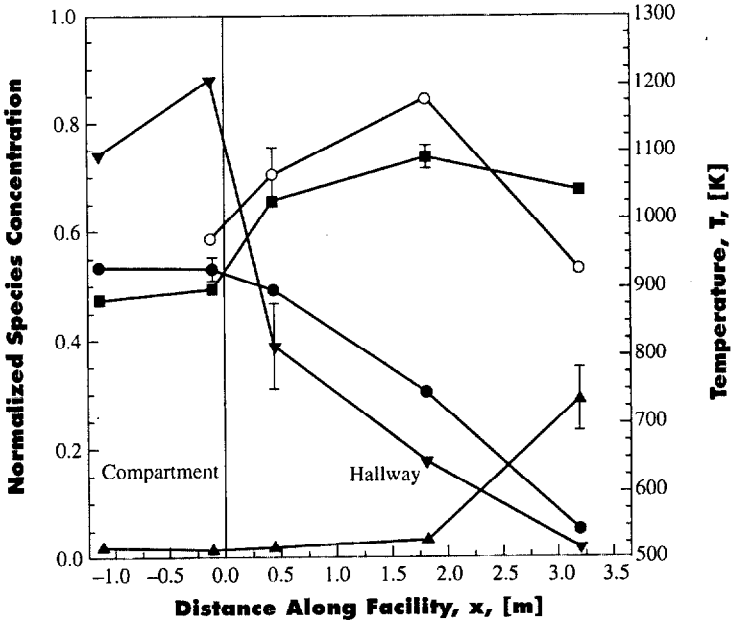

Figure 9. The normalized species concentrations and temperatures within the compartment and hallway for experiments with a door opening and wood in the compartment upper-layer. Symbols and normalization values: ●-CO (15%), ▼-UHC (10%), ■-CO_2 (20%), ▼-O_2 (10.5%), and ○-Temperature. The average fire size was 720 kW.

in-compartment levels. As shown in Table 2, the reduction levels for CO and UHC at the end of the hallway are less than those measured in experiments without wood in the compartment upper layer. The reduction in CO and UHC concentrations was due mostly to oxidation, but dilution of the gases contributed to some of the reduction in concentration. This is evident by the CO_2 concentration being nearly constant from 1.83 to 3.2 m down the hallway and the increase in the O_2 concentration. Temperatures remained above 1000 K, permitting the oxidation of CO. These high temperatures were generated by the flames that extended 3.2 m down the hallway from the compartment.

Discussion

Species Formed Inside a Compartment with Wood in the Upper Layer

The data in Figures 6 through 9 show that the wood in the compartment upper layer has a significant impact on the CO concentrations in the compartment. Only moderate increases in CO_2 and UHC concentrations were measured in the compartment that had wood in the upper layer. The low levels of UHC were attributed to a reduced signal response from the FID, which was due to the presence of oxygenated and aromatic hydrocarbons in the gases produced from wood pyrolysis. The effect of the wood in the upper layer on the species levels in the compartment was attributed to the chemical kinetics associated with the pyrolysis of the wood in a vitiated environment with high temperatures.[2] Wood is a fuel that contains carbon, hydrogen, and oxygen. When wood pyrolyzes in a vitiated environment, the oxygen contained in the fuel forms CO directly. Due to the limited amount of oxygen in the wood, the CO is not converted to CO_2. As a result, wood pyrolyzing in a hot, vitiated environment produces a significant amount of CO and only modest levels of CO_2. This is supported by the data in Figures 6 and 7, which show that the wood in the upper layer caused CO concentrations inside the compartment to increase from an average of 3.2% to 10.1%. Less significant increases were measured for CO_2, with concentrations increasing from 10.4% to 11.6%.

In practice, the species levels formed inside a compartment can be predicted with the global equivalence ratio concept. The basis of this concept is that the compartment global equivalence ratio (CGER) correlates to the species produced by the fire.[8,9,10,11] The CGER is strictly defined as the mass of the gas in the upper layer due to the fuel, divided by the mass of the gas in the upper layer due to the air, all normalized by the stoichiometric fuel-to-air ratio. The CGER is equal to the compartment plume equivalence ratio (CPER), which is defined by Equation 2, during the quasi-steady-state period of the fire.

Beyler[8] and Gottuk, *et al.*[11] determined that for a variety of fuel types, the CGER correlates to a form of the species yield. There are two basic forms of the species yields: unnormalized and normalized. Unnormalized species yields are defined slightly differently, depending on whether the species is being formed or

consumed. For species that are formed during the fire (i.e., CO, UHC, and CO_2), the unnormalized species yield,

$$Y_i = \frac{\dot{m}_i}{\dot{m}_f}, \tag{4}$$

is calculated by dividing the mass flow rate of species formed, $\dot{m}_i$, by the mass loss rate of fuel, $\dot{m}_f$. The unnormalized yield for species consumed by the fire (i.e., O_2) is calculated as the depletion of the species per mass-loss rate of fuel,

$$Y_{O_2} = \frac{\dot{m}_{O_2} - \dot{m}_{O_2,out}}{\dot{m}_f}. \tag{5}$$

Normalized species yields are determined by dividing unnormalized yields by the theoretical maximum species yield. The theoretical maximum yield was calculated by determining the maximum amount of a species that could be formed or consumed by one mole of fuel. Gottuk and Roby[12] provide a list of theoretical maximum species yields for a variety of fuels. In the cases with wood in the compartment upper layer, the stoichiometry varied with time, and, therefore, the theoretical maximum species yield also varied with time.

Beyler[8] and Gottuk, *et al.*[11] determined that for a variety of fuels, the CGER correlates to the normalized yields for all species except CO. For CO, the CGER correlates with the unnormalized CO yield for a variety of fuels. All of these data were developed from a single fuel burning in the lower portion of the compartment. Since compartment fires in the present study are most similar to those studied by Gottuk *et al.*,[11] the data of Gottuk *et al.* will be compared with the results from this study. Plots of the normalized species yields for CO_2, O_2, and UHC, and the unnormalized species yields for CO from Gottuk *et al.* are shown in Figures 10 through 13. The filled symbols in these plots correspond to the data from this study. The filled circles are data from tests with no wood in the upper layer, and the triangles are data from tests with wood in the upper layer. The only data considered in this part of the analysis were from tests with a window opening, during which the air entrainment into the compartment was measured. Also included in Figures 10 through 12 are curves that represent the predicted yields from a model for complete combustion.[8] For fuel-rich cases (CGER>1.0), the model assumes that all of the unburned fuel remains as UHC. The model agrees well with the CO_2 and O_2 data of Gottuk *et al.*, while the model consistently overpredicts the UHC data. This is due to some of the unburned fuel being converted to

other products of incomplete combustion, such CO and H_2. The complete combustion model does not adequately predict all of the global equivalence ratio data, but it does appear to follow approximately the same trends as the data.

For tests with no wood in the compartment upper layer, the data is in good agreement with the data of Gottuk *et al.*[11] for all species. In tests with wood in the upper layer, the CGER was determined to range from 5.2 to 5.6, which is much higher than the CGERs previously measured by Gottuk *et al.*[11] The O_2 and CO_2 yields from tests with wood in the upper layer agree with the trend in the data of Gottuk *et al.*, which is close to the levels predicted by the complete combustion model. The CO yields determined in tests with wood in the upper layer are in agreement with the CO yields previously determined by Gottuk *et al.* at a CGER of 3.0. Assuming that the trend in the data is valid up to a CGER of 5.6, the CO yield results with wood in the upper layer agree with those predicted using the global equivalence ratio concept. The normalized yields for UHC in tests with wood in the upper layer are less than both the data with no wood in the compartment and the data of Gottuk *et al.* As previously discussed, the low levels of UHC were attributed to a reduced signal response from the FID.

Based on the data that currently exists, the global equivalence concept is capable of predicting the CO_2, O_2, and CO yields in a compartment with wood pyrolyzing in the hot, vitiated upper layer. Due to the uncertainty in the UHC data, the agreement between the UHC yields with wood in the upper layer and the UHC yields from the global equivalence ratio concept was not established. The global equivalence ratio concept is also expected to be able to predict species levels in compartments where other fuels containing oxygen (i.e., plastics in a cabinet, cardboard boxes, or fabrics) are pyrolyzing in a hot, vitiated upper layer.

When fuels such as hydrocarbons and polyolefins that do not contain oxygen are pyrolyzing in the hot, vitiated upper layer, they are expected to produce different results than those produced by a oxygen-containing fuels, even though the CGER may be the same. For example, the CGER can be increased by injecting a hydrocarbon fuel such as natural gas into the vitiated upper layer. Without additional oxygen being added to the upper layer, none of the fuel can be converted to CO or CO_2. UHC concentrations would increase with the addition of fuel to the upper layer, causing the UHC yields to increase with the CGER. The UHC would act as a dilutant reducing the concentration of CO and CO_2 in the upper layer. Both the reduced concentrations and the higher mass-loss rates of the fuel would cause the CO and CO_2 yields to decrease. Further testing needs to be performed to determine whether the global equivalence ratio concept can predict species levels when non-oxygenated fuels are injected into the upper layer.

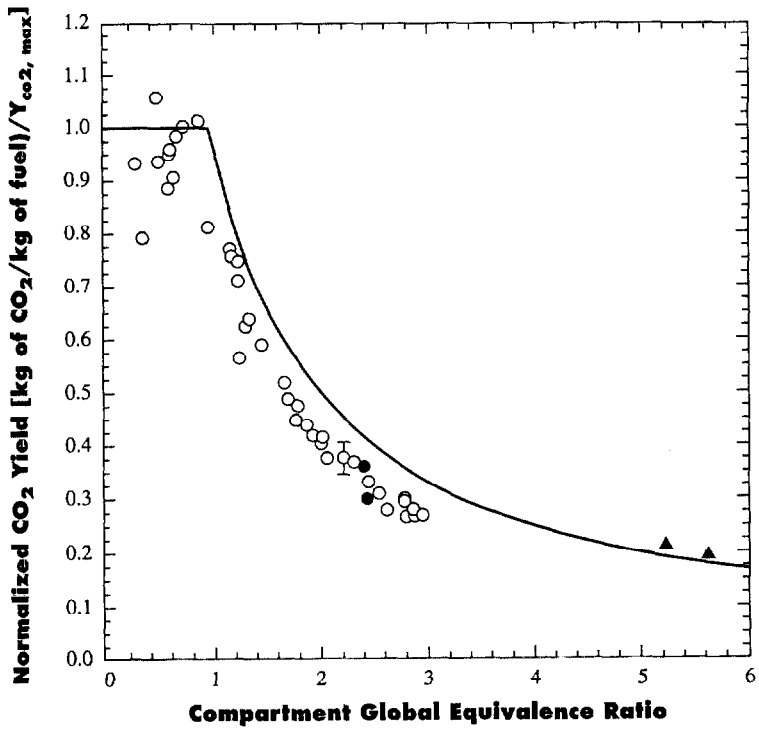

Figure 10. The normalized CO_2 yield data of *Gottuk et al.*[11] (○), data from this study with no wood in the compartment upper-layer (●) and data from this study with wood in the upper-layer (▼). Also shown in this plot is the normalized CO_2 yield estimated using a complete combustion model (—).[8]

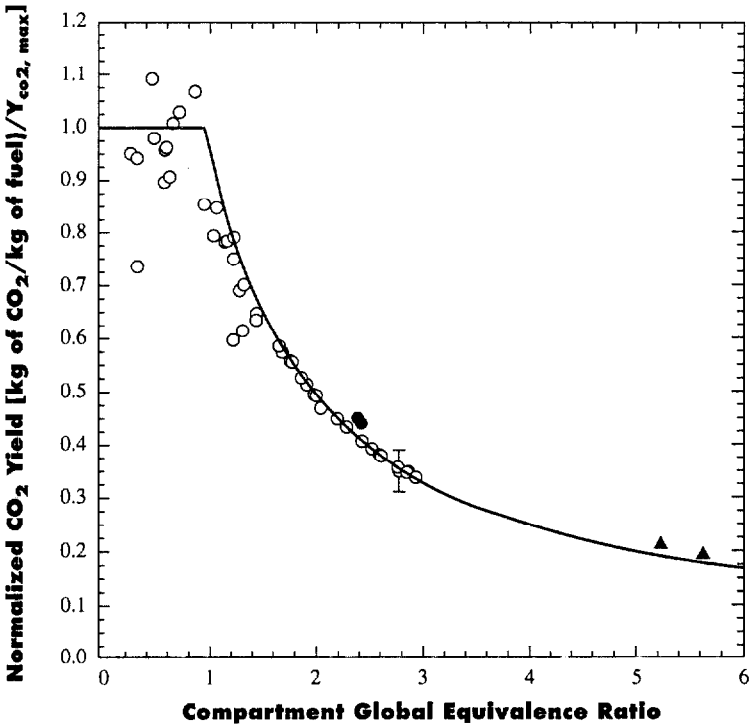

Figure 11. The normalized O_2 yield data of Gottuk *et al.*[11] (○), data from this study with no wood in the compartment upper-layer (●) and data from this study with wood in the upper-layer (▼). Also shown in this plot is the normalized O_2 yield estimated using a complete combustion model (—).[8]

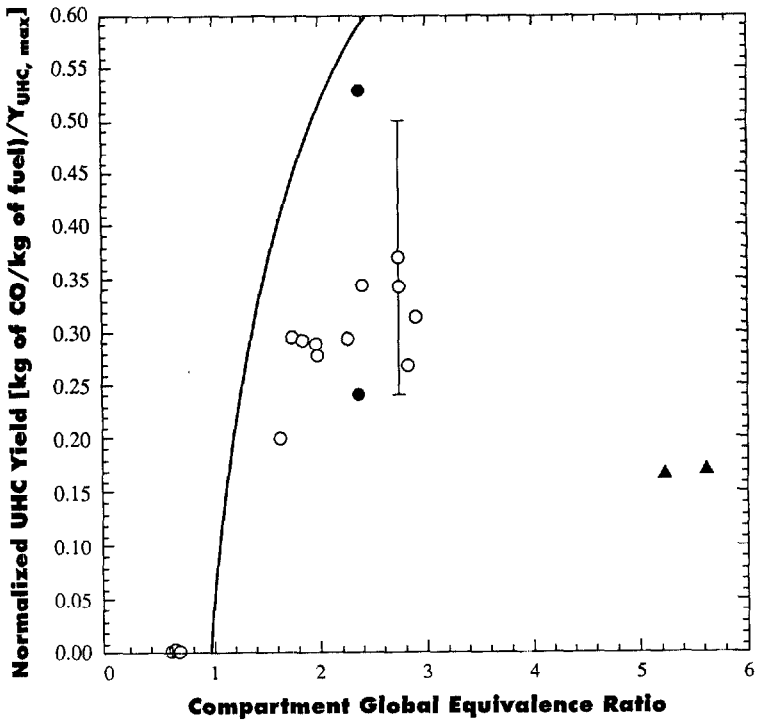

Figure 12. The normalized UHC yield data of Gottuk *et al.*[11] (○), data from this study with no wood in the compartment upper-layer (●) and data from this study with wood in the upper-layer (▼). Also shown in this plot is the normalized UHC yield estimated using a complete combustion model (—).[2]

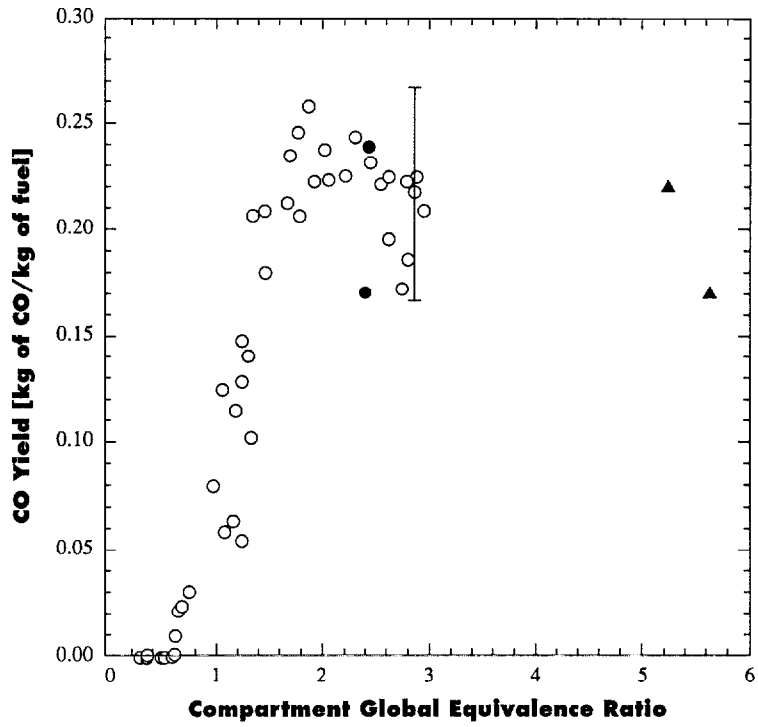

Figure 13. The unnormalized CO yield data of Gottuk *et al.*[11] (○), data from this study with no wood in the compartment upper-layer (●) and data from this study with wood in the upper-layer (▲).

Predicting CO Levels in Compartments with Wood in the Upper Layer

The discussion in the previous section indicates that the global equivalence ratio concept can be used to predict complete combustion product levels and CO levels when unburned oxygenated fuels are present in a hot, vitiated upper layer typical of a room that has reached flashover, for example, a kitchen containing a grease fire. After the room reaches flashover, the wooden kitchen cabinets that were not involved in the initial fire are exposed to the hot upper layer, causing the wood to pyrolyze. With wood pyrolysis occurring in the hot, vitiated upper layer, the CO_2, O_2, and CO levels produced by the fire could be predicted using the yields determined from the global equivalence ratio concept, the ventilation into the room, and the total fuel mass-loss rate in the room.

The total fuel mass-loss rate in the room during flashover is the source fire fuel mass-loss rate plus the mass-loss rate of objects pyrolyzing in the upper layer. Assuming the ideal fire size of the source is known, the fuel mass-loss rate of the source fire can be determined by dividing the fire size by the heat of combustion of the source fire's fuel. The mass-loss rate of objects pyrolyzing in the upper layer is governed by the heat flux incident on the objects, which can be estimated as the black-body heat flux determined using the upper-layer gas temperature. Knowing the upper-layer temperature, and thus the black-body heat flux, the mass-loss rate per unit area of the object can be determined using the cone calorimeter with the incident heat flux equal to the black-body heat flux. The overall mass rate of objects pyrolyzing in the upper layer is determined by multiplying the surface area of the objects exposed to the high temperature upper layer by the mass loss rate per unit area determined from the cone calorimeter.

The accuracy of this method is demonstrated using the test data with wood in the upper-layer and a cone calorimeter test conducted on a sample of the wood used in the fire tests. Figure 14 is a plot of five of the wood mass-loss rate curves measured in the compartment fire tests. The mass-loss rates are shown in this plot normalized with respect to the exposed surface area of 2.2 m^2, total derived from both sides of the wood, for ease of comparison with the cone calorimeter results. The bold line on the plot is the average mass-loss rate of the five tests. Figure 15 is a plot of the mass-loss rate per unit area of a wood sample in the cone calorimeter at 50 kW/m^2. This incident heat flux is nearly equal to the black-body heat flux that was determined using the compartment upper-layer temperature (46 kW/m^2). The mass-loss rate per unit area determined in the cone calorimeter agrees well with the average mass-loss rate per unit area determined in the tests. Even the double peak that was measured in the fire tests was evident in the mass-loss rate per unit area determined using the cone calorimeter.

Effect of the Wood in upper layer on CO Oxidation and Transport in the Hallway

The compartment fire gases exit the vitiated compartment and enter into a hallway with a significant amount of oxygen available. The transport and oxidation of the fire gases in the hallway is highly dependent on the mixing of the gases entering the hallway and the chemical kinetics of the upper-layer gases. When the mixing is similar, the oxidation of CO and other species is primarily a function of the chemical kinetics, which are driven by temperature and the rate of reaction. The rate of reaction is determined using the "law of mass action,"

$$RR = k_{fuel}\left[C_{fuel}\right]\left[O_2\right] \tag{6}$$

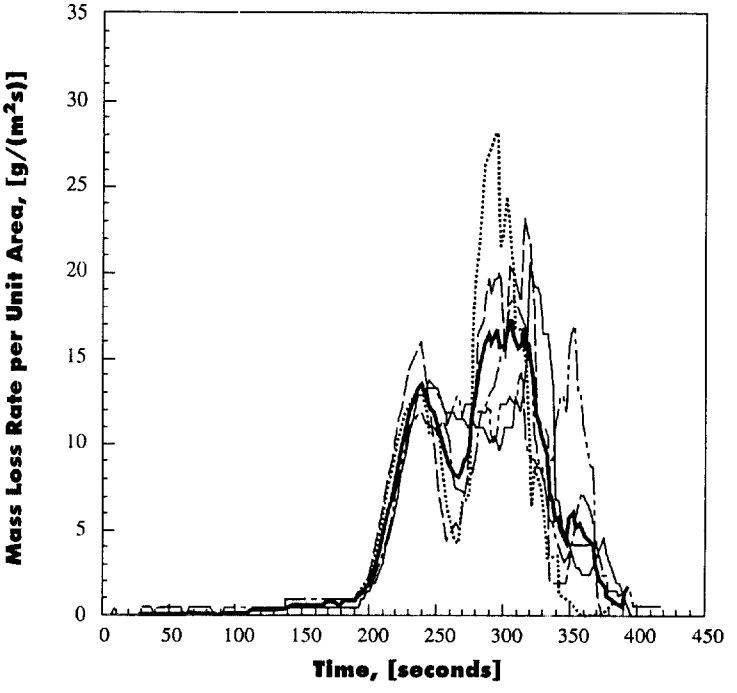

Figure 14. The wood mass loss rate per unit area as a function of time for five different experiments with a window opening. The bold solid line is an average of the five measured mass loss rate curves.

where RR is the rate of reaction, k_{fuel} is the reaction rate constant for the fuel and $[C_{fuel}]$ is the concentration of the fuel.

In tests with no wood in the compartment upper layer, the gases entering the hallway contain UHC concentrations that are greater than the CO concentrations. In these cases, the UHC concentration was shown in Figures 6 and 8 to be reduced faster than the CO concentration. As reported by Westbrook and Dryer,[13] the faster reduction in UHC compared with CO can be attributed to the UHC having a higher rate of reaction than CO and oxidation of UHC producing CO.

Since the reaction-rate constant for UHC is greater than that of CO, the concentration of CO must be significantly greater than that of the UHC for the oxidation of CO to proceed more readily than UHC oxidation. Oxidation in the hallway is seen in Figures 6 and 8 to be significantly slower when the measured temperature fell below 900 K, and the flaming was observed to cease 2.0 to 2.3 m down the hallway. In fire environments with a temperature less than 900 K, CO

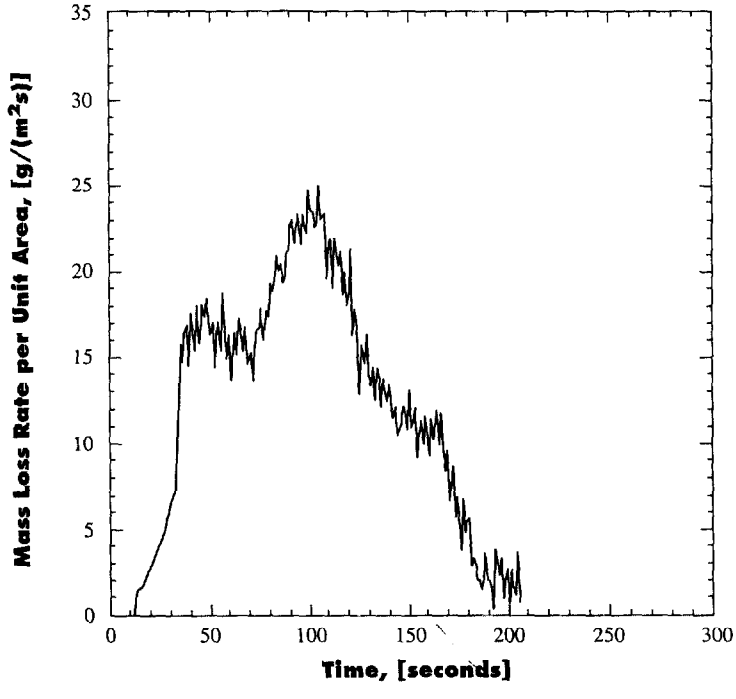

Figure 15. The mass loss rate per unit area of a Douglas Fir plywood sample tested using the cone calorimeter at a incident heat flux of 50 kW/m².

oxidation was determined by Pitts[14] to slow significantly. In general, the CO and UHC oxidation trends were similar in the hallway adjacent to the compartment with wood in the upper layer.

Effect of Opening Type on CO Levels

The opening type had an influence on the mixing that occurred in both the compartment and the hallway. In tests with a window-type opening, the flow paths into and out of the compartment were separate. This resulted in a unidirectional flow out of the compartment. In the tests with the door opening, gases flowed in and out of the compartment through the door. This bidirectional flow of gases at the door allows for more interaction (i.e., mixing) to occur between the inflow and outflow streams.

The CO concentrations in the compartment with the door were measured, on average, at approximately 5.7%, which is approximately 2.5% higher than levels in a compartment with a window opening. With the UHC concentrations approximately 1.0% lower in the tests with a door opening, the higher CO concentration in the door case was attributed to more of the UHC being converted to CO. Due to the inaccuracy of the calculated air entrainment rate into the compartment with a door, the yields in this case were not calculated. In the hallway, the CO concentrations were reduced more effectively with a door opening. As a result, the CO concentrations in the gases leaving the hallway were at approximately the same level. The more effective reduction in CO was attributed to the door opening inducing more air entrainment in the hallway.[15] This increase in air entrainment into the fire gases was attributed to the shear flow effects between the air being entrained into the compartment and the fire gases exiting the compartment, and the gases being able to rise vertically over a larger distance with the door-type opening.

The type of opening also had an effect on the CO concentrations formed inside the compartment with wood in the upper layer. With the door-type opening, the wood in the upper layer caused the CO concentration to increase from 5.7% to 8.0%. The CO concentration with a window-type opening increased from 3.2% to 10.1%, which is significantly more than that measured with a door opening. The difference in the concentrations may be due, in part, to the differences in the residence times of the gases in the two compartments. In the compartment with the window opening, the residence time of the gases was 10 seconds compared to a residence time of 3 seconds for the compartment with a door opening. The higher residence time in the compartment with the window opening may cause more CO to accumulate in the compartment, leading to higher CO concentrations.

Conclusions

The presence of wood in the compartment upper layer was measured to have a significant effect on both the level of CO produced in the compartment and the

degree to which CO was oxidized in the hallway.

Tests with wood in the compartment upper layer produced compartment global equivalence ratios in the range of 5.2 to 5.6. These equivalence ratios are over two times greater than those measured in tests with no wood in the upper layer. Inside the compartment with a window opening, the CO concentrations were measured to increase from an average of 3.2% dry without wood in the upper layer to an average of 10.1% dry with wood in the upper layer. Peak CO concentrations measured in these experiments of 14% are slightly higher than the 12% CO concentrations measured by Pitts *et al.*[2]

The global equivalence ratio concept was determined to be capable of predicting CO_2, O_2, and CO yields in compartment fires with wood pyrolyzing in the hot, vitiated upper layer. These results are expected to hold true not only for fires with wood in the upper layer,but for fires with other oxygenated fuels pyrolyzing in the hot, vitiated upper layer. Additional research needs to be performed to verify the general application of these concepts.

The opening connecting the compartment and hallway had a slight effect on the CO produced in the compartment but a significant effect on the oxidation and dilution of the hallway upper-layer gases. In tests with a door opening, higher levels of CO entered the hallway, but the concentration of CO exiting the hallway was similar to that measured in tests with a window opening. The more effective reduction in CO concentration in the door case was attributed to an increase in air-entrainment rate into the hallway upper layer. Whether there was a window or a door in the compartment, the CO concentration leaving the hallway was measured to be 2.0 to 2.5%, with wood in the compartment upper layer. These levels of CO are fatal to humans after approximately two minutes of exposure.

Acknowledgements

The authors would like to thank the National Institute of Standards and Technology for funding this effort under Contract No. 60NANB4D1651, Dr. W. M. Pitts scientific monitor. Discussions with Dr. W.M. Pitts, Dr. Dan Gottuk and Dr. Craig Beyler were insightful and enhanced the quality of this work.

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Appendix

Uncertainty of Results

Conditions inside the facility for a particular set of experiments were determined by comparing results of five different tests. In each of these tests, gas sampling was performed at a different location to provide information on the evolution of species concentrations and temperature levels within the facility. An error analysis was performed to establish the uncertainty associated with the results.

The error analysis focused on determining the three main sources of uncertainty in the results: repeatability of the test results, error due to diluting the sample gases when sampling inside the compartment with wood in the upper layer, and measurement error.

The repeatability of the results was quantified by calculating the standard deviations of eight sets of replicated tests (16 tests total). The overall standard deviation of the data was determined by taking the root mean square of the standard deviations of each data set. Data sets considered in this analysis were tests where gas sampling was performed both in the compartment and in the hallway. Error analysis on this data provided an average uncertainty (due to repeatability) for data taken both in the compartment and in the hallway. The results of the analysis are provided in Table A-I.

The extraordinarily high CO concentrations inside the compartment with wood in the upper layer exceeded the highest range available on the CO analyzer used in the study (10%). To achieve a gas concentration level that was in the range of the analyzer, the gas stream was diluted by 50% (volume). Four sets of replicated tests (eight tests total) were conducted to verify the performance of the dilution process. The overall uncertainty in the results by the dilution process was determined by calculating the root mean square of the standard deviations of each data set. As seen from the results in Table A-I, the error due to the dilution of the sample gases was determined to be less significant than the uncertainty due to test repeatability.

The uncertainty in the results due to the measurement devices and analytical calculations of different variables was also considered in the error analysis. The three major sources of error in the measuring devices were the errors due to the calibration, the actual measurement and the calibration standard (i.e., calibration gas).[16] The magnitude of these errors was taken to be the manufacturer and supplier quoted values. The magnitude of the error associated with the measurement of the results is shown in Table A-I.

The overall uncertainty in the data was determined by taking the root mean square of the uncertainty associated with the different sources of error. For CO, CO_2 and O_2, overall uncertainty was calculated for situations with and without sample dilution. The uncertainty associated with each measurement is shown in the graphs as error bars.

TABLE A-1
The Uncertainty in Experimental Results

Test Variable	Raw Standard Deviation of Error				
	Repeatability	Gas Dilution	Measurement	Total #1	Total #2
CO [%-dry]	0.26	0.15	0.187	0.32	0.35
CO_2 [%-dry]	0.21	0.18	0.37	0.43	0.46
O_2 [%-dry]	0.56	0.53	0.24	0.61	0.81
UHC [%-wet]	0.77	- -	0.122	0.78	- -
T [K]	39.2	- -	10	40.4	- -
Q [kW]	20.1	- -	26.8	33.5	- -
ϕ	0.14	- -	0.15	0.20	- -

Note:
Total #1 is the expected error when gases are not diluted.
Total #2 is the expected the error when gases are being diluted.