

REDUCED-SCALE VENTILATION-LIMITED ENCLOSURE FIRES - HEAT AND COMBUSTION PRODUCT MEASUREMENTS

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ABSTRACT

The National Institute of Standards and Technology (NIST) recently conducted a series of reduced-scale compartment fire experiments with the purpose of generating a database of comprehensive and accurate measurements that can be utilized both for a better understanding of and improved modeling for compartment fires, especially in the ventilation-limited regime. The series of 17 experiments was conducted in a Reduced-Scale Enclosure (RSE) with dimensions 95 cm wide x 98 cm tall x 142 cm deep and a doorway 81 cm tall x 48 cm wide. This compartment was an approximately 2/5-scale model of the ISO 9705 room. Single, centered burners were used, and the fuels investigated were: natural gas, heptane, toluene, methanol, ethanol, and polystyrene. The liquid fuels were delivered in both pool burner and spray burner configurations. A few half-width doorway experiments were conducted with natural gas and heptane. Two types of wall material were included.

Four to six target heat release rates up to 400 kW were explored with the goal of reaching under-ventilated conditions. Within the 17 experiments, 56 different combinations of fuel, heat-release rate, and doorway width were attained to produce steady state or generally steady periods for which the data were statistically analyzed.

The heat release rate (HRR) was measured through oxygen-depletion calorimetry in the exhaust hood, and the fuel flows were also metered. Measurements of soot and gas species (through extraction) were made at two interior locations near the ceiling and in the exhaust hood. The gas species measured were CO, CO₂, O₂, and total hydrocarbons. Total hydrocarbons were measured with flame-ionization detectors, and hydrocarbon species were measured using gas chromatography. Gas temperatures were measured in several interior and doorway locations with both bare-bead and aspirated thermocouples. Doorway velocities were estimated with an array of bi-directional probes and pressure transducers. Heat flux gauges and surface thermocouples on the enclosure floor provided estimates of the thermal radiation environment.

Results obtained from these experiments, including analysis of measurement uncertainty, are presented and discussed. Particular attention is given to distinctions between fires with different fuels, including some very high temperatures (>1200 °C), heat fluxes (>150 kW/m²), and CO concentrations (>8 %). Insights into the composition of the measured hydrocarbons are detailed, and differences regarding half-width and full-width doorway experiments are described.

INTRODUCTION

This paper summarizes recent reduced-scale compartment fire experiments, which include local measurements of temperature and species composition. The measurements are new to the compartment fire literature and have been described and analyzed in detail in a National Institute of Standards and Technology (NIST) internal report¹. By design, the experiments provided a comprehensive and quantitative assessment of major and minor carbonaceous gaseous species and

soot at two locations in the upper layer of fires in a 2/5 scale ISO 9705 room. Few previous studies have measurements of soot and accurate temperature and species measurements which allow a more comprehensive analysis of thermal effects on species concentrations. A wide range of fuel types were considered, including aliphatic hydrocarbons (natural gas, heptane), aromatic hydrocarbons (toluene, polystyrene) and alcohols (methanol, ethanol).

Field models, such as the NIST Fire Dynamics Simulator (FDS)², are widely used by fire protection engineers to predict fire growth and smoke transport for practical engineering applications. Field models numerically solve the conservation equations of mass, momentum and energy that govern low-speed, thermally-driven flows with an emphasis on smoke and heat transport from fires. All field models have strengths and weaknesses. Among the various assumptions used in the development of FDS, all chemical species are tied to the mixture fraction via state relations. A single mixture fraction variable cannot accurately predict carbon monoxide and soot so the yield of these species is prescribed in FDS 4. Unfortunately, the yield of these species is not constant, but may be a complex function of their time-temperature history. In practice, an engineer using FDS might choose combustion product yields directly from literature values for well-ventilated burning, using data from a bench-scale apparatus³. Using this approach, the CO and soot concentrations for pool fire burning in an under-ventilated compartment can be underestimated by as much as a factor of ten.

The experimental results obtained by this research are the first step of a long-term NIST project to generate the data necessary to test our understanding of fire phenomena in enclosures and to guide the development and validation of field models by providing high quality experimental data. The experimental plan was designed in cooperation with developers of the NIST FDS model to assure that the measurements would be of maximum value. The experimental measurements are currently being used to validate the recently released FDS 5 which implements a *predictive* model of CO production.

Advanced development of FDS and other field models is extremely important, since it will lead to improved accuracy in the prediction of under-ventilated burning, typical of fire conditions that occur in structures. Improving models for under-ventilated burning will foster improved prediction of important life safety and fire dynamic phenomena, including fire and smoke spread, backdraft, flashover, and egress, which are critically important for application of fire models for fire safety.

EXPERIMENTS

Experimental Set-Up

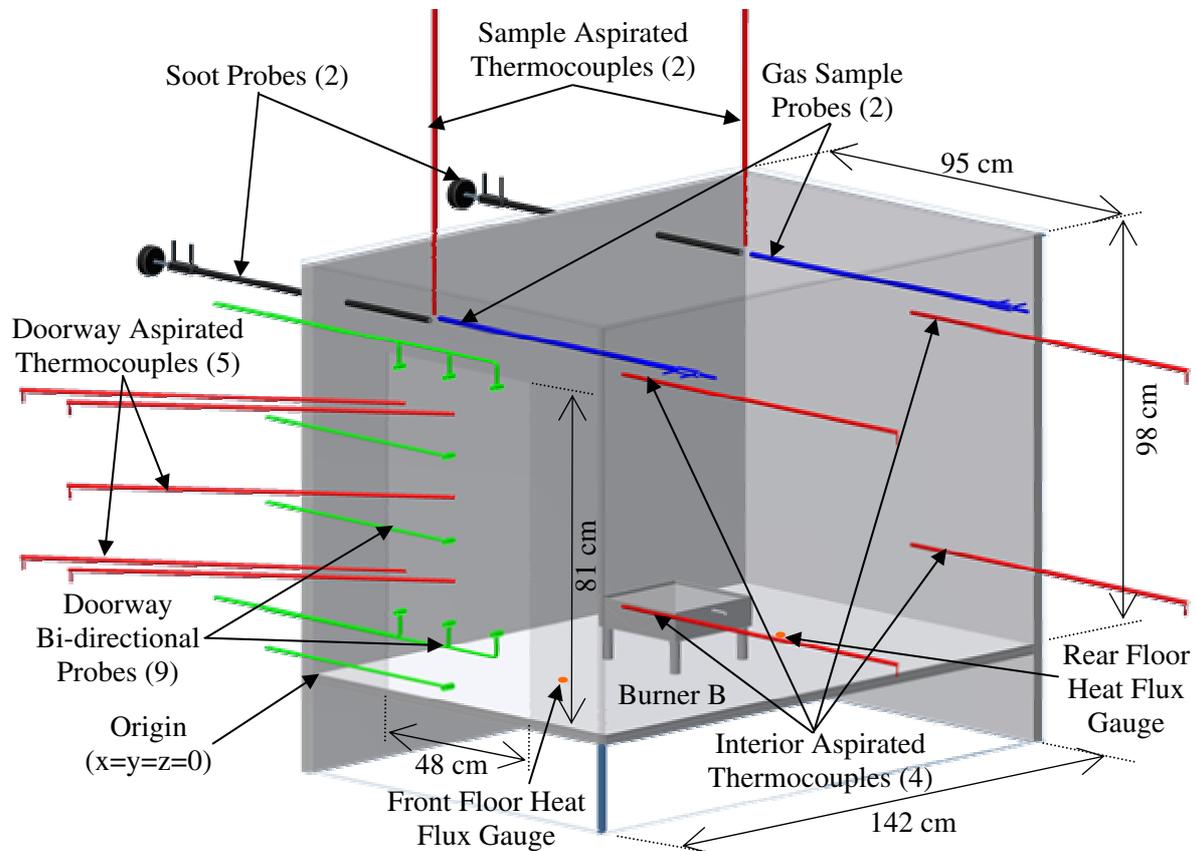
Experiments were conducted using an enclosure, shown in Fig. 1, that is roughly a 2/5 scale replicate of the ISO 9705 room⁴. Details of the design and construction of the Reduced Scale Enclosure (RSE) can be found in the NIST report⁵ which describes its use in the early 1990s to study carbon monoxide production in compartment fires. The internal dimensions were measured as 95 cm wide × 98 cm tall × 142 cm deep, with a pre-burn uncertainty of less than 1 cm on each dimension. The internal dimensions' uncertainty increased as more fire experiments were conducted. The standard doorway geometry (shown in Fig. 1) was 81 cm tall × 48 cm wide and centered horizontally on the 95 cm front wall. The bottom of the door was aligned with the floor. This configuration was used for all but two of the tests described here. The two narrow doorway tests used doorway dimensions of 81 cm tall × 24 cm wide.

The steel frame of the RSE was lined with 2 layers of 1.27 cm thick insulation board. For the first six tests, a calcium silicate board (Marinite I*) was used. For all other tests a rigid self-supporting ceramic fiber (alumina and silica) board (Kaowool M) was used. Each board required different types of fasteners, but an effort was made to keep the attachment patterns similar to the original test series⁵.

* Certain commercial products are identified to adequately describe the experimental procedure. This in no way implies endorsement by NIST.

The performance of the two different lining materials was compared, and fire tests using the different lining materials showed no significant effect on the gas temperature and species measurements.

Figure 1. Isometric semi-transparent view of RSE interior measurement locations and burner.



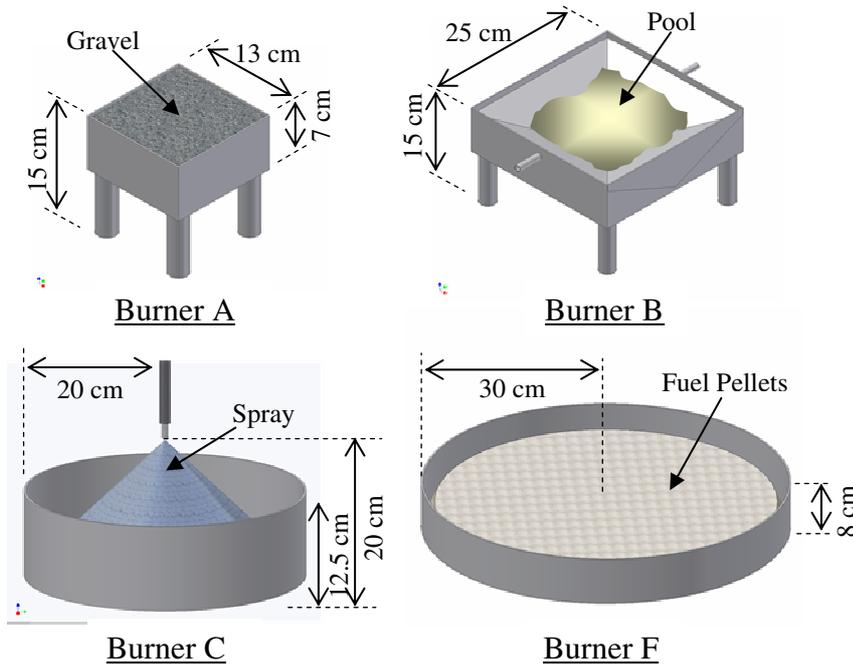
Four different burner designs, shown in Fig. 2, were used in this test series to accommodate the different fuels. A 13 cm square gravel-filled burner (Burner A) was used for the first three tests using natural gas. The area of this burner matched the area of the round burner used in the original test series⁵. The rim of the burner was 15 cm above the floor. Natural gas was delivered to the burner by an insulated 1.3 cm tube that was fed through the floor. A square geometry was chosen for burners A and B to match the rectangular grid used in FDS simulations.

A 25 cm square liquid cooled burner (Burner B) was used for both natural gas and liquid fuels. The burner was designed to have a pool surface area that increased with the depth of the pool. The maximum depth of the pool was 6.5 cm and the burner walls were at a 24° angle with respect to the horizontal plane. This feature allowed for different size steady pool fires with a single burner. Burner B was filled with gravel for some tests with natural gas. Like burner A, the height of the rim was 15 cm from the floor and fuel was delivered by an insulated tube through the floor.

A water-cooled downward spray burner (Burner C) was used for liquid fuels in three tests. The nozzle was located 20 cm above the base of a 40 cm diameter round catch pan with a 12.5 cm rim. The spray was delivered using a 90° full-cone medium atomization ($\approx 250 \mu\text{m}$ droplet diameter) nozzle with a 1.40 mm orifice. The fuel delivery tube was fed through a hole in the ceiling and wrapped with approximately 3 cm thick insulation.

Polystyrene pellets were burned using round pans 22 cm, 40 cm and 60 cm in diameter (Burners D, E and F respectively). Each of the burners was centered on the floor. The pan size was increased for this fuel in order to reach under-ventilated conditions.

Figure 2. Dimensional drawing of burners used in the RSE experiments. Burners D and E were similar to Burner F, but the diameters were 22 cm and 40 cm, respectively.



Experimental Conditions

Experiments were conducted during two separate series. The test number (#), series, and controlled test parameters are listed in Table 1. The two main differences between series 1 and series 2 were the wall lining material and the gas sample conditioning systems.

The fuels included in this test series are listed in Table 1 and included gases, liquids and solids at ambient temperature. The composition of natural gas used for these tests was analyzed and recorded. The heptane fuel was a blend of heptane isomers. The fuel referred to as ethanol was actually a blend of 90 % ethanol and 10 % methanol. The polystyrene fuel was clear, granulated (2.5 g/100 granules), general purpose resin with a manufacturer reported average molecular weight of 231 kg/mol.

Measurement Locations

Temperature, species volume fraction, soot mass fraction, and velocity measurements were conducted at various locations in the compartment doorway and interior. The two primary interior sampling positions were located at the front (10 cm from the ceiling, 29 cm from the left wall, and 10 cm from the front wall) and rear (10 cm from the ceiling, 29 cm from the left wall, and 29 cm from the rear wall). The photograph in Fig. 3 shows the front gas, soot, and temperature measurement probes and their 1.5 cm to 2.5 cm separation distance which is on the order of typical model grid spacing. The sample probe for the gravimetric soot measurement is seen on the right of the image, and the aspirated thermocouple protrudes down through the ceiling. Figure 1 shows the relative positions (drawn to scale) of the measurement probes in the doorway and inside the enclosure respectively. The measurement locations inside the RSE are listed in the comprehensive report¹.

Instrumentation

Heat Release Rate and Fuel Metering

Heat release rate (HRR) measurements were conducted using the 3 m × 3 m calorimeter at the NIST Large Fire Laboratory (LFL). The HRR measurement was based on the oxygen consumption

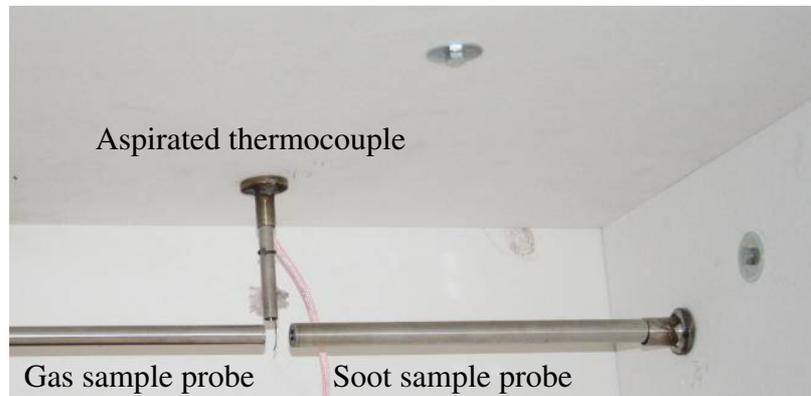
calorimetry principle and used measurements of exhaust flow velocity and gas volume fractions (O_2 , CO_2 and CO) along with the formulation derived by Parker⁶. A detailed description of the methodology used for this measurement can be found in a previous report along with a propagation of uncertainty analysis⁷. Additional modifications to the experimental apparatus are described in the comprehensive report¹. The combined expanded relative uncertainty of the measured HRR was 14 %.

Table 1. List of test numbers and key experimental conditions.

Test #	Series	Fuel	Heat Release Rates [†] (kW)	Door Vent	Burner	Wall Material
1	1	Natural Gas	75, 190, 75	Full	A	Marinite I
2	1	Natural Gas	255, 395, 180, 115, 50	Full	A	Marinite I
3	1	Natural Gas	265, 410, 180, 115, 75	Full	A	Marinite I
4	1	Heptane	155, 270, 375	Full	B	Marinite I
5	1	Heptane	140, 220	Narrow	B	Marinite I
6	1	Natural Gas	75, 175, 270, 420, 80	Narrow	B	Marinite I
6.5	2	Natural Gas	95, 425, 270, 180, 85	Full	B	M board
7	2	Heptane	150, 245, 340	Full	B	M-board
8	2	Methanol	15	Full	B	M-board
9	2	Ethanol	20	Full	B	M-board
10	2	Toluene	50, 140, 200, 295, 340	Full	B	M-board
11	2	Ethanol	80, 145, 265, 335	Full	C	M-board
12	2	Methanol	70, 140, 240, 305	Full	C	M-board
13	2	Polystyrene	15	Full	D	M-board
14	2	Polystyrene	70	Full	E	M-board
15	2	Heptane	90, 160, 225, 300, 375, 85	Full	C	M-board
16	2	Polystyrene	360, 310	Full	F	M-board

[†] Nominal pseudo steady state heat release rate values from calorimetry measurements

Figure 3. Photograph of sampling probes and aspirated thermocouple at the front sample location.



Two different fuel delivery systems were used to control and measure the flow rate of fuel to the burners. The natural gas tests used a positive displacement flow meter with a standard relative uncertainty of 1 % to measure the fuel volume flow rate. Combined with measurements of the fuel temperature, pressure, and measured heat of combustion, the ideal natural gas burner heat release rate was determined with a combined expanded uncertainty of 2.4 %.

The liquid fuel delivery rate was measured using a dual rotor turbine flow meter. Although the liquid fuel volume flow rate was measured, the fuel mass burning rate was not. In some cases, the amount of fuel (depth) in the burners was observed to vary with time, even with a constant fuel delivery rate.

Gas Species and Extractive Soot Measurements

Gas species were continuously measured at two locations (front and rear) inside the RSE during each of the tests. Oxygen was measured using paramagnetic analyzers. Carbon monoxide and carbon dioxide were measured using non-dispersive infrared (NDIR) analyzers. Total hydrocarbons (THC) were measured using flame ionization detectors (FID). A gas chromatograph (GC) with a twenty minute cycle time was used intermittently during some of the tests at the front gas sampling location. The dried sample gas dew point temperature was measured using a thin polymer sensor.

The THC analyzers were designed to measure high volume fractions of hydrocarbons (over 50 % volume fraction as methane). Each analyzer had an internal filter to prevent soot accumulation and loss of sensitivity. External soot filtration was added to protect the analyzer and enable a sufficient time period for sampling soot-laden flows.

Two liquid cooled probes were used to sample gas inside the enclosure at the front and rear locations. The 1 m long probes were constructed of 3 concentric stainless steel (type 304) tubes. Liquid coolant was forced through the inner shell and returned through the outer shell. The inner tube (4.0 mm diameter) was lined with glass to reduce catalytic reactions. Two different gas sample configurations were used during the tests described here. Series 1 used a 120 °C recirculating bath to cool the probes and two stage water traps and filters for moisture and soot removal. Series 2 used 55 °C water to cool the probes and a membrane type drier and large area filter to remove moisture and soot. For both configurations, the front and rear gas analyzer systems were identical, except the GC measurement was conducted only at the front location.

The interactions between the aspirated thermocouples and the gas sampling probes were investigated because of the high suction flow rate. Before the tests were conducted, numerical simulations were used to determine the effect of the probes on the flow field for various operating conditions. It was found that inter-probe impact was negligible even when sampling within the same $\approx 10 \text{ cm}^3$ volume.

A gas chromatograph (GC) was used at discrete times during the RSE tests to identify and quantify the major hydrocarbon species for each fuel and fire size at the front gas sampling location. The majority of the stable intermediate species were identified and quantified with a Hewlett-Packard 5890 GC with flame ionization detector (FID). For chromatographic separation, a Restek Rt-QPLOT column (30 m, 0.32 mm ID) was installed. Identification of unknown species was accomplished by retention time matching. The FID was used to quantify identified compounds employing either the calibration curve for the specific identified molecule or a calibration curve of a similar molecule. The correction techniques used generated relative uncertainties of 1 % to 3 %, and correction factors for unknown compounds were generally limited to a 1 or 2 carbon number difference.

A gravimetric sampling system was used to measure soot mass fractions at the two sample locations within the enclosure. The design of the soot probe was similar to the gas sampling probe's except the soot probe's sample tube inner diameter was 6.4 mm and it used 65 °C cooling water. The sampling duration was determined by monitoring the pressure drop across the 47 mm round membrane filter to ensure an optimal filter loading. Desiccant dried filters and cleaning pads were weighed using a mass balance with a 0.12 mg expanded uncertainty. After each soot sampling period, the probe was cleaned twice with gun cleaning pads. The total soot mass collected on the filter and 2 cleaning pads was used in determining the soot mass fraction with all masses measured on a dry basis. For most tests, between 10 mg and 200 mg of soot was collected during the 1 min to 5 min sample time. The extracted gas volume was corrected for removed water. The combined expanded relative uncertainty of the soot measurement (for mass fractions greater than 0.001 g/g) was in the range of 2 % to 5 %.

Temperatures, Pressures, Velocities, and Heat Flux

To reduce the effect of radiative energy exchange between thermocouples and the hot environment on temperature measurement accuracy, aspirated thermocouple probes were used in addition to bare-bead

thermocouples. The aspirated thermocouple probes in this study used two concentric cylindrical tubes as shields and were based on a design by NASA's predecessor agency⁸. Each aspirated thermocouple was connected to a set of wet-ice and dry-ice traps, a flowmeter, and a pump using 9.5 mm OD copper and polyethylene tubing with flows set at 24 L/min. Due to the large flows pumped through the aspirated thermocouple probes, the resulting temperature represents a volumetric average over a several centimeter diameter region at the probe end. Further discussion of the probe and gas interactions, a probe model analysis, and measurement uncertainty evaluation is in the main report¹ along with a description of several surface temperature measurements that were also made.

Dynamic pressure was measured at 9 locations in the doorway of the enclosure in order to determine velocities in the doorway. The differential pressure transducers had a 133 Pa range. The transducers were connected to 1.3 cm diameter bi-directional probes⁹ with 6.4 mm diameter copper tubing. Probe leads were routed to ensure exposure to similar heating levels, and transducers were shielded from heat effects. Temperatures near the bi-directional probes were required to calculate velocities. Because aspirated thermocouples can intrude on the pressure measurement, bare-bead thermocouples were used to measure temperature although the uncertainties can be extremely large. The measured doorway velocities were in the range of -7 m/s (flow out of the enclosure) to $+1.5$ m/s (into the enclosure). The combined expanded ($k = 2$) uncertainty in the speed measurement varied from ± 0.5 m/s to ± 2.3 m/s with the pressure fluctuation due to turbulence being the most significant component of the variation.

Total heat flux was measured at two locations during each experiment. The heat flux gauges were 6.4 mm diameter, Schmidt-Boelter type, 150 kW/m^2 range, water cooled gauges with embedded type-K thermocouples. Each gauge was inserted flush with the surface of the floor and facing upward. The gauges were located on the centerline of the enclosure with the rear gauge about $\frac{3}{4}$ of the way toward the rear from the front and the front gauge about $\frac{1}{4}$ of the way toward the rear from the front. The main sources of uncertainty related to the total heat flux measurements were: the calibration, soot and dust deposition, and shifting of the gauge surface below the floor. The Bryant et al.¹⁰ model of uncertainty for fire environment heat flux gauge measurements was used, and a conservative uncertainty estimate of $\pm 6 \%$ for gauge calibration was used since the NIST calibration was within the 3% range in a recent round-robin study¹¹. For those experiments with sooty fuels and under-ventilated conditions, combustion products including soot periodically impinged on the floor, and it was estimated that soot on the gauge would add an additional uncertainty of $\pm 10 \%$.

EXPERIMENTAL RESULTS

This section highlights certain measurements and measurement locations which are only a small portion of all the experimental results¹. Unless otherwise noted, uncertainty results reported here, including error bars on steady state average values, represent the combined expanded (coverage factor $k = 2$) uncertainty generated from a propagation of uncertainty analysis.

Average temperatures were calculated over pseudo-steady periods for all of the tests. Figure 4 shows the steady temperatures at the rear gas sample location for all of the fuels included in this study. In general, the soot producing fires (heptane, toluene, polystyrene) generated hotter gas temperatures inside the enclosure than the cleaner fires (natural gas, alcohols) at the same measured HRR.

The heat flux measurements to the floor of the enclosure help to characterize the thermal environment within the enclosure and the transient nature of interior burning. In general, the heat flux levels were significantly higher ($>100 \text{ kW/m}^2$) for the fuels with high soot yields. In addition, for the clean burning fuels, the heat flux was fairly constant above HRRs of 200 kW . Heat flux levels in excess of 150 kW/m^2 were measured for under-ventilated toluene fires and some heptane fires. Although these values are reasonable based on the measured temperature of the upper layer, they are well beyond the calibrated range of the transducer. The actual net heat flux to the floor (that has been heated by the fire) would be somewhat less than the measured net heat flux to the water-cooled gauge in the floor. For the highest fluxes and floor temperatures, this effect is on the order of 15% of the measured flux.

Figure 5 shows the time-averaged species volume fractions as a function of HRR for all of the natural gas tests with the full-door configuration (see Table 1). The trend lines are included in this figure to help visualize general trends in the data, but do not have a theoretical basis. The figure demonstrates the excellent reproducibility of the gas species measurements and lack of sensitivity of the results to the two different wall lining materials and burners used in this study.

Figures 6 and 7 show the O₂ volume fraction at the front and rear sample locations, respectively, as a function of heat release rate for the six different fuel types included in this study. Oxygen was depleted for fires larger than about 280 kW. There were some minor variations among the fuel types, with the natural gas fires exhibiting oxygen depletion at a slightly lower HRR.

Figure 4. Steady state average aspirated thermocouple temperatures at rear gas sampling location

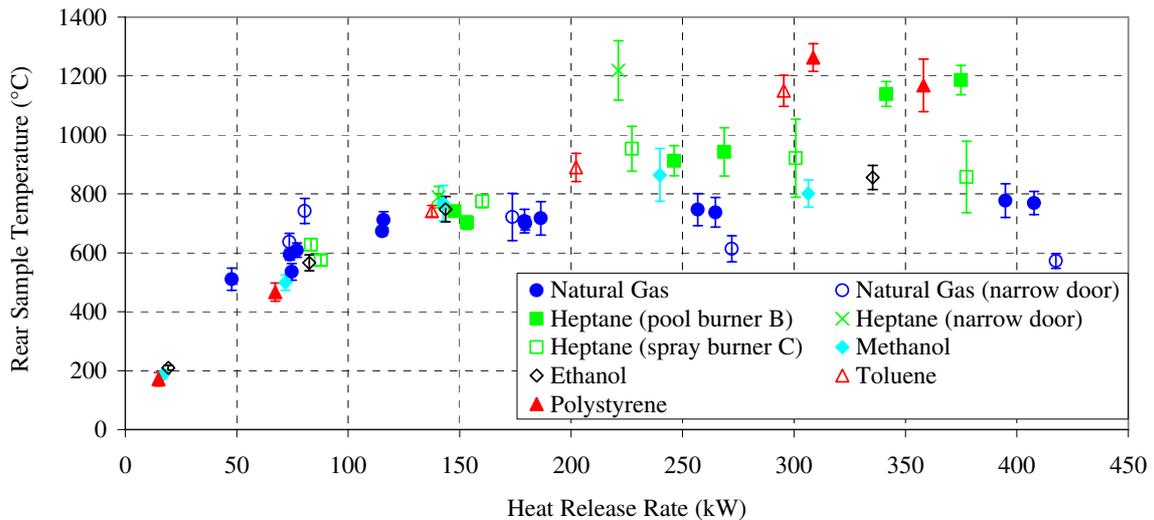


Figure 8 shows the steady state CO results for all of the different fuels at the front location. As expected, the measured CO values were significantly increased after the fire reached a ventilation-limited regime (as indicated by depleted oxygen at the sample locations). The results of the THC volume fraction measurements at the front location are shown in Fig. 9. Figure 10 shows the results of the gravimetric soot mass fraction measurements.

For the experiments using the half-width doorway, the most obvious effect was that the transition to ventilation-limited burning occurred at a much lower HRR than for the full doorway configuration. This transition was made evident by the reduced O₂ and increased CO volume fractions as well as the appearance of flames outside the doorway. For natural gas, the magnitudes and front to rear variations of gas temperatures and species concentrations were similar for the narrow and full door tests. For heptane, the internal structure of the fire was reversed for the narrow doorway in that higher temperatures and CO concentrations were at the rear sample location.

For comparison with the GC results, the HRR, the THC (FID), and the CO volume fraction were averaged over a 30 s window ending at the injection time. The THC volume fractions determined using the GC were calculated for comparison with the THC analyzer results, with all species converted to an equivalent methane basis. The results of this comparison are illustrated in Fig. 11. For the liquid and solid fuels included in this study, a large number of intermediate hydrocarbon species were quantified. In all cases, methane was the largest measured component of hydrocarbon species, including the parent fuels. Even though the GC measured species only as large as C₆, the similarity between the THC results from the GC and the THC analyzer provides evidence that there were no species of significant quantity missed by the GC analysis.

Figure 5. Steady state average gas species and soot for natural gas full doorway tests.

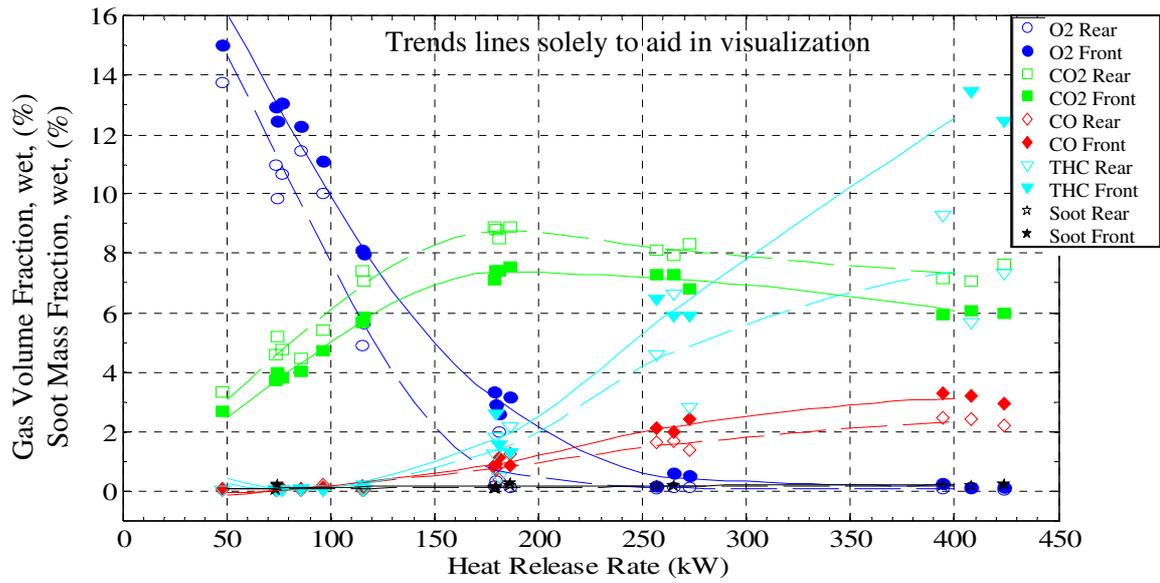


Figure 6. Steady state average oxygen volume fraction measurements at front sample location.

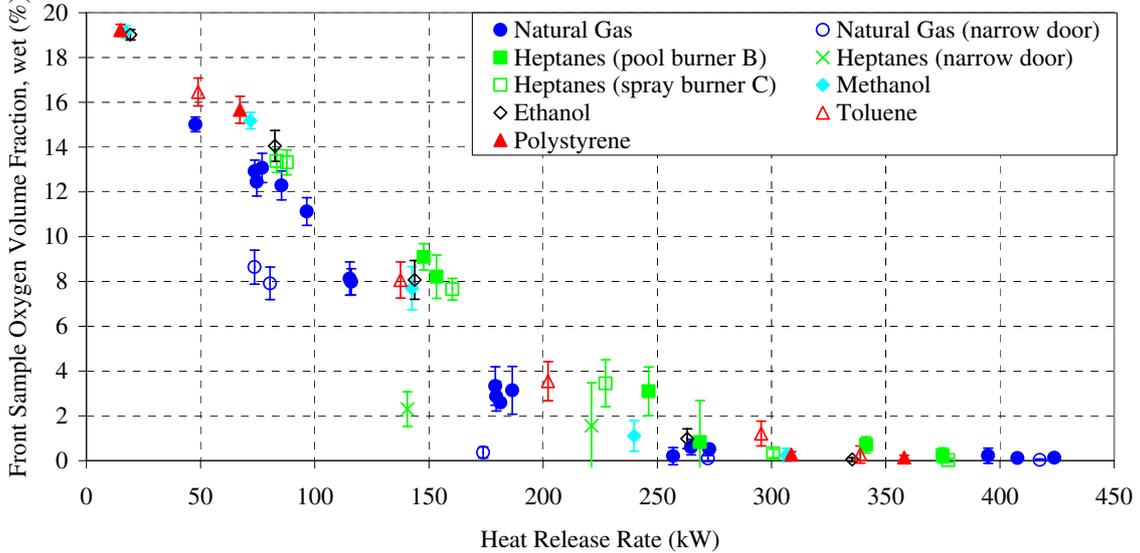


Figure 7. Steady state average oxygen volume fraction measurements at rear sample location.

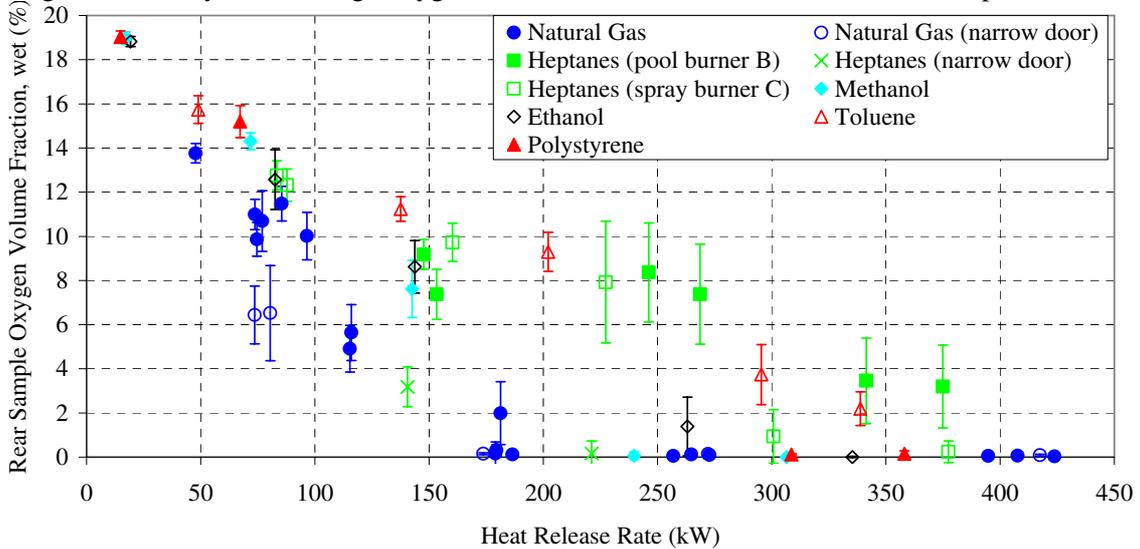


Figure 8. Steady state average carbon monoxide volume fraction at front sample probe location

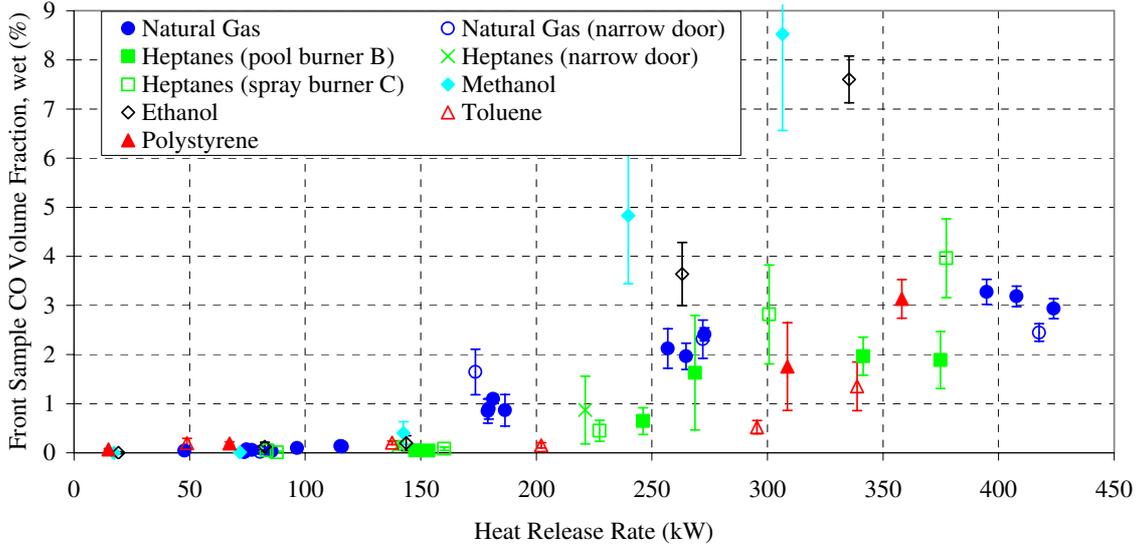


Figure 9. Steady state average total hydrocarbon volume fraction at front sample probe location

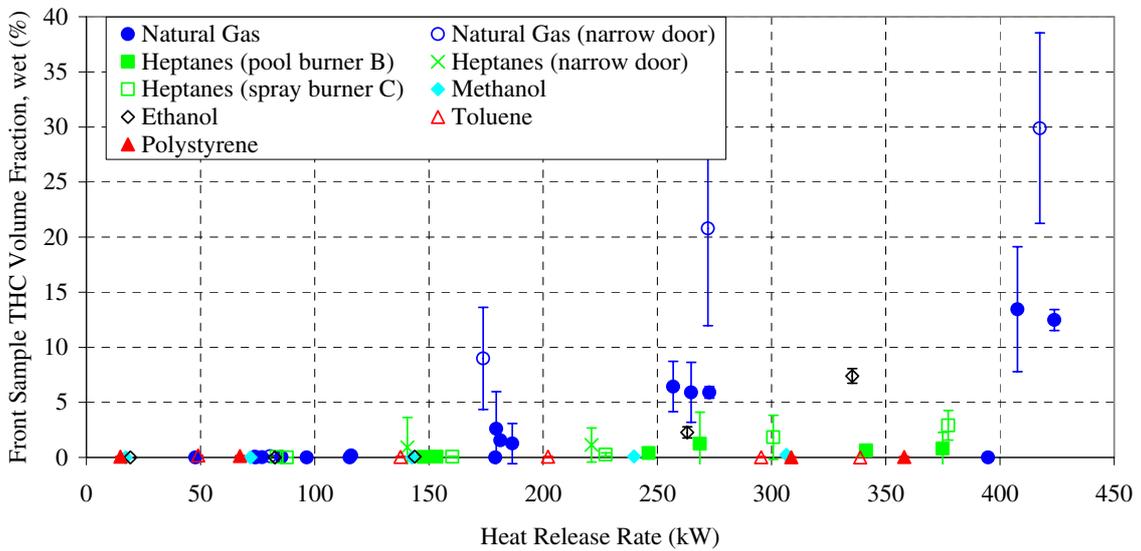


Figure 10. Steady state gravimetric soot mass fraction at front sample probe location

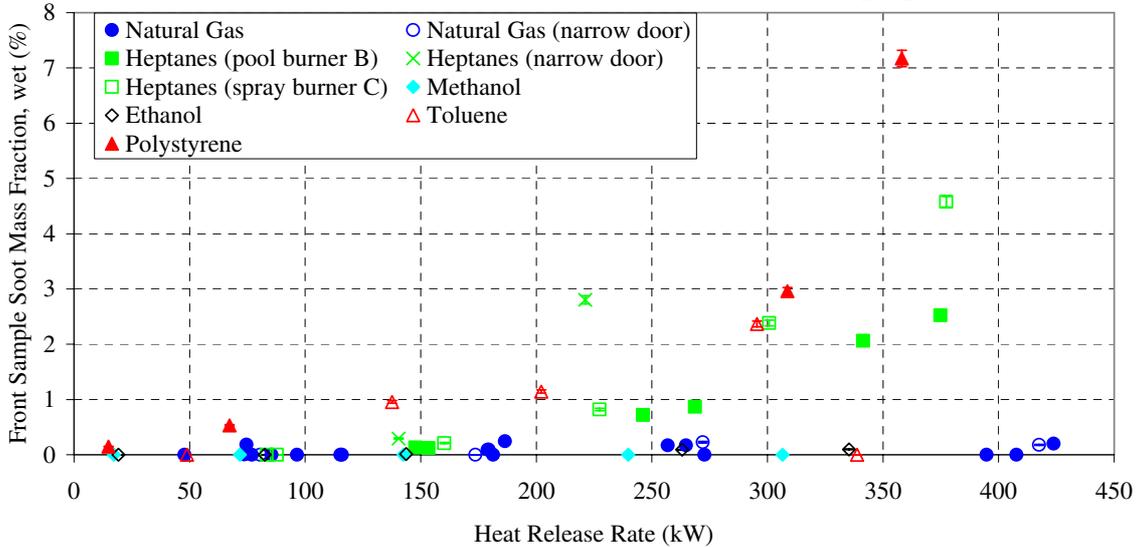
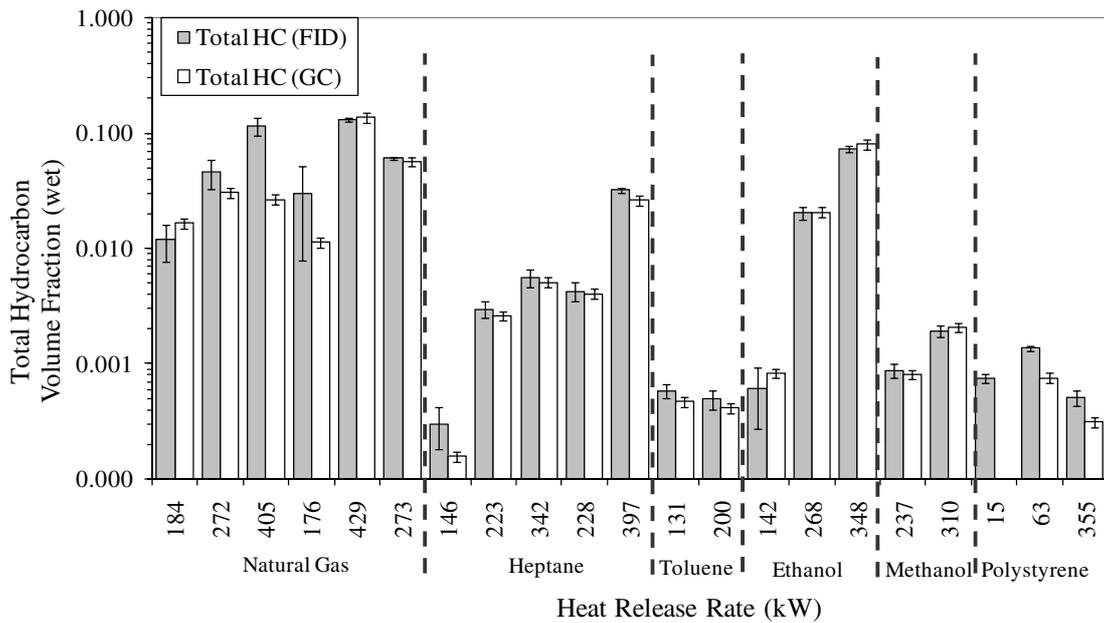
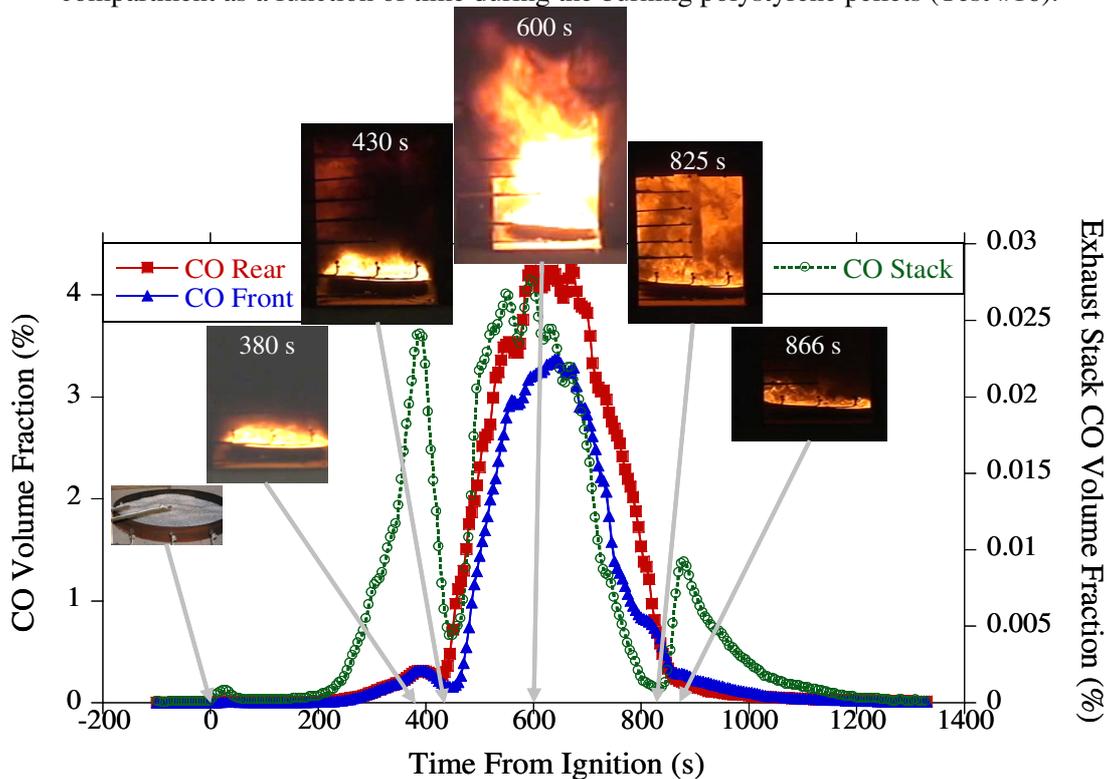


Figure 11. Comparison of total hydrocarbons measured using the GC and the total hydrocarbon analyzer (THC Front), both expressed on a CH₄ basis.



For Test #16, 6.0 kg of polystyrene pellets were burned in a 60 cm diameter pan. This test differed from all of the other tests as it involved a solid material in which heat feedback from the fire controlled the burning rate after ignition with a heptane spray. Figure 12 shows the CO volume fraction in the exhaust stack and two compartment sampling locations as a function of time. Photographs at various times during the experiment show the appearance of the fire. At both compartment locations, the CO increased as a function of time, reached a maximum, and then decreased to near-zero. The CO measurements show that the peak at 600 s observed inside of the compartment was also reflected in the stack. More detailed analysis of this experiment is available¹.

Figure 12. The CO volume fraction measured in the stack and at the front and rear of the compartment as a function of time during the burning polystyrene pellets (Test #16).



SUMMARY AND CONCLUSIONS

This paper summarizes the test methods and experimental results from a series of fire experiments in the reduced scale enclosure. The following describes selected findings from the detailed report¹:

- New measurements of total hydrocarbons, and soot were successfully performed and provide a more complete data set for validating and improving predictive fire models.
- As much as 60 % of the carbon in a polystyrene fire was present in the form of soot, which was twice as much as for the other hydrocarbons tested.
- No significant amount of THC was measured in the upper layer of the compartment in the toluene or polystyrene fires.
- The mass fraction of CO in the upper layer of a reduced-scale compartment fire did not systematically correlate with the local temperature or mixture fraction.
- The gas species composition measurements showed that methane was the most abundant hydrocarbon species in the upper layer for all of the fuels and fire conditions tested, and was higher in concentration than the parent fuel in all cases (excluding natural gas).
- Further flashed-over, under-ventilated enclosure fire experiments are planned in a full-scale ISO 9705 room to explore the effects of scale on temperatures, CO, soot, and THC with a special focus on more realistic fuels like polystyrene and toluene which exhibited distinctive behaviors.

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