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COMPARTMENT FIRE COMBUSTION DYNAMICS

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COMPARTMENT FIRE COMBUSTION DYNAMICS

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Annual Report

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1.0 EXECUTIVE SUMMARY

The overall scope of this research is to investigate the phenomena that control the generation and oxidation of compartment fire exhaust gases, specifically carbon monoxide (CO), total unburned hydrocarbons (THC) and soot, which are transported down an adjacent corridor. The first year of the investigation concentrated on the formation of exhaust gases, mainly CO, within the compartment. In the second year, a hallway was attached to the compartment in such a manner that the gases from the compartment entered at the ceiling of the corridor. The oxidation of the exhaust gases down the hallway was studied for a corridor having no soffits at either end. During the past year, three additional hallway soffit combinations were added to see the results of varying the fluid mechanics of the exhaust gases within the hallway. Experiments were also performed to observe the effects of varying the air entrainment into the hallway and the compartment. This was followed by an investigation which examined the effect of a combustible ceiling within the compartment on the exhaust gas levels seen in the compartment, in the hallway and downstream of the hallway.

The four soffit combinations within the hallway were no soffits at either end of the corridor (0/0), a 20 cm soffit at the exit of the corridor only (0/20), a 20 cm soffit at the inlet of the corridor only (20/0) and 20 cm soffits at both the exit and inlet of the corridor(20/20). The (0/0) case was performed during the second year of the investigation while the other three have been done in the past year. By adding a 20 cm soffit at the end of the hallway (0/20), the upper-layer of exhaust gases in the hallway became thicker and inhibited the oxidation of the fuel rich gases. The addition of the soffit at the beginning of the hallway, (20/0), dramatically improved the oxidation of the exhaust gases. This was attributed to the soffit enabling the gases to form a buoyant plume at the entrance of the hallway as opposed to the cases where no inlet soffit present and a ceiling jet is formed at the exhaust vent. This is verified by numerous studies which state that the air entrainment into a vertical, buoyant plume is more efficient than that of a ceiling jet. When the 20 cm soffit was added to the end of the corridor with a 20 cm soffit at the entrance (20/20), the oxidation of the exhaust gases decreased but not as much as it did in the (0/20) case. This is due to the oxidation of the exhaust gases occurring in the first half of the hallway because of the efficient air entrainment.

The entrainment of air into the hallway and into the compartment were altered to study its effects on the CO oxidation. By physically partially blocking off the end of the hallway in 1/4 ceiling height increments (0.43 m), the air entrained into the hallway was limited. This had no effect on the oxidation of the exhaust gases for the two soffit cases investigated, (20/0) and (20/20).

In order to compare results with BFRL / NIST, the compartment had to be altered so it was similar to their facility. The plenum underneath the burning room of the compartment was blocked off from the atmosphere. A door size exhaust vent, instead of a window size vent, at the entrance of the hallway was where air entered the compartment and combustion gases exited the compartment. The entrainment of air into the external burning was better in the door case compared to the window case due to the increased interfacial area between the buoyant fire jet exiting the compartment and the air in the hallway. Large vortical structures extending out of the compartment exhaust vent are also believed to aid in the entrainment of the air into the combustion gases in the hallway.

The last set of tests performed were those with a Douglas fir wood ceiling inside the compartment with and without the plenum blocked. These tests confirmed results obtained by Pitts et al. (1993) in which higher CO levels were generated within the compartment and lower in-compartment temperatures were produced due to the endothermic process of wood pyrolysis. The in-hallway experiments showed that the extremely fuel rich gases exiting the compartment cause the temperature of the upper-layer to rise down the hallway. The peak temperature in the hallway occurs approximately half way down the corridor while the temperatures at the end of the hallway are equal to or greater than those seen in the compartment. This aids in the oxidation of the exhaust gases but increases the heat flux seen by objects near the external burning.

2.0 INTRODUCTION

The loss of lives in building fires due to carbon monoxide (CO) inhalation at locations remote from the fire itself continues to be an issue in densely populated areas. With a colder and longer winter than in the previous years, the death toll due to fires during the winter of 1994 reached levels close to the totals from 1993 in many localities. The issue of carbon monoxide levels inside building fires has also caught the attention of law makers, as evidenced by the new ordinance in Chicago requiring the installation of a CO detector, in addition to a smoke detector, in newly built buildings.

The present research is investigating the formation and destruction of carbon monoxide from compartment fires. The formation of CO within the compartment was explored in the first three year stage of the investigation. The transport and oxidation of CO outside of the compartment is the focus of the second three year stage of the investigation.

During the first year of the second stage, gases from inside a burning compartment were allowed to exhaust into the open atmosphere. When these fuel rich gases ignited outside the compartment, due to flame propagation and radiation from inside the compartment, a burning buoyant jet of fire issued out of the compartment into the open atmosphere, termed free-jet external burning. The free-jet external burning was successful in reducing the carbon monoxide yield to 10-25% of the CO yield in the upper layer inside the compartment (Gottuk, 1992). Gottuk (1992) also showed the free-jet external burning reduced soot yields to 0-50% of the soot yields in the upper layer of the compartment. The free-jet exhausts into a thermally unstable environment where there is a large interfacial area between the gases and ambient air. The oxidation of CO and soot, which is controlled by how well air is entrained into the jet, seen in the buoyant free-jet experiments is thus considered the most efficient since the free-jet offers the best unforced mixing.

The second year concentrated on the transport and oxidation of exhaust gases, mainly CO and THC, in a hallway adjacent to the burning compartment. The experiments consisted of a hallway, with no soffits at either end, which was oriented with the compartment window style vent so that combustion gases flowed directly down the corridor into an exhaust hood. When the compartment fire became underventilated, the fuel rich gases spilling into a connected hallway would ignite, termed confined-jet external burning. When no soffit is present at the hallway entrance, the confined-jet is a ceiling-jet exhausting into a thermally stable atmosphere (hot gases at the ceiling and cool ambient air at the floor). The stratified environment of the hallway made it more difficult for the ceiling-jet to entrain the air necessary to oxidize the combustion gases. As a result, the carbon monoxide levels were reduced to 32-46% from in-compartment levels while unburned hydrocarbons and soot were reduced to 7-17% and 14-52% from in-compartment levels, respectively. As expected, the yield levels of the combustion gases are much higher than those seen in the free-jet experiments.

During the past year, the transport and oxidation of the exhaust gases in the hallway has been the focus of the investigation. The hallway was kept in the same orientation relative to the compartment, but the soffit heights at both ends of the hallway were varied. A soffit at the entrance of the hallway, where the compartment is located, had a strong effect on the reduction of CO levels outside of the compartment while a soffit at the end of the hallway inhibited the reduction of CO outside of the compartment. In addition to these experiments, the effects of limiting the amount of air entrained into the hallway was investigated by gradually blocking off the end of the hallway open to the surroundings. This was not found to affect the oxidation of the exhaust gases in the two soffit cases considered. It was then requested that experiments be run with the plenum underneath the burning compartment blocked off from the surroundings to be able to compare results with researchers at BFRL / NIST. The compartment exhaust vent was enlarged to be door-like in size allowing air from the hallway to flow into the compartment and combustion gases to flow out of the compartment and down the corridor, termed the "door case". The term "window case" will be used to describe the experiments where the plenum is open and a smaller, window size exhaust vent is present. Air entrainment into the combustion gases in the hallway was found to be more efficient in the "door case" compared to "window case". The last experiments included in this report will be those with a combustible wooden ceiling inside the compartment. These experiments were run with both the "door case" and the "window case". The levels of CO were seen to be much higher within the compartment and the hallway compared to those experiments with no combustible ceiling inside the compartment, while the CO concentrations between the "door" and "window" case experiments were comparable.

In addition to the experimentation, several facility improvement projects were completed. These projects include: an automated fuel supply, an automated sampling cart for the hallway, a new roof over the facility, and a new, more versatile hallway design.

The remainder of the report will include a brief summary of the first and second year results, the current experimental apparatus, the improvement projects, a results and discussion section of the past year's results and finally the plans for future work.

2.0 SUMMARY OF FIRST YEAR RESULTS

The first year of the investigation focused on the generation of exhaust gases from a compartment fire and the reduction of these exhaust gases when a free-jet of external burning occurred at the exhaust vent, see Figure 1. These experiments were performed using the same compartment used in the current investigation. The insulated compartment exhausted directly into the open atmosphere, and the combustion products were collected in an exhaust hood duct system. Species measurements made in the exhaust duct were compared to the in-compartment measurements made during the first stage of this investigation to determine the efficiency of external burning of the oxidation of exhaust gases. The soot measurements were not performed within the compartment so, the effect of external burning on soot had to be based on a comparison of soot levels before and during external burning.

Two distinct types of external flames were observed during the compartment fires. Chronologically, external flame jets which extended from the main fire within the compartment and out through the exhaust vent occurred first. During significantly underventilated burning in the compartment, the exhausting gases from the compartment would mix with ambient air and ignite creating external burning. Three different types of external burning occurred: 1) quick flashes, 2) short bursts and 3) sustained external burning (Gottuk, 1992)

Overventilated fires never produced external burning due to the availability of oxygen in the compartment, resulting in complete combustion of the fuel inside the compartment, thus no flammable gases were exhausted. For underventilated fires, there existed characteristic equivalence ratios that make the onset of external flashes and then sustained external burning. Flashes were reported to occur at an equivalence ratio of 1.4 $\pm$ 0.3 (Gottuk, 1992). The characteristic equivalence ratios showed a slight dependence on the exhaust vent area, reported as 2.1 $\pm$ 0.3 for exhaust vents of area less than about 400 cm^2, and 1.8 $\pm$ 0.2 for exhaust vents of area in the range of 800 to 1600 cm^2 (Gottuk, 1992). This exhaust vent dependence was explained by the smaller flame jets observed with smaller exhaust vent areas, providing a smaller ignition source for the exhausting gases. Although the flammability of the exhaust gases mixing with ambient air was determined by the equivalence ratio, the occurrence of sustained external burning was also found to be dependent on the presence of an ignition source.

Although an instantaneous equivalence ratio of 1.9 was required for sustained external burning to begin, compartment fires required "quasi-steady state" averaged equivalence ratios of 1.7 to provide sustained external burning. The occurrence of sustained external burning was the only form of external burning observed to reduce CO and soot levels significantly. Compared to CO yields measured in the compartment for underventilated fires, 0.22 , CO yields during external burning were reduced to 10 - 25% of this value (Gottuk, 1992). The CO_2 yields also approached their theoretical maximum, indicating near complete oxidation of all carbon to CO_2 (Gottuk, 1992).

The effect of sustained external burning on soot yields was significant, following the same trends of CO oxidation, but with a larger amount of scatter in the data. Soot was oxidized to 0 - 50% of the levels observed just prior to sustained external burning (Gottuk, 1992). The average soot yields prior to sustained external burning reached 0.015 (Gottuk, 1992).

The total hydrocarbons (THC), taken to be ethylene (C_2H_4), within the compartment were also experimentally determined by Gottuk (1992). It was found that

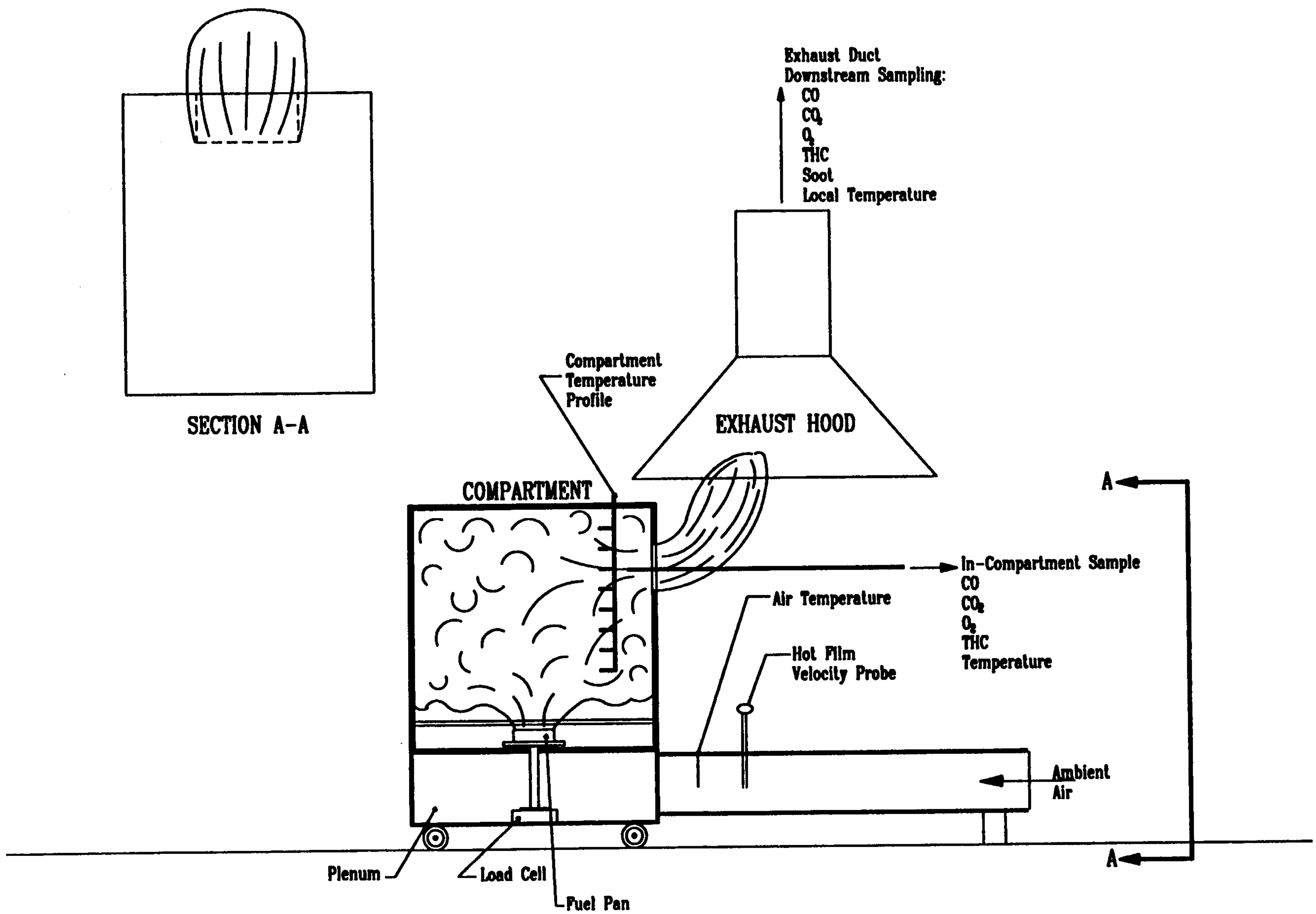


Figure 1. The free-jet experiments performed by Gottuk (1992).

the yields of total hydrocarbons averaged 0.33. The efficiency of oxidation of the hydrocarbons was not determined for the free-jet experiments.

3.0 SUMMARY OF SECOND YEAR RESULTS

During the second year of the study, a hallway was connected to the compartment in such a way that the exhaust gases inside of the compartment would spill into the upper part of the corridor. The investigation concentrated on the occurrence of external burning within the hallway followed by exhaust duct and in-hallway sampling of species for the purpose of studying the oxidation of the exhaust gases down the hallway. These results were then compared to the results obtained in the free-jet tests.

By attaching a corridor to the compartment with no soffit at the entrance of the hallway, a confined ceiling-jet is formed during external burning, see Figure 2, as opposed to the buoyant free-jet which was seen in Gottuk's experiments. The confined ceiling-jet varied in length along the hallway and only in the highest powered fires did the vortical structures described by Hinkley et al.(1984) form down the length of the hallway. These vortical structures were never seen to separate from each other as noted by Hinkley et al.(1984) but instead were connected by the ceiling-jet of fire traveling down the hallway. Flashes and bursts of fire which occur just prior to sustained external burning were found to take place at an equivalence ratio which decreased exponentially with vent area for a particular pan size. These flashes and bursts also vary exponentially with pan size. Sustained external burning (SEB) was found to be a complex function of both the exhaust vent area and the fuel pan size and cannot easily be correlated like the flashes and bursts.

In addition to identifying when external burning occurs within the hallway, the oxidation of the exhaust gases as they are transported down the corridor was investigated. The two types of experiments performed were exhaust duct tests, where gases were sampled within the exhaust duct downstream of the hallway, and in-hallway tests, where gases were sampled at various locations inside the hallway upper-layer. The yields of the species exiting the hallway were found in the exhaust duct tests so that the overall oxidation of the gases within the hallway

$$\eta_{oxid} = \left(1 - \frac{(X_i)_{duct}}{(X_i)_{comp}} \right) 100 \qquad [\%] \qquad (1)$$

could be determined based on the in-compartment yields found by Gottuk(1992). As stated earlier, soot measurements were not performed in the compartment so yields of soot prior to external burning were used instead of in-compartment yields. The in-hallway tests were conducted to study the variation of the exhaust gases within the hallway. The tests in the hallway also aided in the understanding of how the exhaust gases were oxidized within the hallway in addition to the identification of the phenomena which controlled this oxidation. The only soffit combination considered in this investigation was the case of no soffits at either end of the hallway.

In the exhaust duct experiments, the pan size, the vent area and the initial compartment temperature were all varied to generate different powered fires, different fluid mechanics within the entrance of the hallway and different equivalence ratios. The

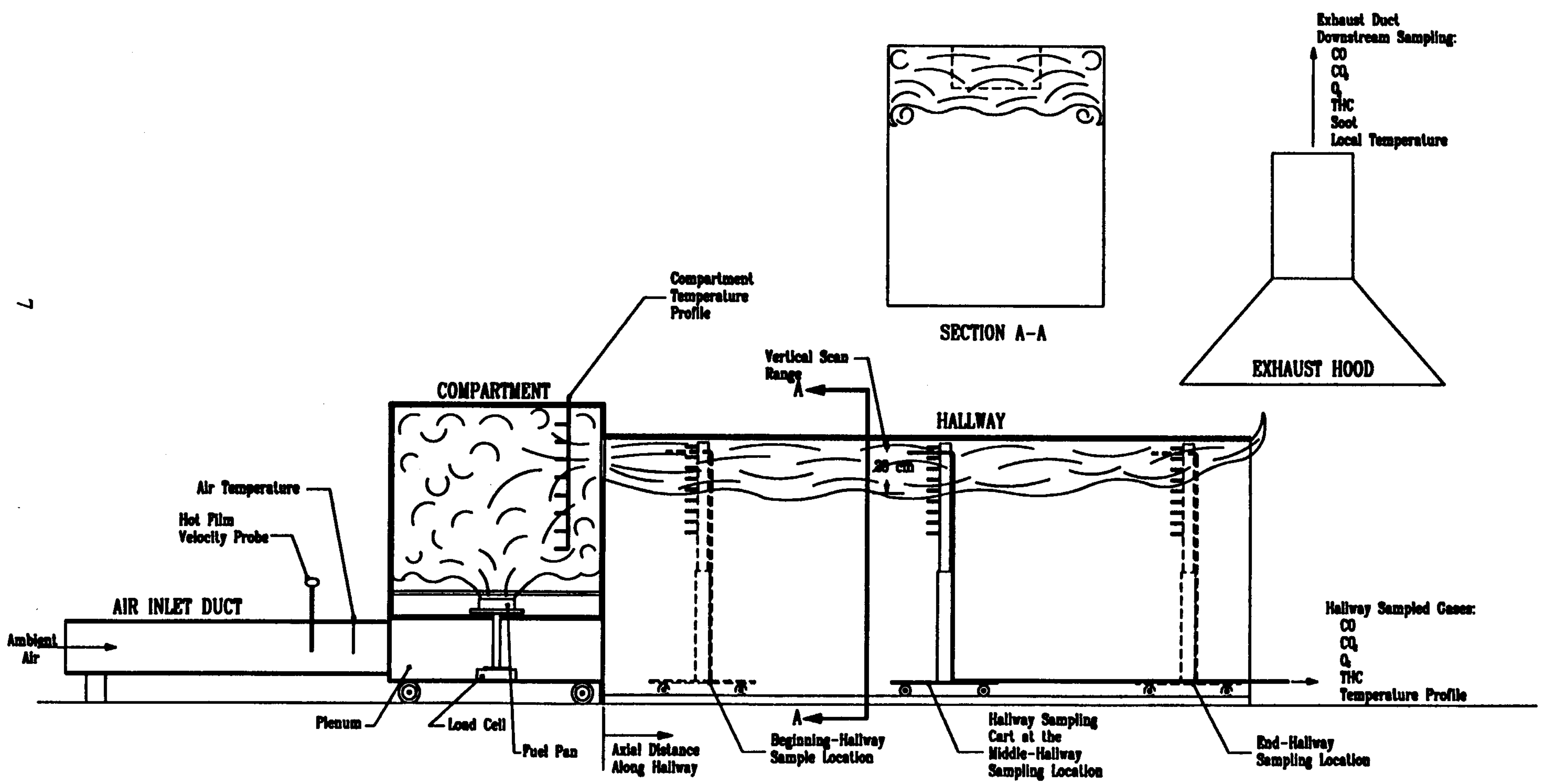


Figure 2. The hallway experiments performed by Ewens (1994) showing the confined ceiling-jet external burning within the hallway.

equivalence ratios varied from 1.7 to 3.5 while both a 20 cm and a 23 cm diameter fuel pans were used in the experiments. The CO yield ranged from 0.100 to 0.070 which corresponds to an oxidation efficiency of 54-68%. The variance in the THC yield was 0.022 to 0.055 resulting in an oxidation efficiency of 83-93%. The soot data varied between 0.0077 and 0.0021 giving rise to an oxidation efficiency of 52-87%.

The in-hallway experiments investigated the variation in the exhaust gases within the hallway in all three directions, axially, vertically and horizontally. The exhaust gases were found to be fairly uniform across the width of the upper-layer. The vertical scans performed at different locations along the length of the hallway showed the visible flame region to be become closer to the ceiling with distance down the hallway. The upper-layer, which consists of the unburned, fuel rich gases and the visible flame region, varied from 10-15 cm to 0-5 cm from the beginning to the end of the hallway, respectively. The axial profiles, which looked at how the exhaust gases varied with the length of the hallway, showed that the THC oxidized faster than CO. With a refined enough profile, the flame length within the hallway can be estimated by a rise in O_2 and a fall in CO, CO_2, THC and temperature.

4.0 THIRD YEAR RESULTS

This section of the report describes the progress over the past year. The current experimental apparatus is first described followed by the improvement projects which have been implemented at different times over the last twelve months. The experimental results which have been obtained over the course of the year are then presented in chronological order.

4.1 Current Experimental Apparatus

A schematic of the current experimental apparatus is given in Figure 3. The two level fire compartment structure consists of a 1.2 x 1.5 x 1.2 m compartment located above a 1.2 x 1.5 x 0.3 m air distribution plenum. The inside surface of the compartment is insulated using 2.54 cm thick Fire Master, UL rated, fire insulation board. A 1.8 m long, 30.5 cm diameter air inlet duct allows air to be drawn naturally into the back of the plenum. The air is distributed uniformly to the compartment through two thermally shielded vents, one on each side of the compartment floor. The majority of the confined-jet external burning tests were run with a short air inlet duct (1.83 m), but upon the erection of a roof above the facility and an extension of the concrete pad, the 4.0 m air inlet duct is presently being used. This is desirable for a more accurate measurement of the velocity within the duct. A window style exhaust vent, centered in the width direction, is located on the front wall of the compartment and opens into the hallway. The exhaust vent size is adjustable in order to vary the overall equivalence ratio in the compartment and the fluid mechanics of the exhausting jet. Exhaust vent sizes used in the hallway experiments varied from 25 x 16 cm to 51 x 24 cm with corresponding areas of 400 cm^2 to 1200 cm^2. A soffit of 20 cm exists inside the compartment to allow the formation of an in-compartment upper-layer. A fixed initial mass of liquid hexane is burned in a steel circular fuel pan placed in the center of the compartment floor. Fuel

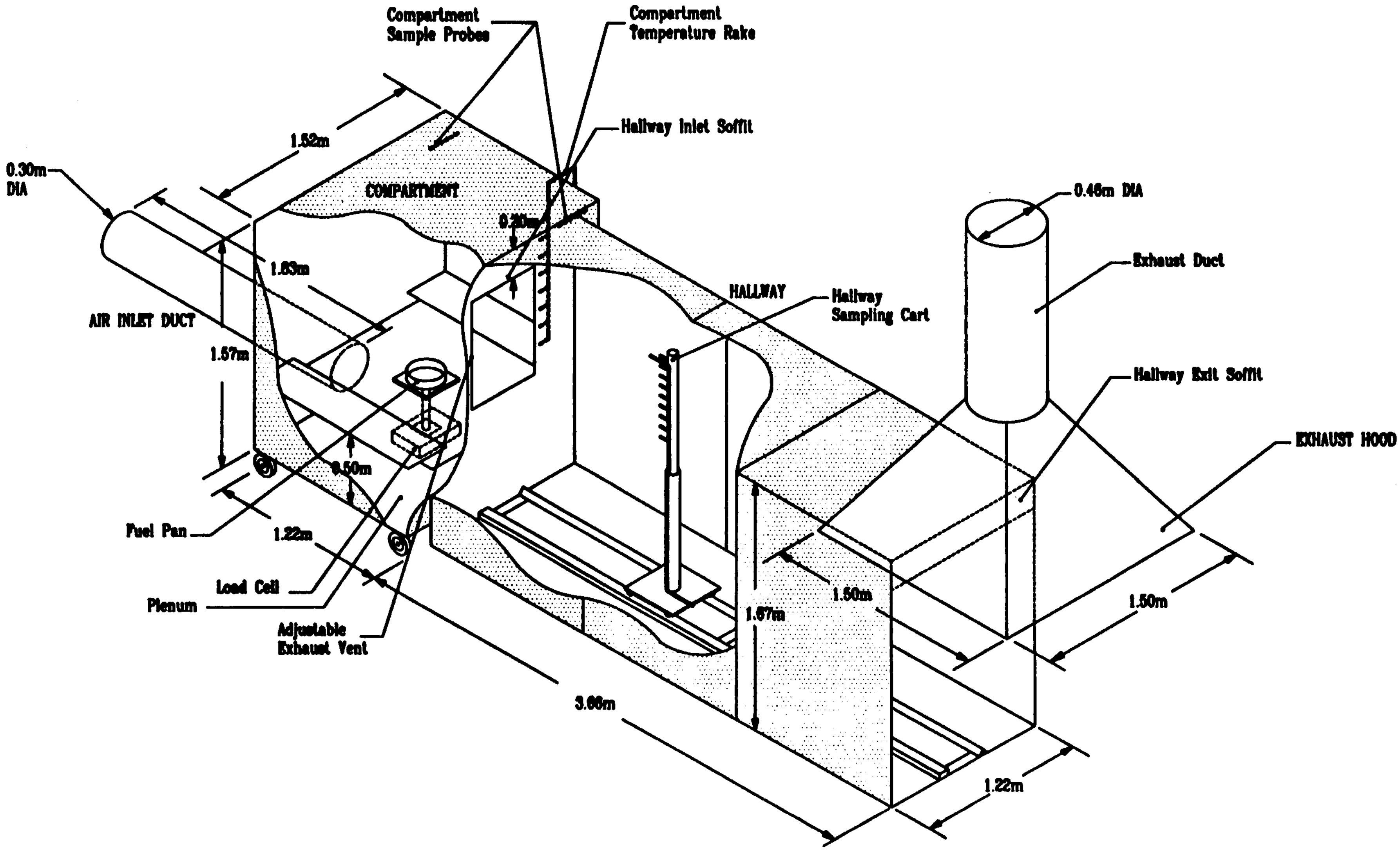


Figure 3. The current experimental apparatus.

pans of 20 and 23 cm in diameter, both 6.4 cm deep, were used in the experimentation. The compartment is also equipped with a vertical aspirated temperature rake holding 8 type K, 30 gauge thermocouples in the front corner of the compartment. The in-compartment thermocouples are spaced vertically 10 cm apart, starting at 10 cm below the ceiling, and are all 10 cm from the walls to avoid wall jet effects. Recently, two sampling probes have been added to the front and the back of the compartment upper-layer. Both probes extend into the compartment 23 cm and are 10 cm from the ceiling and the walls. These were added specifically for the wooden ceiling tests but will be used in the future for in-compartment sampling.

As seen in Figure 1, a 3.66 m long, 1.14m wide and 1.47 m tall hallway is connected to the compartment. The hallway ceiling consists of the same fire board present in the compartment while the walls are made of dry wall covered with Fiberfax fireproof insulating paper. The soffit heights at both ends of the hallway are adjustable and were varied from 0 cm to 20 cm. A sampling cart containing a sampling probe and an aspirated vertical thermocouple rake exists to measure the evolution of the exhaust gases inside the hallway. The cart allows for three dimensional position adjustment of the thermocouple rake and the gas sampling probe. A piece of high temperature, flexible Teflon tubing attaches the lower part of the sampling probe to the heated stainless steel line at the end of the hallway. The rake holds 9 type K, 30 gauge thermocouples spaced 5.1 cm apart vertically.

A 1.5 x 1.5 m hood connected to a 45.7 cm diameter duct collects all exhaust gases exiting the end of the hallway. A heated gas sampling line from the exhaust duct to the data acquisition room allows for continuous measurement of exhaust species concentrations. A laser extinction system in the exhaust duct also allows for the continuous measurement of soot volume fraction. The volumetric flow rate through the duct is measured using an orifice plate arrangement inside the exhaust duct.

All gas samples feed through a selector valve which leads to a single gas analysis system. This system consists of two Rosemont Analytical NDIR model 880 analyzers which measure CO and CO_2 concentrations and a Siemens paramagnetic Oxymat 5E analyzer which measures O_2 concentrations. A Gow-Mac FID is used to measure the total unburned hydrocarbon concentrations as ethylene, C_2H_4.

A compartment plume equivalence ratio,

$$\phi = \frac{\dot{m}_{fuel} / \dot{m}_{air}}{\left(\dot{m}_{fuel} / \dot{m}_{air} \right)_{st}} \qquad (2)$$

as defined by Beyler (1986), was obtained by measuring the air entrainment rate into the compartment and the fuel vaporization rate. The air entrainment rate was experimentally determined in the air duct connected to the plenum using a hot film, 0-2 m/s linear Kurtz model 415 velocity probe. The fuel vaporization rate was measured using an A&D 15 kg load cell. Different combinations of exhaust vent sizes, fuel pan sizes and initial compartment temperatures produced compartment plume equivalence ratios ranging from 1.7 to 3.5. For the remainder of the paper, the compartment plume equivalence ratio will simply be the equivalence ratio.

A VHS video camera was used to record the development and burning of the exhaust gas upper layer in the hallway during each experiment. The video camera was placed about 1 m outside of the open end of the hallway and about 0.5 m below the height of the hallway ceiling. From this position, the exhaust gas flow inside the hallway was observed from below. Taping of each fire allows determination of the time when sustained external burning and other important events occur in the hallway, in addition to providing a visual record in the case that any additional information is needed.

4.2 Renovations and Modifications

Over the past year several renovations and modifications have been made on the laboratory to protect the facility which exists, accelerate the experimentation process, and make data acquisition more efficient. A description of the projects which accomplished these tasks is given below.

At the expense of the Mechanical Engineering Department at VPI&SU, a 11.6 m (38 ft.) by 9.7 m (32 ft.) A-frame roof, Figure 4, was constructed over the entire experimentation portion of the facility. A 9.1m (30 ft.) wide concrete pad was also extended 4.3 m (14 ft.) out beyond the existing concrete pad. The roof will protect the compartment and hallway from weather damage which has caused numerous delays in the past.

A new modular hallway, Figure 5, has been fabricated to allow more versatility and ease in altering the compartment-hallway orientation and the soffit heights. The ceiling and the top half of the hallway are made of 2.54 cm (1 in.) thick Firemaster, UL rated, fire insulation board. The gypsum board covered with Fiberfax fireproof paper in the upper- layer of the old hallway had a tendency to crumble when it was repeatedly exposed to the high temperatures of the upper-layer. The bottom half of the new hallway is made of 1.5 cm (.625 in.) thick gypsum board which is covered with 1.6 mm (.0625 in) thick Fiberfax fireproof paper.

An automated fuel supply has been developed and tested so the external burning time can be extended, see Figure 6. The automated fuel supply operates off of the signal from the fuel weight inside the compartment. When the weight of the fuel falls below a certain preset level, a controller triggers fuel pumps to begin filling the fuel pan inside the compartment. Once the fuel weight has reached its preset full level, the controller triggers the fuel pumps to be shut off. The fuel supply was not used in experiments over the past quarter because the upper portion of the gypsum walls in the old hallway were not durable enough to withstand the constant high temperatures which were a result of the extension in the sustained external burning.

To take full advantage of the extended external burning time, an automated sampling cart has been developed and constructed, Figure 7. The computer controlled sampling cart will enable sampling to occur at several locations within the hallway during a single test. This will accelerate data acquisition in addition to allowing for more detailed mapping of species within the hallway.

Further progress has been made on the measurement of soot within the hallway. The accumulation of soot on the access windows of the hallway and the thermal beam steering of the laser are the two largest problems faced in this task. Access windows will

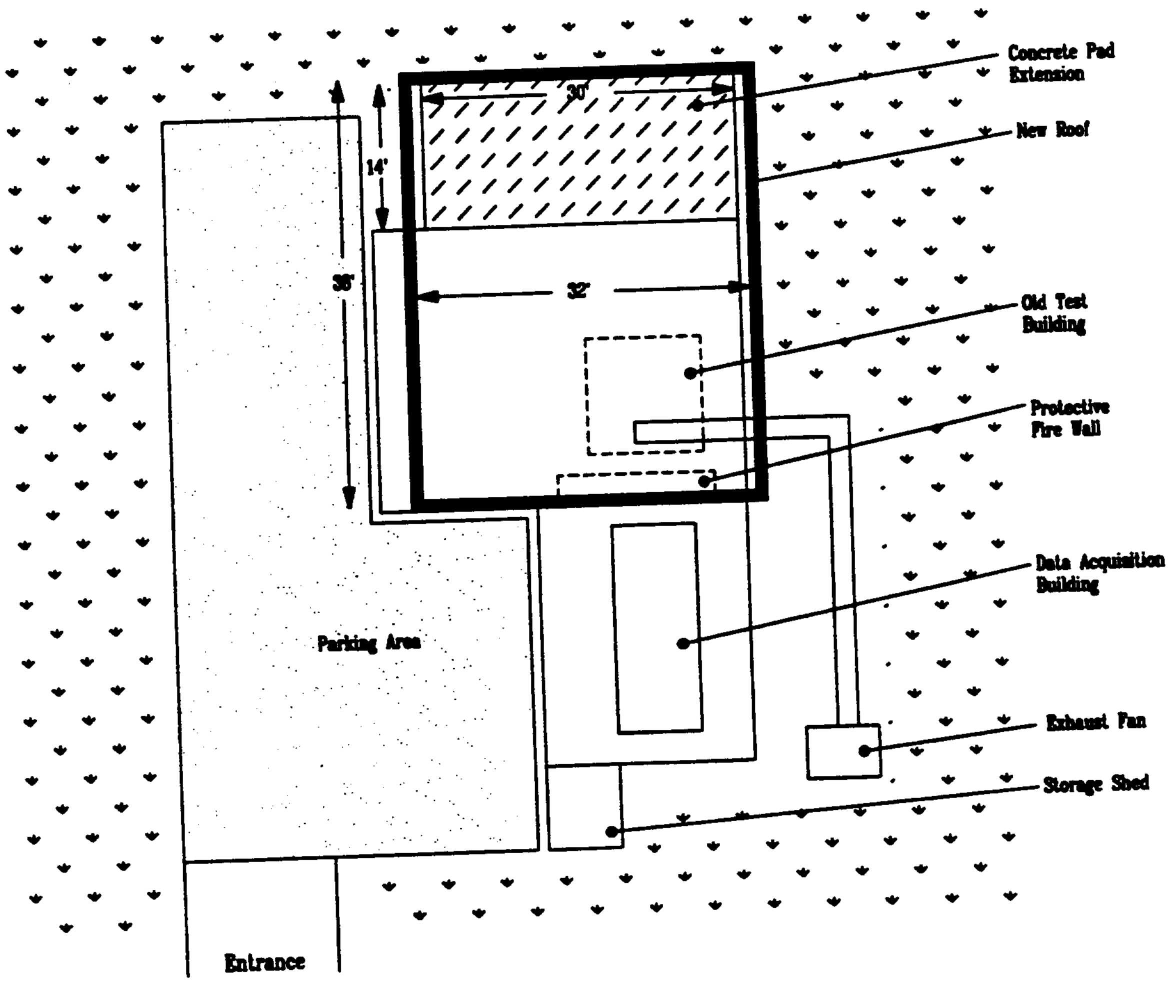


Figure 4. An overhead view of the fire facility showing the position of the new A-frame roof and the concrete pad extension.

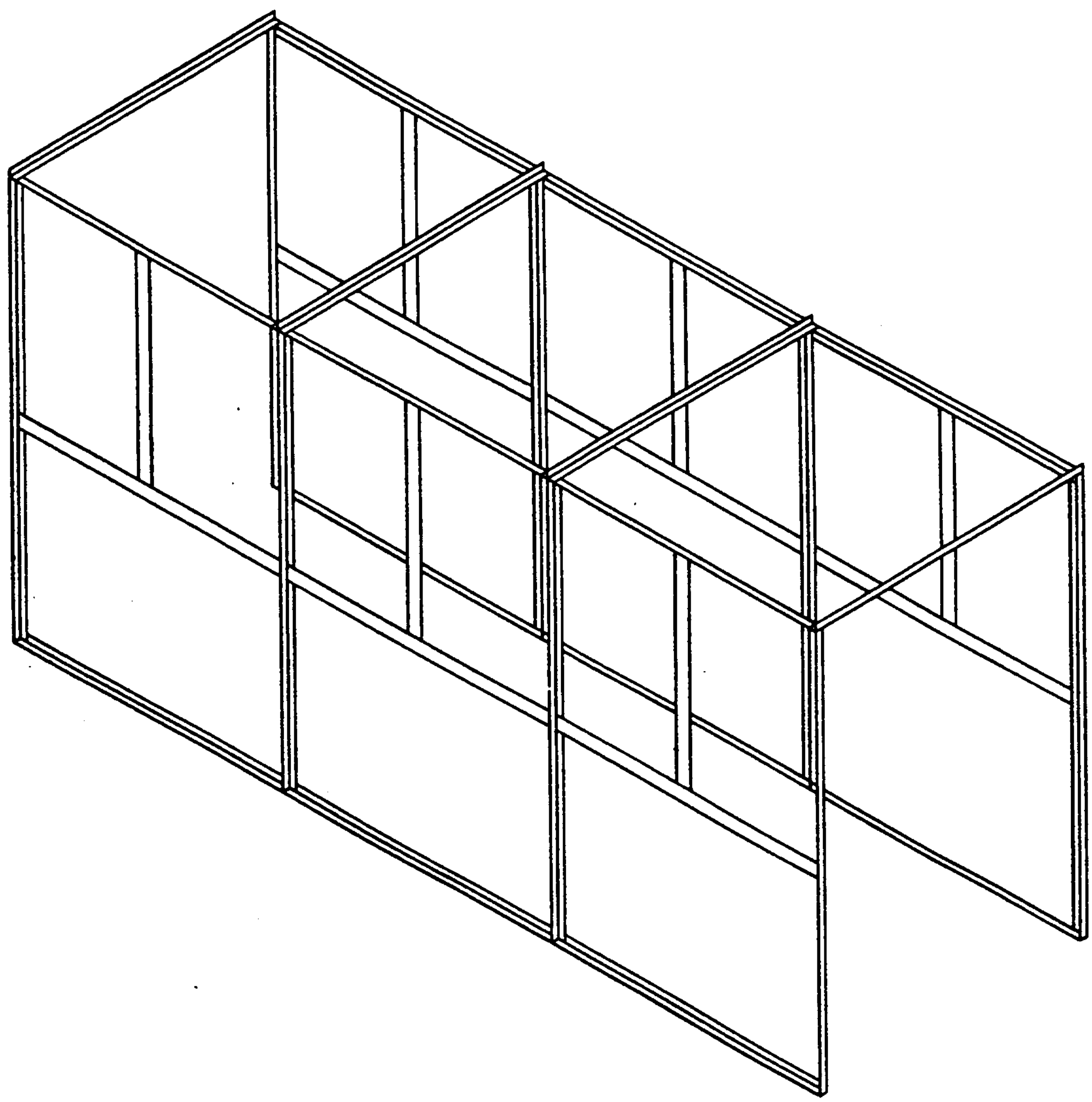


Figure 5. The modular hallway design.

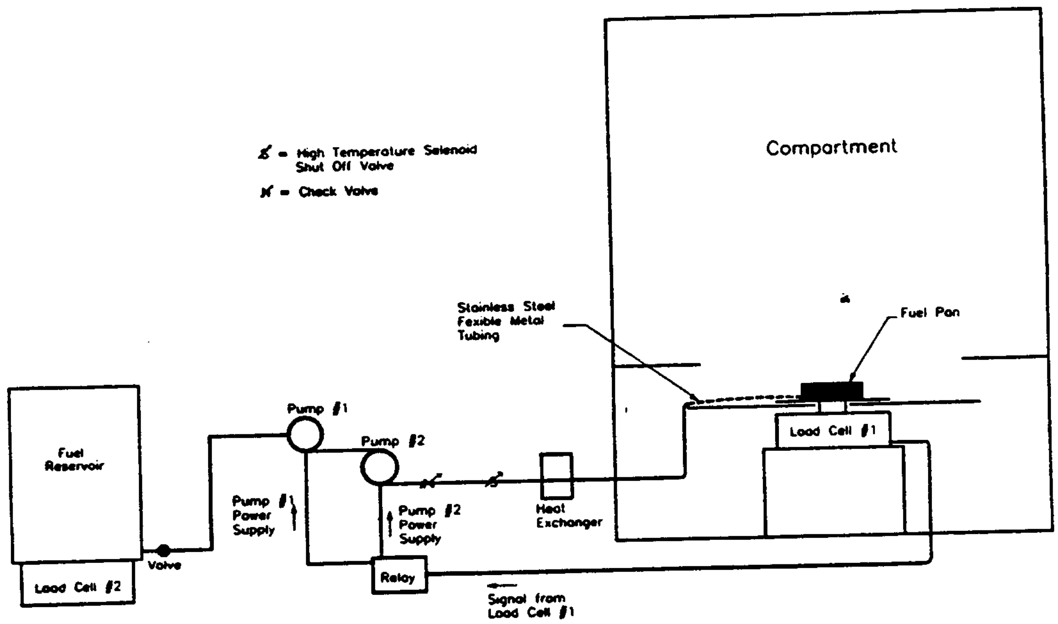


Figure 6. The automated fuel supply.

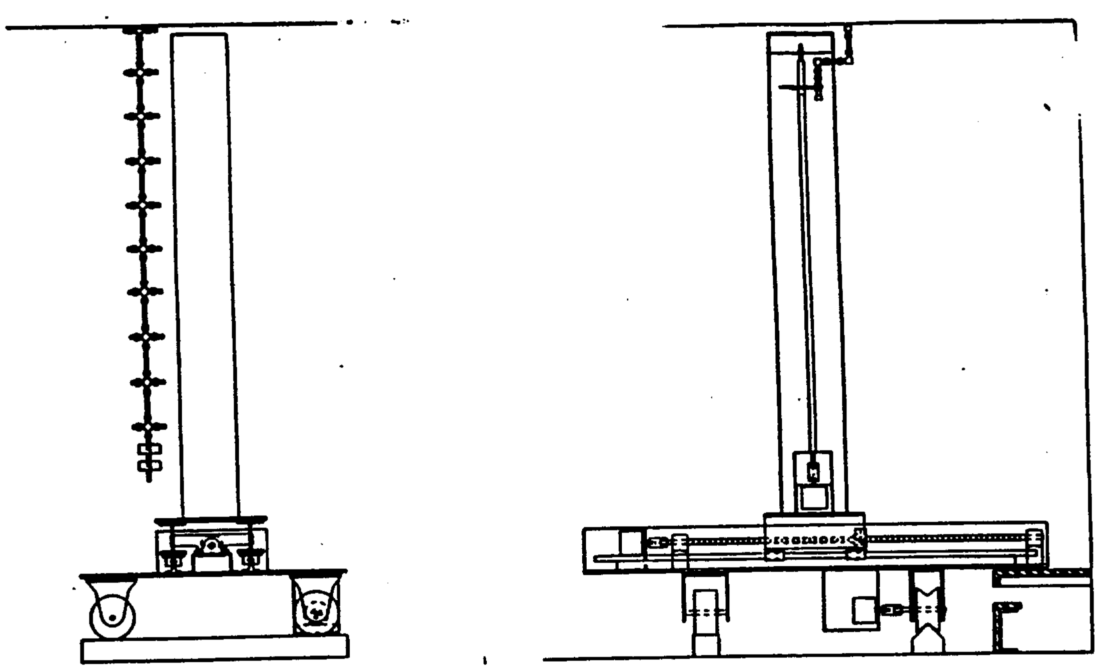


Figure 7. The computer controlled sampling cart.

be designed so an inert gas will be injected on the surface of the glass to keep it free of soot deposits. The thermal beam steering will be handled using diffusers and lenses. The measurement of soot during external burning will be done by subtracting the signal of the photodiode with the laser impinging upon it from the signal of a second nearby photodiode with no laser light on it.

4.3 Results and Discussion

The results of the experiments which have been performed over the past year are presented in this section. The findings of the hallway experiments where the soffit heights were varied are shown first . This is followed by presenting the results of limiting the air entrained into the hallway. An examination of the effect on the oxidation of the exhaust gases when the plenum is blocked off from the open atmosphere is then presented. Results of experiments with a combustible Douglas Fir plywood ceiling within the compartment with and without the compartment plenum blocked off from the atmosphere are described.

4.3.1 Hallway Experiments with Variable Soffit Heights

These experiments investigated the effects of different soffit heights at the entrance and exit of the hallway on the oxidation of exhaust gases in the hallway. Two types of experiments were run, 1) post-hallway sampled experiments and 2) in-hallway sampled experiments. The post-hallway experiments were sampled in the exhaust duct. These tests investigated the overall oxidation of the combustion gases as the pan size, the compartment vent size, the initial compartment temperature and the soffit heights at the beginning and end of the hallway were varied. The variation in the equivalence ratio was achieved by using different combinations of the first three parameters listed above. Highest equivalence ratios were generated with the largest fuel pan size, the smallest vent area size and the highest initial compartment temperature. High equivalence ratios did not necessarily correspond to the highest downstream yield in combustion species, specifically CO. The in-hallway experiments were performed to investigate the evolution of exhaust gases down the hallway. For an in-hallway investigation with a particular soffit combination and vent size, the equivalence ratio, the power of the fire and the initial compartment temperature were kept as close to constant as experimentally possible. Results of in-hallway experiments are in species concentrations not yields since the amount of air entrained into the hallway was not measured.

Post-Hallway Sampled Results

The yields of CO, THC and soot were measured within the exhaust duct to determine the overall oxidation of the species. The efficiency of the overall oxidation of CO and THC after they spilled out of the compartment and traveled down the hallway will be calculated with the use of the average in-compartment yield, as seen in equation (1). As stated previously, the average CO yield and THC yield within the compartment was determined by Gottuk (1992) to be 0.22 and 0.33, respectively. The reduction in soot as a result of sustained external burning (SEB) will be based on soot yield measurements just prior to SEB and was found to average 0.015 (Gottuk, 1992). Different yields for each soffit combination were obtained by varying the equivalence ratio between 1.7-3.5. Each data point plotted is a single experiment and is formed by averaging over 30 seconds during SEB.

The first soffit combination which was used in the experiments was a 0 cm soffit at both the entrance and exit of the hallway (0/0). These tests were performed during the second year of the investigation and were reported in Section 3.0. For completeness, these results will be presented here also. The downstream CO yield varied between 0.100 and 0.070 which corresponds to a 54-68% oxidation efficiency. The THC yield varied from 0.022 to 0.055 resulting in a oxidation efficiency of 83-93%. The soot yields experimentally varied from 0.00077 to 0.0021 translating to an oxidation efficiency of 48-68%. The CO, THC and soot yields are plotted versus equivalence ratio and compared with Gottuk's data (1992) in Figures 8, 9 and 10, respectively. As can be seen from the graphs, the reductions in the levels of CO, THC and soot are much greater in the free-jet external burning experiments as opposed to the ceiling-jet external burning experiments. In the free-jet experiments, the external burning from the compartment is a buoyant jet exhausting into the cooler atmosphere making for a thermally unstable situation which enhances the entrainment of air into the free-jet. When the external burning from the compartment is fed into a hallway at the ceiling level, the ceiling-jet is already in a thermally stable environment; the hot gases are at the ceiling and the cool gases are on the floor. The ceiling-jet of fire within the hallway is in stratified atmosphere which hinders the entrainment of air into the jet. Since the oxidation of the exhaust gases is dependent on how efficient the air is entrained into the fuel rich combustion gases, the arguments above are the basis in the explanation of the yield difference in the two cases.

The next set of experiments had a 0 cm soffit at the entrance of the hallway and a 20 cm soffit at the exit of the hallway (0/20). The yield in CO varied between 0.171 and 0.128 resulting in a 22-42% oxidation efficiency. The THC yields ranged between 0.082 and 0.037 which corresponds to an oxidation efficiency of 75-89%. The levels of the soot yield varied from 0.0117 to 0.0065 producing a 22-57% oxidation efficiency. The results of post-hallway sampled CO, THC and soot yields plotted against the free-jet experiments of Gottuk(1992) are shown in Figures 11, 12 and 13, respectively. The addition of the soffit at the exit of the hallway gives rise to poor oxidation of exhaust gases resulting in higher yields downstream of the hallway as compared to the case without a soffit at the exit. As will be shown in the vertical profiles within the hallway, the upper-layer in the corridor is thicker with a 20 cm soffit at the exit. The thicker upper-layer makes the mixing of the exhaust gases with air more difficult resulting in more toxic gases escaping the hallway not oxidized.

To create a 20 cm soffit at the entrance of the hallway and keep the same conditions within the compartment, the ceiling of the hallway had to be raised 20 cm. After completing this task, tests were first run with a 20 cm soffit at the hallway entrance and a 0 cm soffit at the exit (20/0) of the hallway. The CO yield varied from 0.024 to 0.121 resulting in a 45-89% oxidation efficiency range. The THC yield ranged from 0.009 to 0.038 causing the oxidation efficiency to be 88-97%. The soot yield levels in the post-

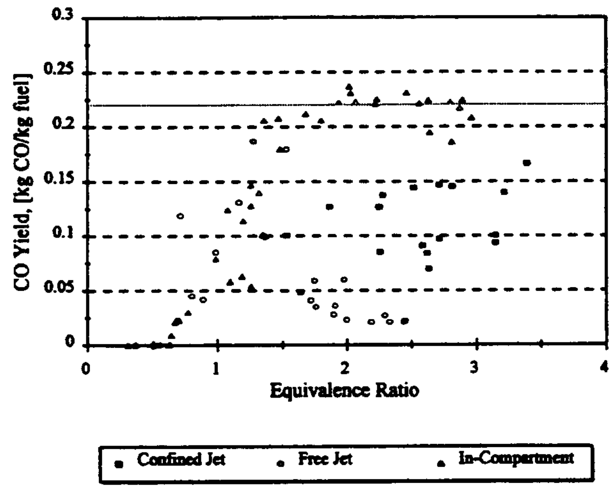


Figure 8. CO yield for the (0/0) soffit combination.

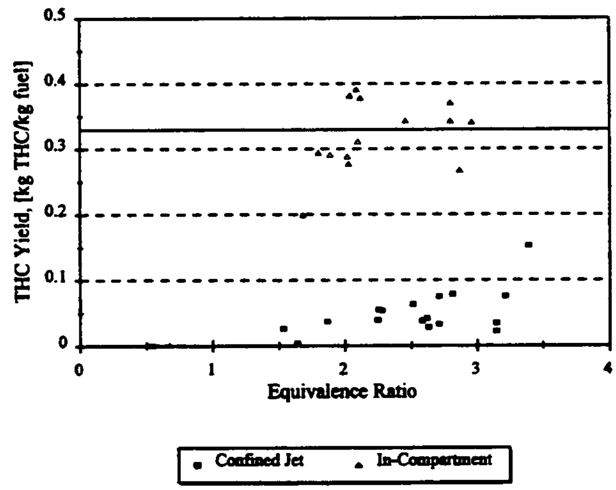


Figure 9. THC yield for the (0/0) soffit combination.

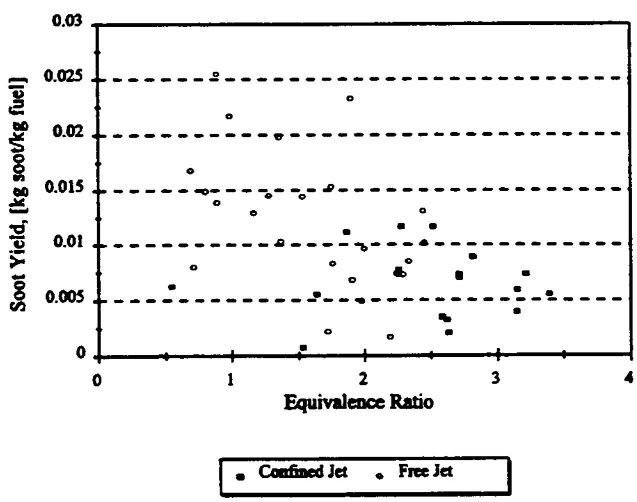


Figure 10. Soot yield for the (0/0) soffit combination.

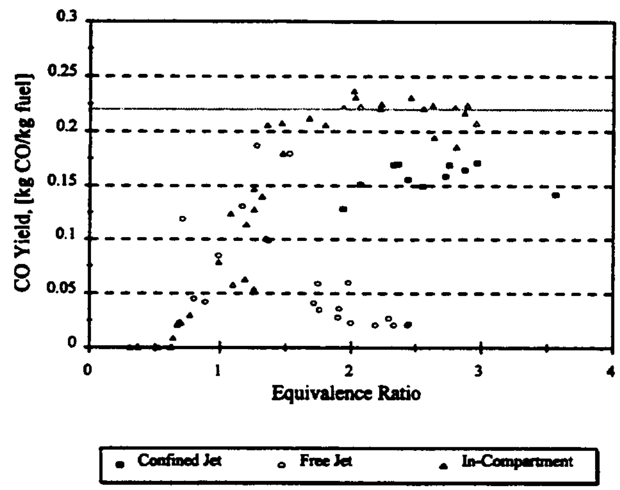


Figure 11. CO yield for the (0/20) soffit combination.

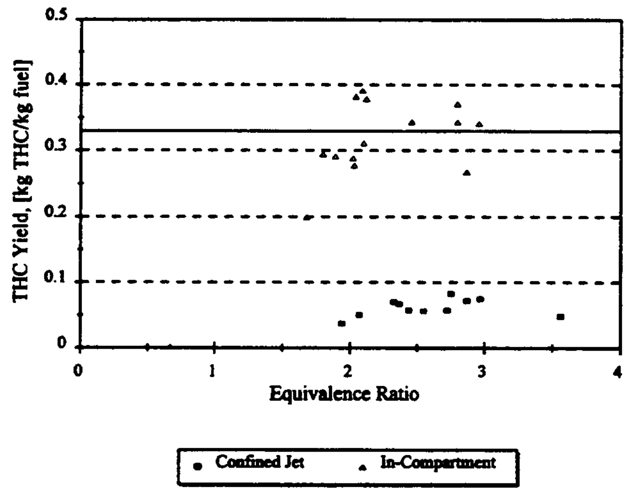


Figure 12. THC yield for the (0/20) soffit combination.

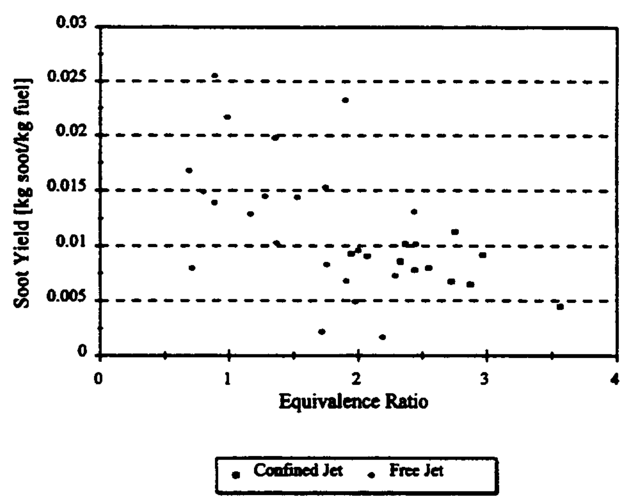


Figure 13. Soot yield for the (0/20) soffit combination.

hallway varied between 0.0087 and 0.0012 which results in a 42-92% oxidation efficiency. The plots of CO, THC, and soot versus the equivalence ratio are shown in Figures 14,15 and 16. The addition of the soffit at the beginning of the hallway clearly improves the oxidation efficiency. The soffit at the hallway inlet allows the fire jet exiting the compartment during SEB to initially be a buoyant plume impinging on the ceiling. In a lower power fire with a 400 cm^2 exhaust vent area, the fuel rich gases are oxidized just as the fire impinges upon the ceiling causing the plume to extinguish at this point, termed a confined buoyant-jet. With higher powered fires having a 1200 cm^2 exhaust vent area, fuel rich gases are oxidized two-thirds of the way down the hallway allowing the buoyant plume to be transformed into a ceiling jet as the external burning proceeds down the corridor, termed a confined buoyant, ceiling-jet. These two situations, shown in Figures 17 and 18 respectively, are the two extreme cases of the external burning which is seen with the 20 cm soffit at the hallway entrance. Previously it was suggested that the broad range of yields obtained from the experiments with this soffit combination could be explained from the fuel vaporization rate or the power of the fire (Ewens, 1994). Though this has an effect, the prediction of the exhaust species yields can not solely be described on this basis. A correlation is presently being developed and will be published in the paper accepted by the *Journal of Fire Protection Engineers*. The correlation will be based upon the momentum of the gases flowing from the exhaust vent, the stoichiometry of the gases and the power of the fire.

The last soffit combination tested was with a 20 cm soffit at the hallway entrance and a 20 cm soffit at the hallway exit. The CO yield varied from 0.134 to 0.020 resulting in a 39-91% oxidation efficiency. The THC yield results ranged between 0.045 and 0.006 which corresponds to an oxidation efficiency which varies from 86-98%. The soot yield values ranged from 0.0109 to 0.0017 which is analogous to an oxidation efficiency of 28-88%. The CO, THC and soot results are plotted versus equivalence ratio in Figures 19,20 and 21. Again, the addition of the soffit reduced the efficiency of the oxidation within the hallway compared to the situation where no exit soffit was present at the exit, (20/0). The effect was not as pronounced for this soffit combination as compared to the (0/20) soffit combination. This is attributed to the highly efficient oxidation which occurs in the first half of the hallway due to the 20 cm inlet soffit. As stated above, a correlation which will predict the CO yield downstream of the hallway is presently being developed.

A summary of the post-hallway results is shown in Table I below.

Table I. Post-hallway oxidation efficiency ranges for underventilated fires with equivalence ratios varying from 1.7-3.5.

		Hallway Experiments			
Species	Free-Jet Experiments (Gottuk,1992)	(0/0) Soffits	(0/20) Soffits	(20/0) Soffits	(20/20) Soffits
CO	75 - 90%	54 - 68%	22 - 42%	45 - 89%	39 - 91%
THC	N/A	83 - 93%	75 - 89%	88 - 97%	86 - 98%
Soot	50 - 100%	48 - 86%	22 - 57%	42 - 92%	28 - 88%

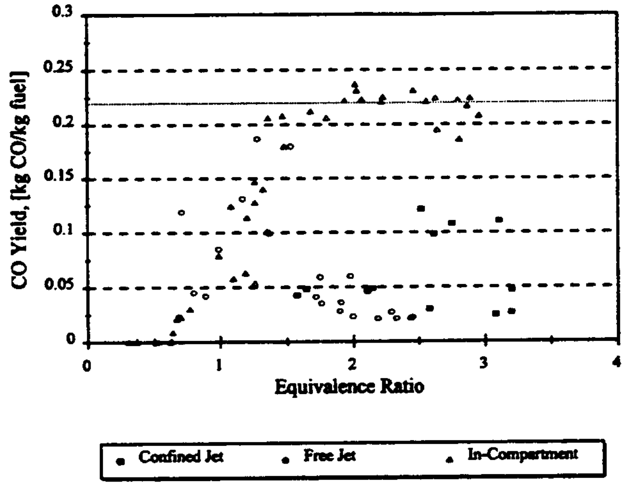


Figure 14. CO yield for the (20/0) soffit combination.

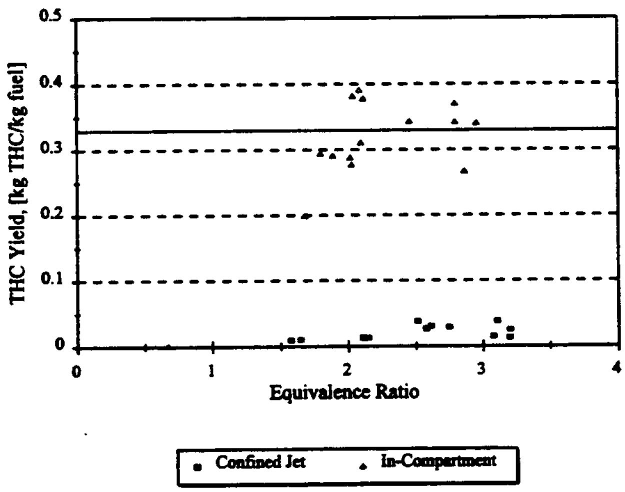


Figure 15. THC yield for the (20/0) soffit combination.

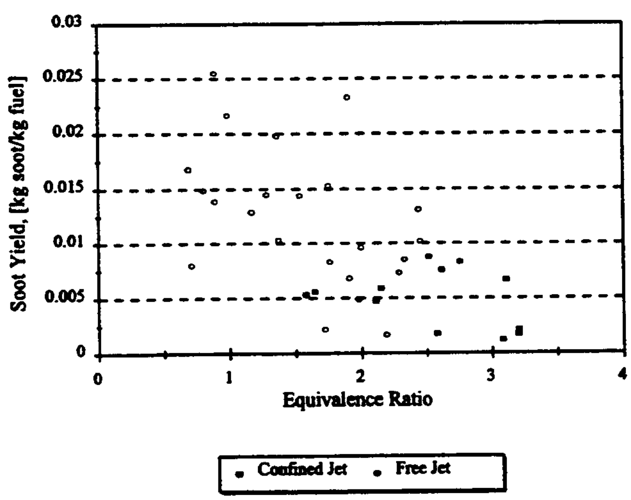


Figure 16. Soot yield for the (20/0) soffit combination.

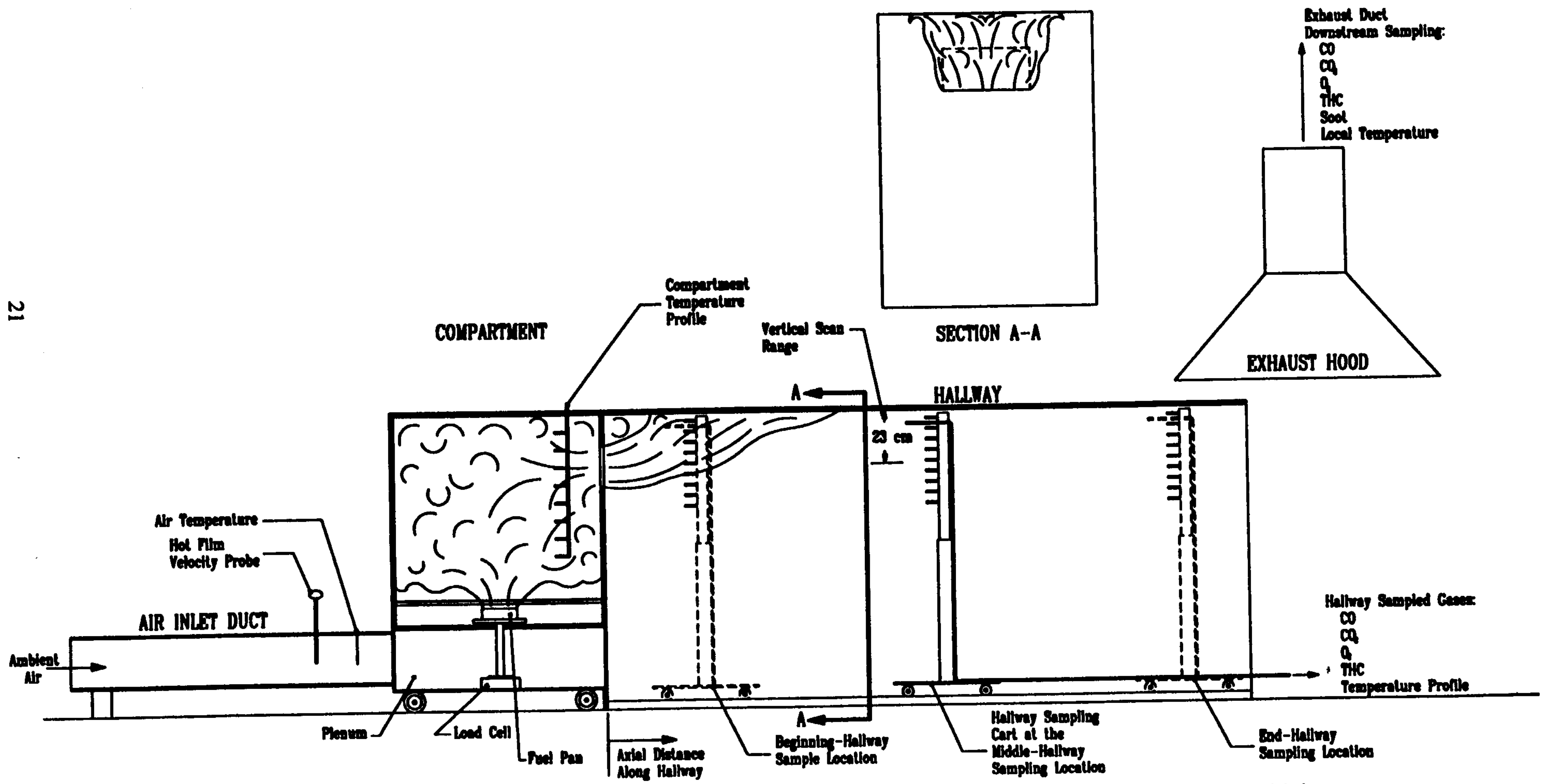


Figure 17. A graphical representation of the confined buoyant-jet external burning which exists when a 20 cm soffit is at the hallway entrance, low power fire is in the compartment and a small vent area (400 cm^2) is present.

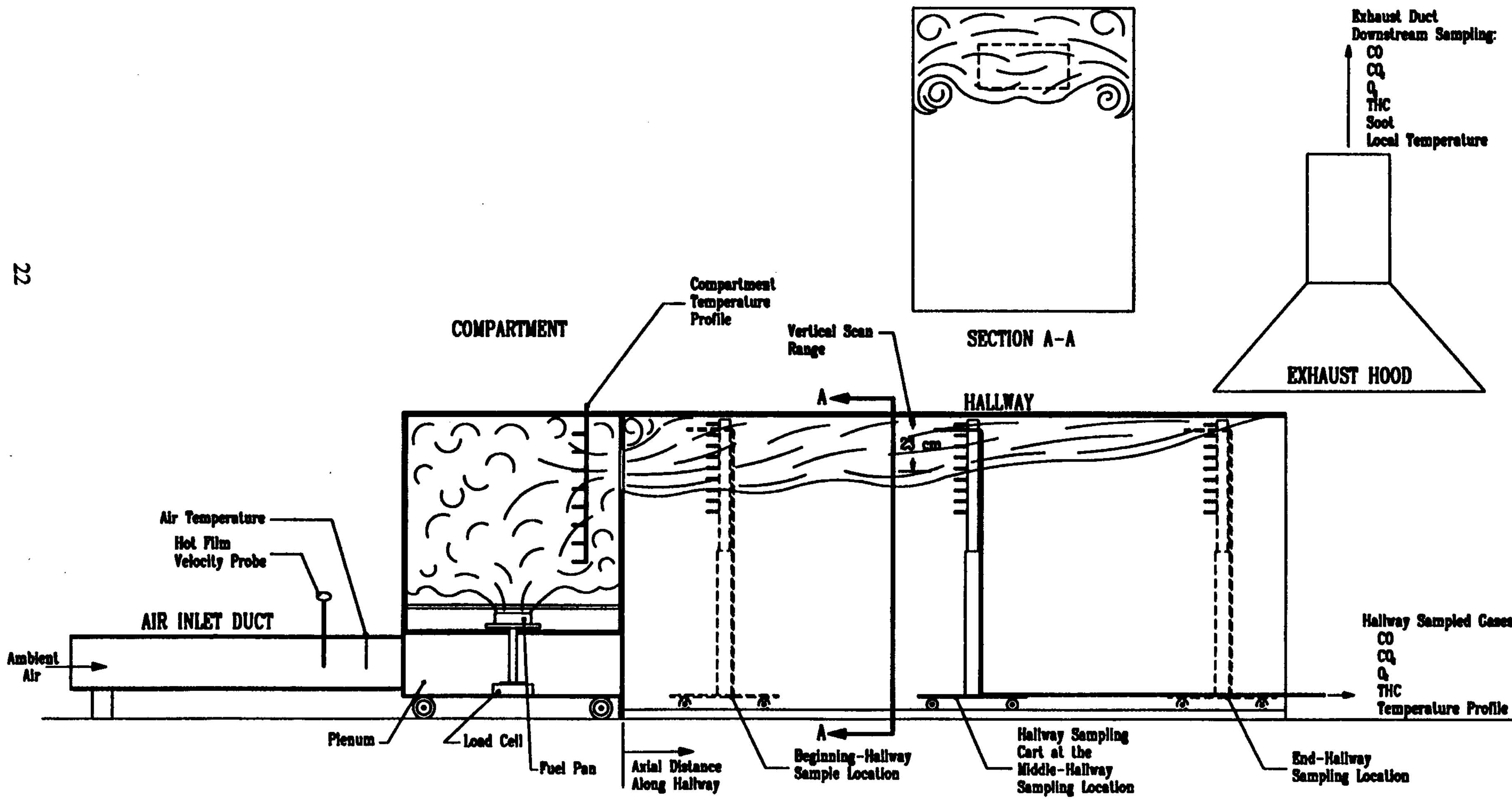


Figure 18. This is a graphical representation of a confined buoyant, ceiling-jet which exists when a 20 cm soffit is at the hallway entrance, a high power fire is in the compartment and a large vent area (1200 cm^2) is present.

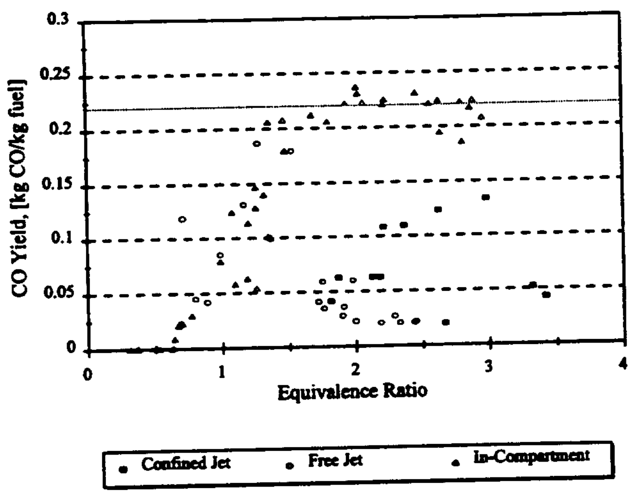


Figure 19. CO yield for the (20/20) soffit combination.

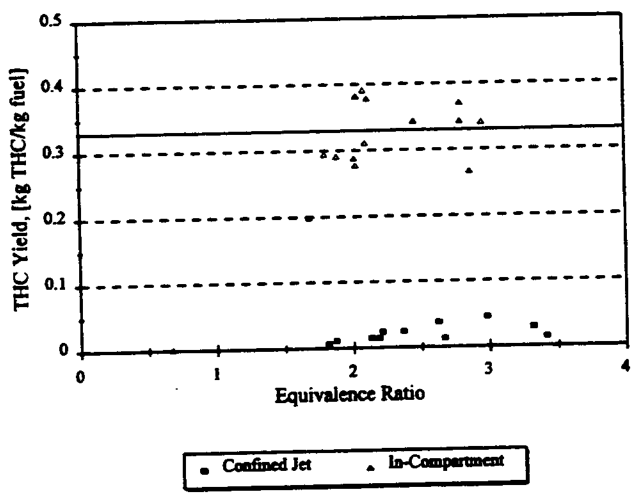


Figure 20. THC yield for the (20/20) soffit combination.

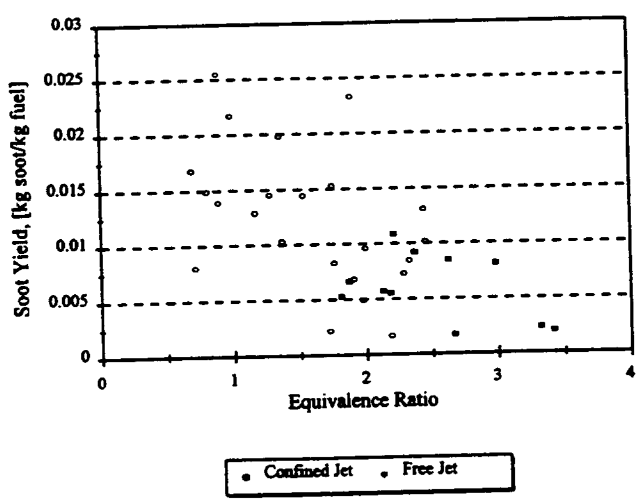


Figure 21. Soot yield for the (20/20) soffit combination.

Hallway Sampled Results

After determining the overall oxidation of the exhaust gases from the post-hallway experiments, it was of interest to examine the behavior of the exhaust gases as they traveled down the hallway. The variation in species concentrations within the hallway was sampled in two ways, 1) along the length of the hallway, termed an axial-profile and 2) from the ceiling down within the hallway upper-layer, termed a vertical-profile. The axial-profiles were performed 5.1 cm below the ceiling and gave information on the changes in the concentrations of exhaust gases as they moved down the hallway. The vertical-profiles, the majority of which were performed halfway down the corridor, presented information about the depth of the upper-layer and the variation of the gases within the upper-layer. All profiles were executed along the center of the hallway. Each point on the profile was the result of a single experiment and was generated by averaging over 20 seconds during SEB. All species concentrations are wet and are normalized by the quantities in the parentheses within the graph legend. It should be noted that the hallway temperatures for the (0/0) and the (0/20) soffit combinations are low. This was due to the long aspirator tubes cooling the gases before they hit the recessed thermocouple. This problem was overcome in the other two soffit combinations by cutting the aspirator tubes off so that the thermocouples were not recessed as far.

The change in concentration of exhaust gases along the hallway with no soffits at either end is shown in Figure 22. The fires were burned in a 20 cm diameter fuel pan while a 1200 cm^2 exhaust vent connected the compartment and the hallway. The average equivalence ratio was 2.31 while the average heat release was 444 kW. The THC clearly oxidized at a faster rate compared with CO in the first quarter of the hallway. As air was entrained into the ceiling-jet the exhaust gas temperature dropped causing a freezing out of the CO reaction. The flame is seen to end at approximately 2.25 m down the hallway. This was estimated by the drop in CO, CO_2, THC in conjunction with a steep rise in O_2. The concentration changes in the upper-layer of the hallway after 2.25 m are due to the dilution of the exhaust gases with the entrainment of ambient air.

The vertical profile of the upper layer within the hallway where no soffits were present at either end was taken at the beginning, middle and end of the corridor for this soffit combination only. A progression of the upper-layer down the hallway is shown by vertical profiles at 0.457 m, 1.83 and 3.20 m away from the compartment in Figures 23 a-c. In these tests a 20 cm diameter fuel pan and a 1200 cm^2 exhaust vent were used. The average equivalence ratios were 1.92, 2.33 and 2.20, respectively, while the average heat releases were 402 kW, 434 kW and 438 kW, respectively. The fuel rich region shown in the figures had high temperatures, high levels of CO and THC and nearly no O_2 present. From the steep gradients of CO, THC and O_2 and the drop in temperature, the location of the visible flame region below the ceiling was 10 to 15 cm when 0.457 m from the compartment, 5 and 10 cm when 1.83 m from the compartment and 0-5 cm when 3.20 m from the compartment. The region where the lowest CO, THC and temperatures were present along with a high O_2 concentration is labeled the post flame region.. As would be expected, the location of the visible flame gets closer to the ceiling the further the sampling is from the compartment.

An axial profile of the gas concentration within the upper-layer of a hallway with

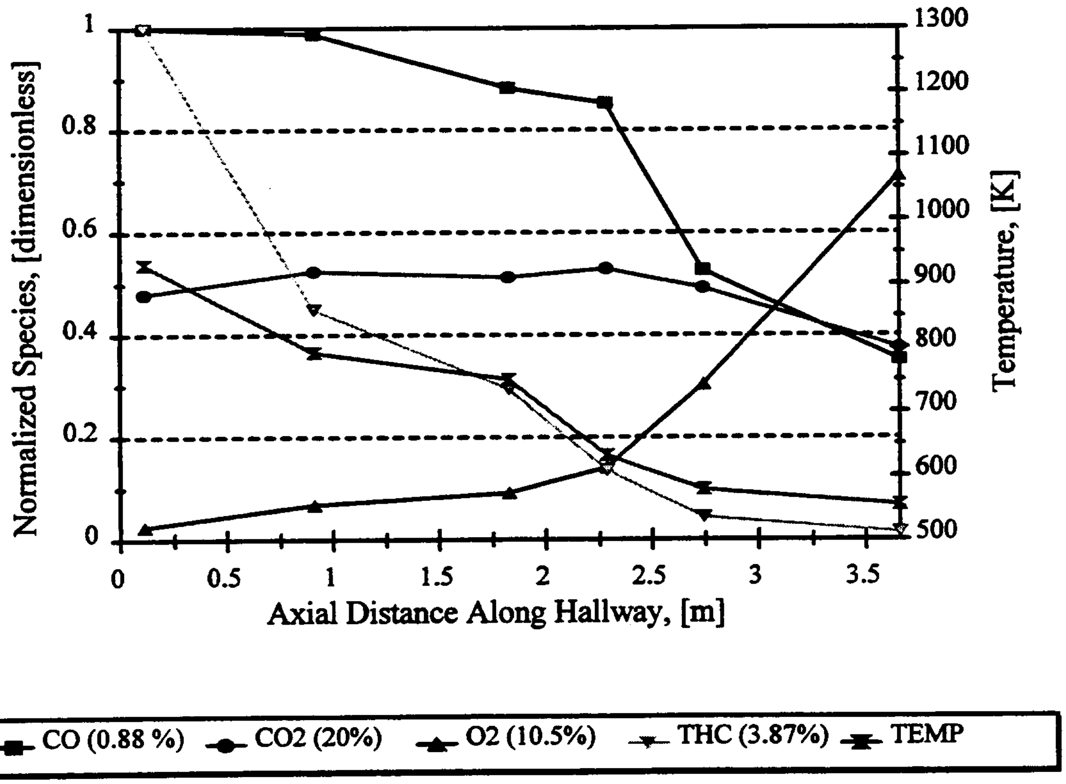


Figure 22. An axial profile of the upper-layer gases within the hallway is shown for a (0/0) soffit combination. The fuel pan diameter was 20 cm, the vent area was 1200 cm^2, the average equivalence ratio was 2.31 and the average heat release was 444 kW.

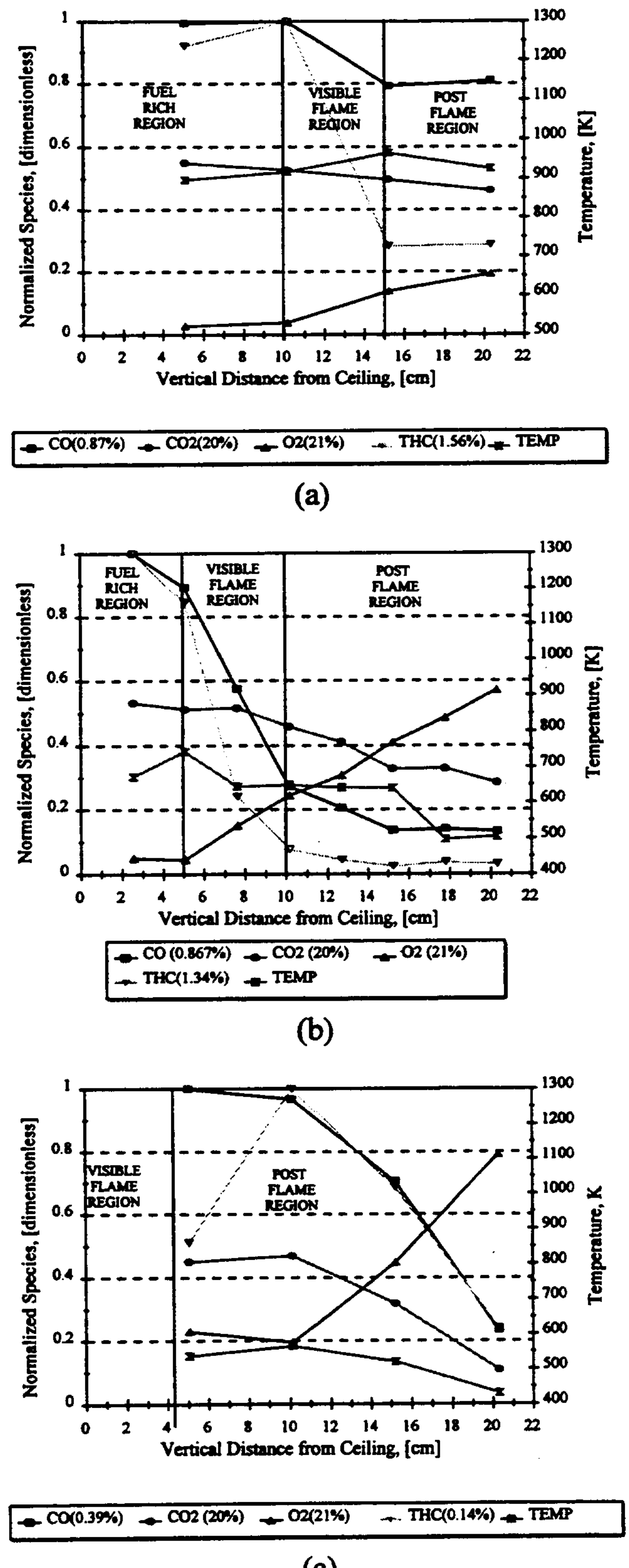


Figure 23. Vertical profiles of the upper-layer gases in the hallway at a distance of (a) 0.46 m, (b) 1.83 m and (c) 3.20 m away from the compartment, (0/0) soffits.

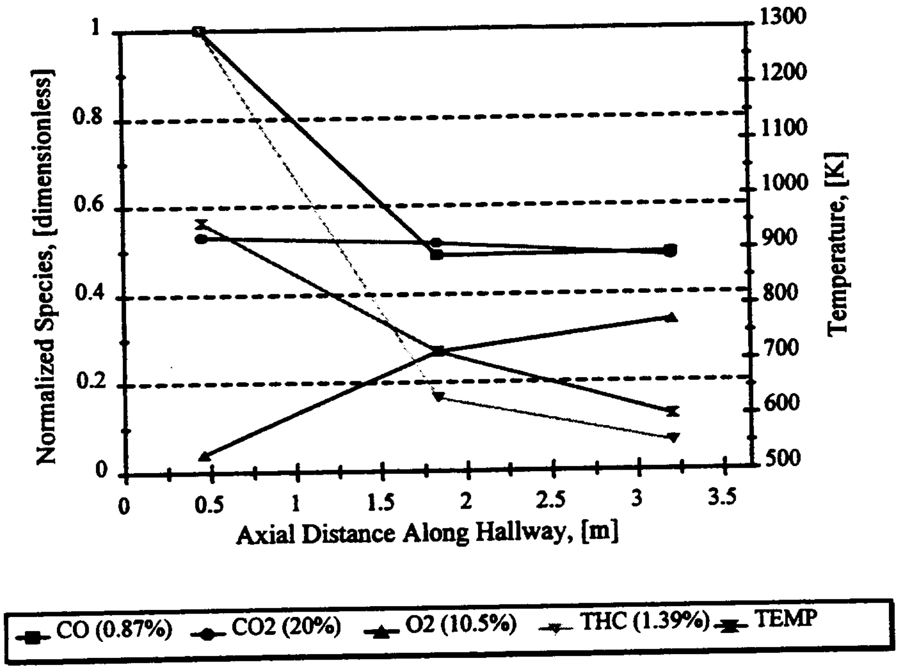


Figure 24. An axial profile of the upper-layer gases within the hallway is shown for the (0/20) soffit combination. The fuel pan diameter was 20 cm, the vent area was 800 cm^2, the average equivalence ratio was 1.90 and the average heat release was 409 kW.

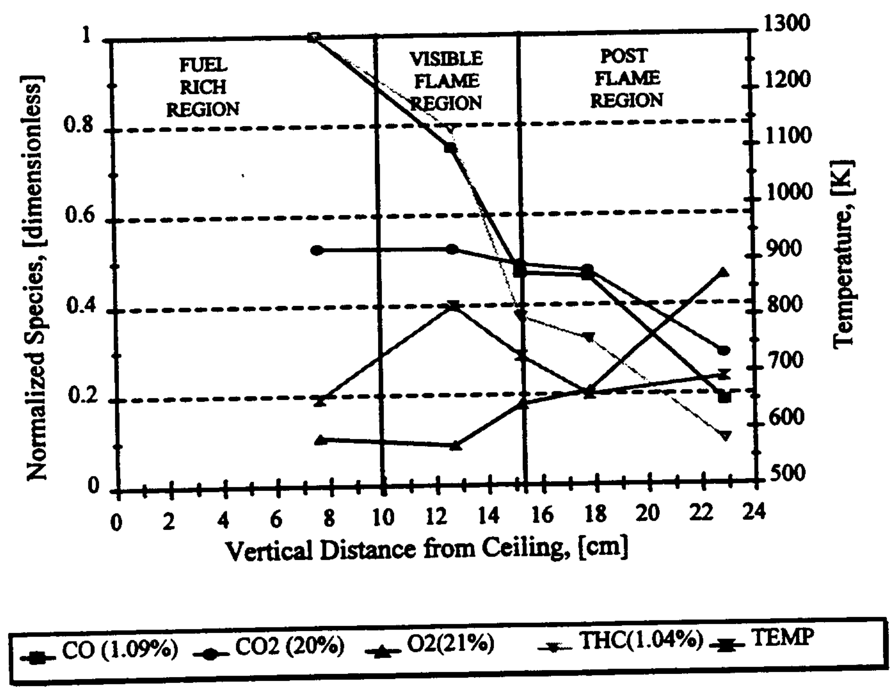


Figure 25. A vertical profile of the upper-layer gases within the hallway is shown for the (0/20) soffit combination. The fuel pan diameter was 20 cm, the vent area was 800 cm^2, the average equivalence ratio was 2.8 and the average heat release was 445 kW.

no soffit at the entrance and a 20 cm soffit at the exit is displayed in Figure 24. A 20 cm diameter fuel pan was used along with an 800 cm^2 exhaust vent area. The average equivalence ratio was 1.90 while the average heat release was 409 kW. The same trends occur in this plot as compared with the hallway having no soffit at the exit except for the presence of higher CO and THC levels. Although it appears the oxidation has improved from the (0/0) case, the effects being seen are caused by the smaller vent area. Though difficult to determine with only three sampling positions, the flame length appears to be around the middle of the hallway, 1.83 m.

The upper-layer vertical profile with no soffit at the hallway entrance and a 20 cm exit soffit is shown in Figure 25. These tests were performed with a 20 cm diameter fuel pan and a 800 cm^2 vent area. The average equivalence ratio was 2.8 with an average heat release of 445 kW. The upper-layer within the hallway visually was thicker. The vertical profile verifies this by showing the visible flame region, using the same criteria stated above, to be between 13 and 18 cm below the ceiling. This corresponds to a layer almost twice as thick as the layer with no soffit at the exit.

For a hallway with a 20 cm soffit at the entrance and no soffit at the exit, the axial variation in the species concentrations within the corridor are presented in Figure 26. A 20 cm diameter fuel pan was used with a 1200 cm^2 vent area. The average equivalence ratio was 1.58 with an average heat release of 390 kW. CO and THC are both oxidized within the first half of the hallway. The rapid oxidation of the exhaust gases is due to the increase in the air entrainment efficiency, as stated before. The oxidation is not complete because the air entrained cools the gases causing the reactions to freeze out by approximately the middle of the corridor. Less efficient oxidation of the exhaust gases was present with larger powered fires. These axial profiles are similar to those seen when no soffits are present at either end of the hallway. The correlation being developed will better explain why there seems to be two different types of oxidation present for one soffit combination.

The vertical profile for the 20 cm entrance soffit and the 0 cm exit soffit is shown in Figure 27. A fuel pan having a diameter of 20 cm was used in conjunction with a 1200 cm^2 vent area. The average equivalence ratio was 1.54 while the average heat release was 367 kW. Noting the low values of CO and THC present at this position in the hallway, 1.83 m downstream of the compartment, and the high levels of O_2 it is clear that the post flame region dominates this graph. From the video recordings, it is seen that the visible flame is present right at the ceiling and extinguishes shortly after it reaches the sampling probe.

The last soffit combination to be considered was a hallway with a 20 cm soffit at both ends. The axial profile for this combination is shown in Figure 28. The 20 cm diameter pan with a 1200 cm^2 vent area was used once again. The average equivalence ratio was 1.72 while the average heat release was 397 kW. Initially, the species concentrations look very similar to those with no soffit at the exit and a 20 cm inlet soffit. The exit soffit allowed more of the combustion gases, CO and THC, to escape the hallway not oxidized. The reason for this is explained using the vertical profile of the upper-layer in the middle of the hallway. Though difficult to tell from only three data points, the flame length is longer compared to the (20/0) case.

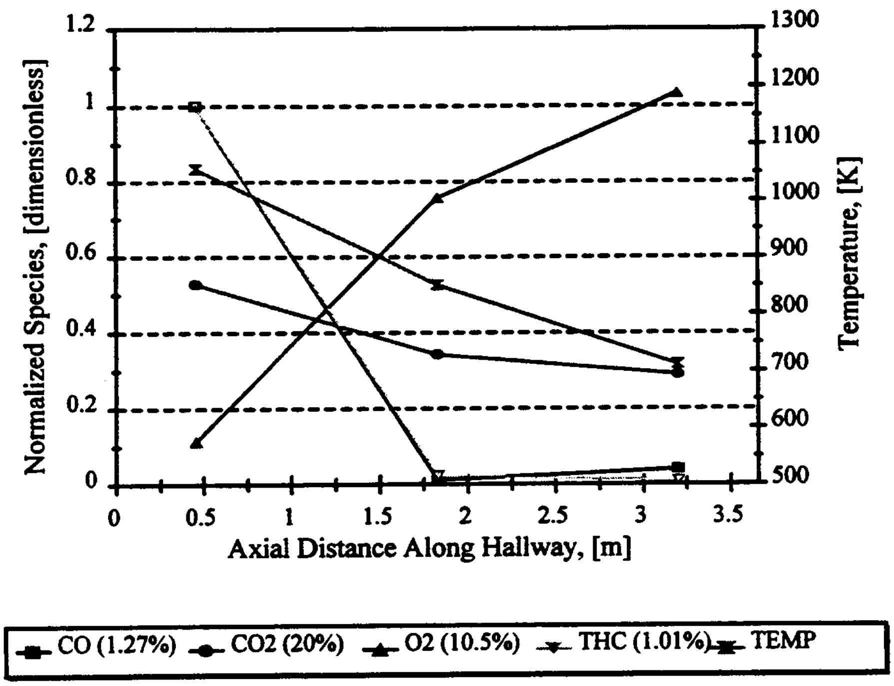


Figure 26. The axial profile of the gases in the upper-layer of the hallway with a (20/0) soffit combination present. The fuel pan diameter was 20 cm, the vent area was 1200 cm^2, the average equivalence ratio was 1.58 and the average heat release was 390 kW.

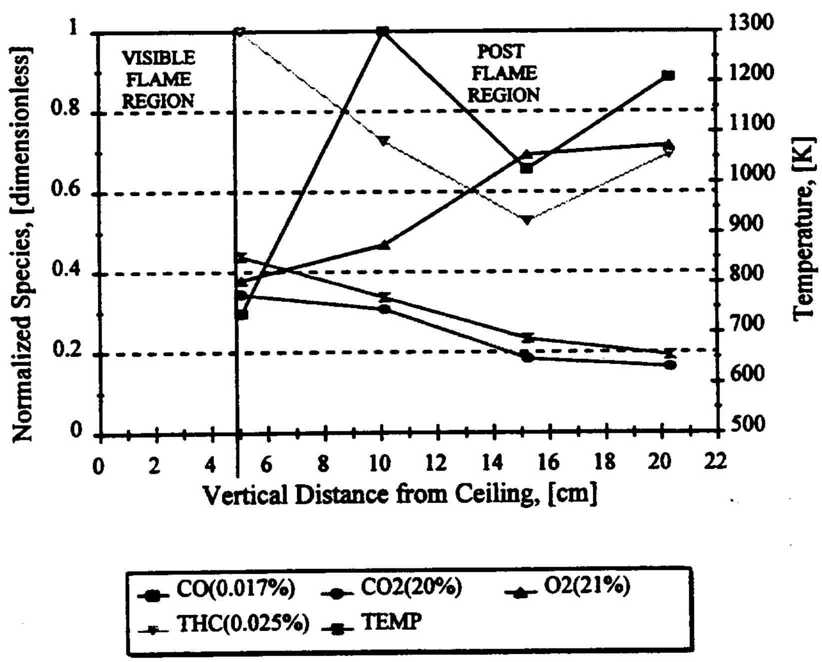


Figure 27. The vertical profile of the hallway upper-layer gases is shown for a (20/0) soffit combination. The fuel pan size was 20cm, the vent area was 1200 cm^2, the average equivalence ratio was 1.54 and the average heat release was 367 kW.

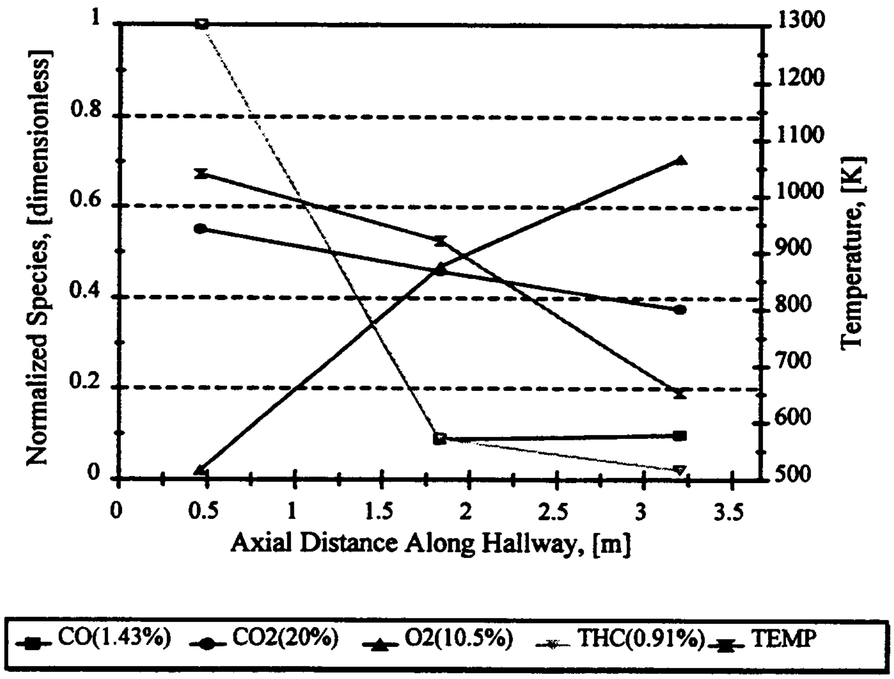


Figure 28. The axial profile of the hallway upper-layer gases is shown for a (20/20) soffit combination. The fuel pan diameter was 20 cm, the vent area was 1200 cm^2, the average equivalence ratio was 1.72 and the average heat release was 397 kW.

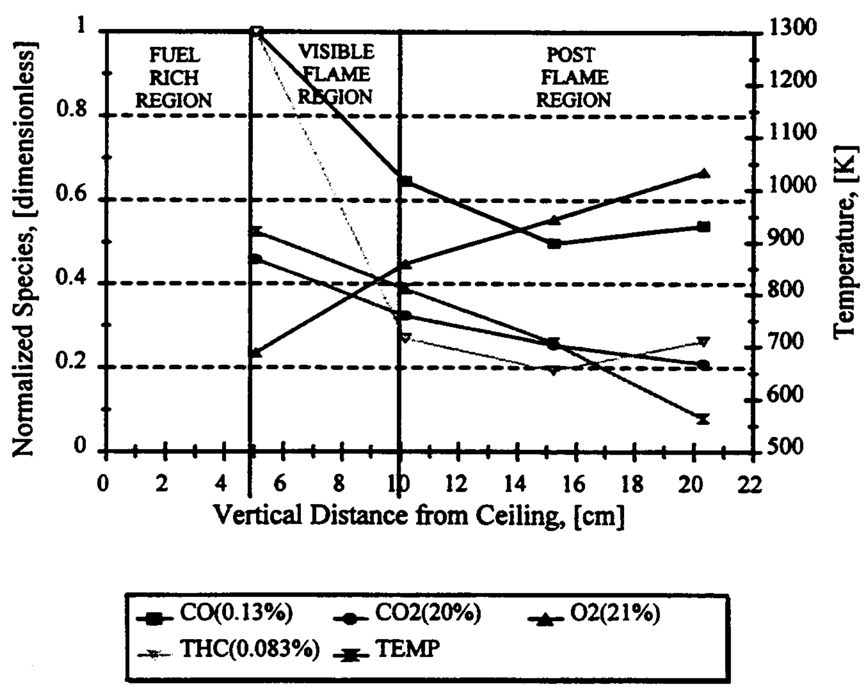


Figure 29. The vertical profile of the hallway upper-layer gases is shown for a (20/20) soffit combination. The fuel pan diameter was 20 cm , the vent area was 1200 cm^2, the average equivalence ratio was 1.74 and the average heat release was 381 kW.

The vertical profile for the 20 cm soffit at both ends of the hallway is seen in Figure 29. The 20 cm diameter fuel pan with a 1200 cm^2 vent area were used in the experiments. The average equivalence ratio was 1.74 while the average heat release was 381 kW. At the middle of the hallway, all three regions are present. This confirms that the flame extended past the middle of the hallway making it longer than that of the (20/0) soffit combination. This is also consistent with the exit soffit causing the upper-layer within the hallway to become thicker. Though it was slightly thicker for the (20/20) soffit combination, the efficient air entrainment still enables the gases to oxidize very efficiently.

4.3.2 Limited Air Entrainment into Hallway

Experiments were run where the exit of the hallway was slowly blocked off to see the effects of limiting the amount of air which was allowed to enter the hallway. The hallway was blocked off from the ground up in 1/4 ceiling height (42 cm) increments. Vent areas of 1200 cm^2 and 400 cm^2 were used to include low equivalence ratio tests and high equivalence ratio tests, respectively.

Eight experiments were performed with the hallway having a 20 cm soffit at both ends. For these experiments only a 20 cm diameter fuel pan was used. Sixteen additional experiments, eight with a 20 cm diameter fuel pan and eight with a 23 cm diameter fuel pan, were conducted with the hallway having a 20 cm soffit at the hallway entrance and a 0 cm soffit at the hallway exit. The results of all of these test are seen in Figures 30-35.

The overall oxidation of the gases in all of the cases seems to be relatively unaffected by the blockage of the end of the hallway. The air necessary to oxidize the exhaust gases is already contained within the hallway so the oxidation of CO and THC is unchanged. The upper layer of gases within the hallway prior to external burning does become very thick when the blockage is 1/2 and 3/4 of the height of the hallway. When external burning does occur, the thick layer of fuel rich gases is instantly ignited and totally disappears. The efficient oxidation of the 20 cm entrance soffit enables the reduction of CO and THC to quantities similar to no blockage at the hallway exit.

4.3.3 Blocked Compartment Plenum

Two types of air entrainment into the compartment were used in the investigation. In the situation termed the "door case", the plenum underneath the fire compartment is blocked off from ambient air causing the fire to entrain air into the compartment via the exhaust vent opening at the compartment-hallway interface, see Figure 36. The cool ambient air from the hallway entered the compartment from the bottom of the exhaust vent while the hot combustion gases exited the compartment through the top portion of the exhaust vent. The bottom of the 51 cm wide, 75 cm high exhaust vent (3825 cm^2) was located 74 cm above the hallway floor. In the other situation, termed the "window case", the plenum underneath the compartment supplied the fire with air, see Figure 18. The hot combustion gases exited the compartment through a 51 cm wide, 24 cm high (1200 cm^2) window style exhaust vent. The circular duct connected to the plenum is used so the air entrained into the fire can accurately be measured, knowing that no air is able to

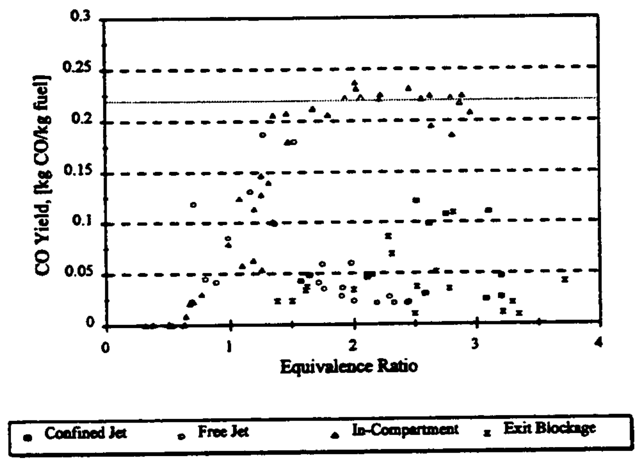


Figure 30. CO yields for the limited hallway air entrainment tests with the (20/0) soffit combination present.

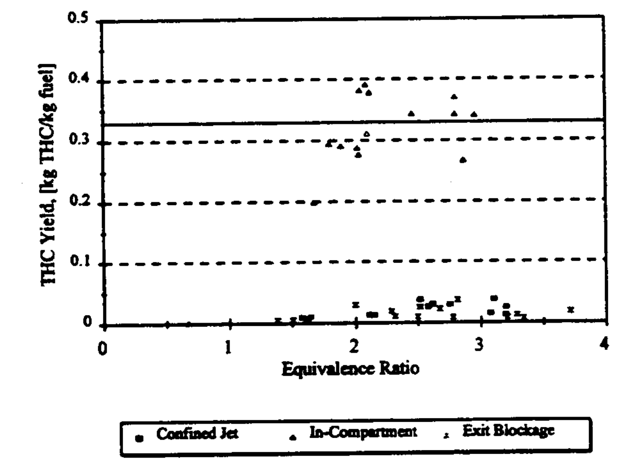


Figure 31. THC yields for the limited hallway air entrainment tests with the (20/0) soffit combination present.

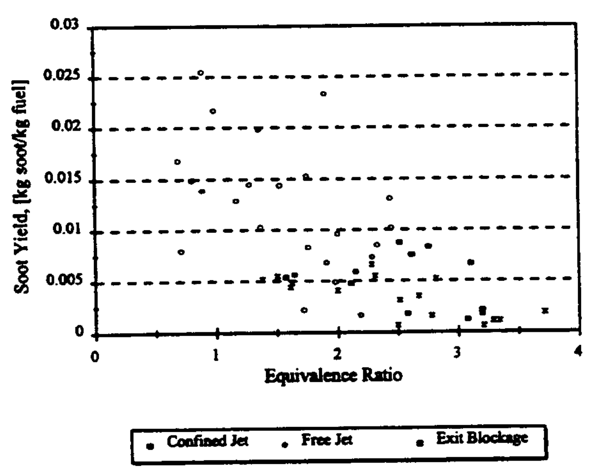


Figure 32. Soot yields for the limited hallway air entrainment tests with the (20/0) soffit combination present.

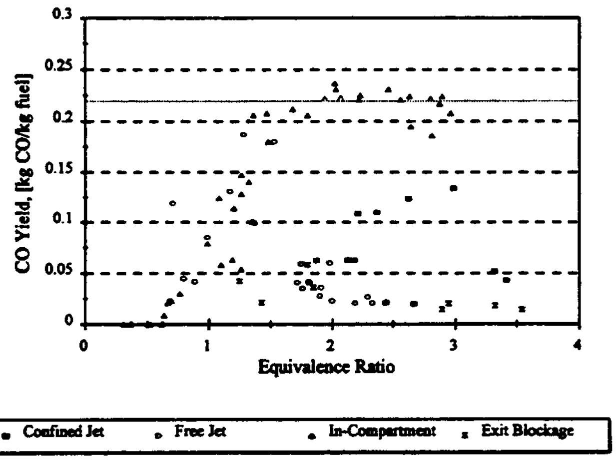


Figure 33. CO yields for the limited hallway air entrainment tests with the (20/20) soffit combination present.

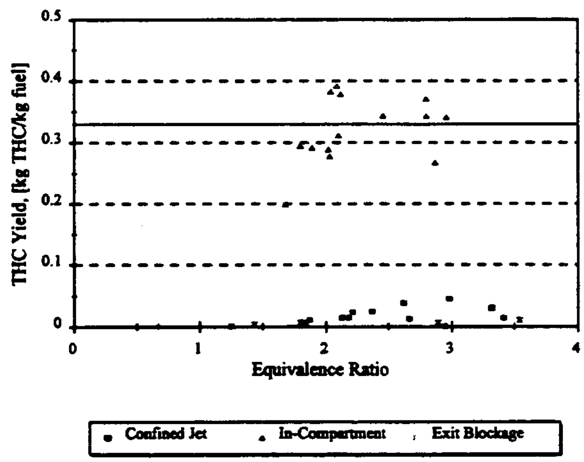


Figure 34. THC yields for the limited hallway air entrainment tests with the (20/20) soffit combination present.

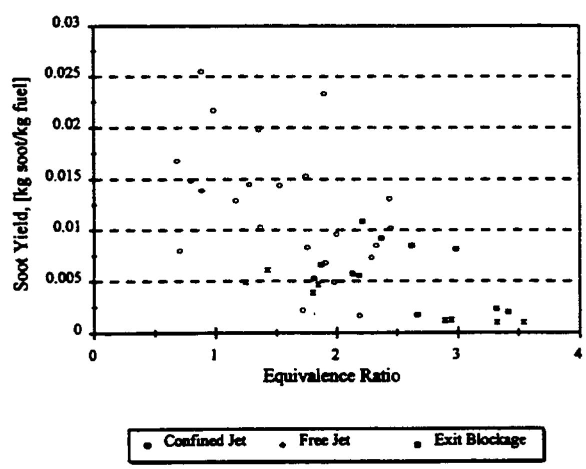


Figure 35. Soot yields for the limited hallway air entrainment tests with the (20/20) soffit combination present.

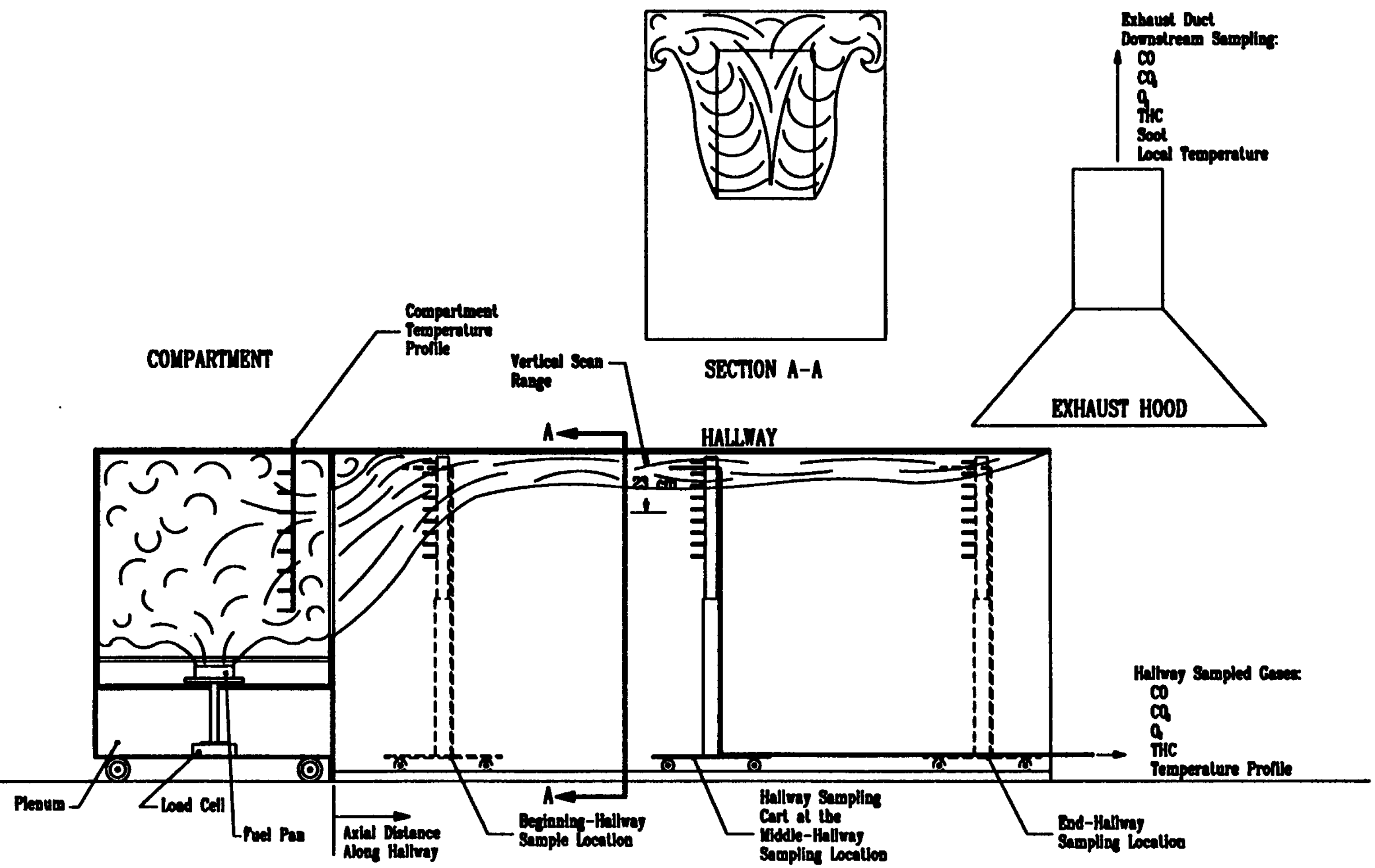


Figure 36. The compartment with the air distribution plenum blocked off and an enlarged exhaust vent area of 3825 cm^2, termed the "door case". Also shown is a graphical representation of the external burning which is present for this situation.

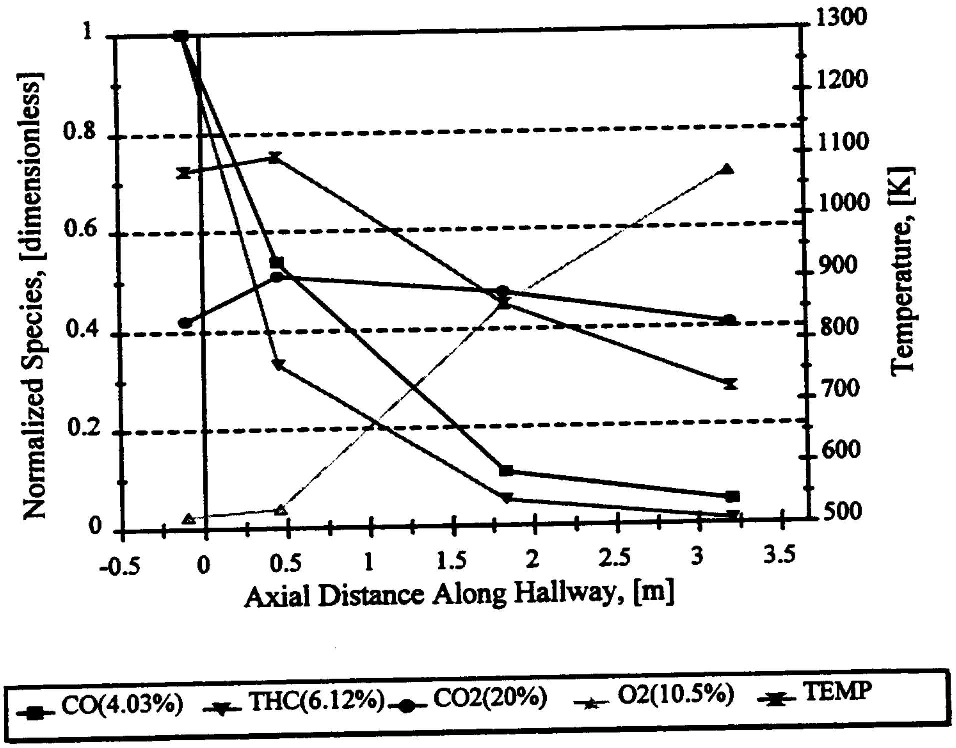


Figure 37 An axial profile of the upper-layer gases in the hallway for the "door case".

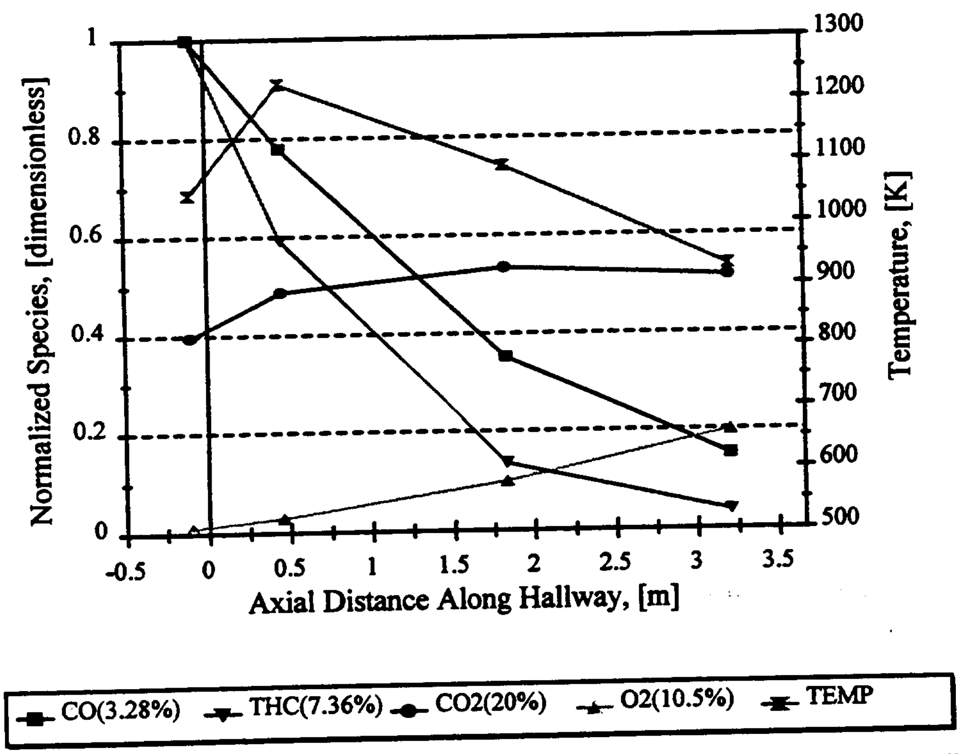


Figure 38. An axial profile of the upper-layer gases in the hallway for the "window case".

enter the compartment through the window style vent leading into the hallway during external burning. This enables an easy calculation of the equivalence ratio since the fuel vaporization rate is also monitored. Equivalence ratios were not calculated for the "door case". A 20 cm soffit was located at the entrance of the hallway while no soffit was at the hallway exit.

Axial profiles of the combustion gases from the "door case" and the "window case" experiments are shown in Figures 37 and 38, respectively. Axial locations smaller than zero indicate sampling inside the compartment. The average power of the fires in the "door case" was 576 kW while it was 542 kW in the "window case". Noting the values in parentheses inside the graph legend, the levels of CO inside the compartment are slightly higher in the "door case". The efficiency of the entrainment of air in the "door case" is also much higher. This can be seen by the rapid rise in the oxygen concentration within the upper-layer. The massive entrainment of cool air enabled the gases to oxidize quickly, but this air also reduced the temperature of the upper-layer. This reduction in temperature resulted in the freezing out of the CO oxidation reaction midway down the corridor. These reactions do not appear to freeze out until near the end of the hallway in the "window case". The post-hallway yields of CO and THC in the "door case" were 0.1035 and 0.0294, respectively. The post-hallway yields of CO and THC for the "window case" of 0.121-0.110 and 0.0388-0.0377, respectively, are only slightly higher than those seen in the "door case". The reduction in the concentration of CO and THC at the end of the hallway was higher in the "door case". The concentration reduction

$$\eta_{red} = \left(1 - \frac{(X_i)_{hallexit}}{(X_i)_{comp}}\right)100 \qquad [\%] \qquad (2)$$

in CO and THC was 95% and 99%, respectively for the "door case" and 85% and 96%, respectively, for the "window case". Noting that approximately the same amount of CO and THC leave the hallway, the higher concentration reduction efficiency in the "door case" is the result of a dilution of the combustion gases via increased air entrainment into the upper-layer. These concentration reductions should not be confused with overall oxidation within the hallway. The concentration reduction is based on percent volume within the sample and is affected by air diluting the gases while the overall oxidation is based on yields and is not affected by dilution.

An explanation of the difference in the upper-layer air entrainment between the two cases is in order. Experiments were performed by Hinkely et al.(1984) and Alpert (1972) where a fire, located a certain distance below the ceiling of a corridor, impinged upon a hallway ceiling and then traveled down the corridor as a ceiling-jet. The largest amount of air entrainment into the fire occurred in the vertical buoyant plume rising from the source to the ceiling. The section of the fire where it impinged upon and turned down the ceiling was where the second largest amount of air entrainment occurred while the ceiling-jet entrained the least amount of air. These trends were verified in a paper summarizing the prediction of flame lengths under ceilings by Babrauskas (1980). There are two basic differences between the "door case" and the "window case" external burning. First, there are two large vortical structures, starting at the exhaust vent and extending out into the corridor until the flame impinges on the ceiling, present in the first half of the hallway in the "door case". The vortical structures are present in the "window case", but they are much smaller. Secondly, there is an increased interfacial area between the vertical portion of the fire and the hallway air in the "door case". For the "door case", a nearly vertical plume of approximately 0.94m in height exits the compartment, impinges on the ceiling and travels down the hallway as a ceiling-jet. The vertical plume exiting the compartment consists of two vortices of fire, as seen in Figure 36, rotating from the outside towards the middle of the exhaust vent. These vortices further increase the vertical buoyant plume's air entrainment abilities. Upon the fire plume impinging on the ceiling and spreading the width of the hallway, vortical structures are formed where the ceiling and wall intersect. The vortical structures do not separate as Hinkley et al. (1984) reported but are instead connected by a sheet of fire. At the entrance of the hallway, the O_2 concentration remains low because the air being entrained is used to oxidize the fuel rich exhaust gases. In the region where the jet impinges on the ceiling and then travels down the hallway as a ceiling-jet, the air entrainment rate into the upper-layer is still high and this entrainment begins to cool the gas temperature causing the CO oxidation reaction to freeze out. Since the O_2 cannot be used to oxidize the CO and THC any longer, it begins to accumulate in upper-layer. The window case has a smaller inclined buoyant plume, whose height is approximately 0.43 m, which also contains two vortical structures. These structures are much smaller than those seen in the "door case" and thus are not as effective at entraining air. In the region downstream of where the fire impinges on the ceiling, two vortical structures are again formed down the hallway where the ceiling and the walls intersect and are connected by a ceiling-jet of fire. The less efficient air entrainment in the first half of the hallway for the "window case" is obvious through the slower oxidation rate of THC and CO and the higher gas temperatures in this region. The O_2 begins to accumulate in the upper-layer near the end of the hallway where the gas temperatures have been reduced to a level where the CO oxidation reactions do not occur as readily.

4.3.4 Combustible Ceiling inside the Compartment

A wooden ceiling, whose weight was continuously monitored, was placed in the upper-layer of the compartment as seen in Figure 39. The two different types of air entrainment into the compartment described in Section 4.3.3, the "door case" and the "window case", were utilized in these experiments. It has been previously documented that CO levels reach up to 14%-dry at the back and 6.5%-dry in the front of a compartment with a wood lined ceiling and a 400 kW burner fire (Pitts et al., 1993). Experiments were performed to verify these findings, to examine the effect the different flow field structures generated by the "door case" and the "window case" and to investigate the evolution of the exhaust gases from the compartment as they travel down the hallway. The results of the "door case" and the "window case" experiments with a non-combustible ceiling, shown in Figures 37 and 38, respectively, will be compared to the results obtained with a combustible ceiling inside the compartment. The highest the available CO gas analyzer can be calibrated for is 10%-dry CO and values greater than 10% will give off a signal equivalent to 10% due to the linearizer within the analyzer. The concentration of CO at the back of the compartment, located by the wall opposite the exhaust vent, was greater than 10%-dry causing the gas analyzer signal to the computer to be cut off. The display screen on the analyzer showed levels of CO at the back of the compartment to rise to approximately 14%-dry for the "door case" and to 16%-dry in the "window case", though the accuracy of this measurement is questionable. Controlled dilution of the exhaust gases sampled from the back of the compartment will be done in the next quarter to obtain these values.

The wooden ceiling consists of 3 sheets of 0.91 m long, 0.30 m wide, 6.35 mm thick Douglas fir plywood. The average initial mass of the ceiling was 4.67 kg ± 0.21kg. A light wood truss rests on top of a 10 kg A&D load cell located on the roof of the compartment as shown in Figure 39. Nine 10 cm long steel screws were connected to the truss and fed into the ceiling of the compartment. These screws were used to suspend the wood ceiling in the compartment upper layer using molly bolts. The burn rate of the wood was then measured by numerically taking the derivative of the weight of the wood with time. The mean burn rate for the "door case" experiments was 0.0327 kg/s ± 0.0058 kg/s while the mean burn rate was 0.0280 kg/s ± 0.0057 kg/s for the "window case" experiments.

For the "door case" having a 3825 cm^2 vent size and a fuel pan diameter of 20 cm, the evolution of the wet combustion gases from the compartment to the end of the corridor is shown in Figure 40. The average heat release of the pool fire was 515 kW which is slightly less than the heat release for the pool fire with a non-combustible ceiling. The average heat release of the wood ceiling was 870 kW. The exhaust vent is located at an axial distance equal to zero, therefore, the axial locations which are less than zero signify sampling inside the compartment. The only in-compartment sampled results shown are those in the front of the compartment. The results for a non-combustible ceiling inside the compartment are seen in Figure 37. Due to the high temperature of the upper-layer, both CO and THC are oxidized the entire length of the hallway. The long flame length, which stretched far enough to extend past the end of the corridor and up into the exhaust hood, was proof that exhaust gases were being oxidized down the length of the hallway ceiling. Yet another way of confirming that the decrease in the exhaust gas concentrations near the end of the hallway is not caused by the dilution of air is the continuous rise in the magnitude of CO_2. Also, notice how the temperature of the upper-layer gases within the hallway rises during the first part of the hallway. Using additional temperature profiles at locations other than those shown, the temperature reaches a maximum of around 1225°K at approximately 1.2 m downstream of the compartment. The temperature at the end of the hallway is only 15°K less than the temperature inside the compartment. The maximum temperature within the hallway for the non-combustible ceiling case, Figure 37, is just outside of the compartment followed by a fall in temperature with the high entrainment rate of air. Though the levels of O_2 in the hallway upper-layer are less with a combustible ceiling compared to those levels reached with a non-combustible ceiling, the entrainment of air into the hallway gases is similar. Instead of diluting the gases, the O_2 entrained in the combustible ceiling case is used to oxidize the fuel rich exhaust gases and is made possible by the high temperatures of the upper-layer. The magnitude of CO at the front of the compartment is 8.18%-wet and is reduced to 1.09%-wet by the end of the corridor which corresponds to a concentration reduction *of 86%. This is lower than the 95% concentration reduction in CO present in the non-*

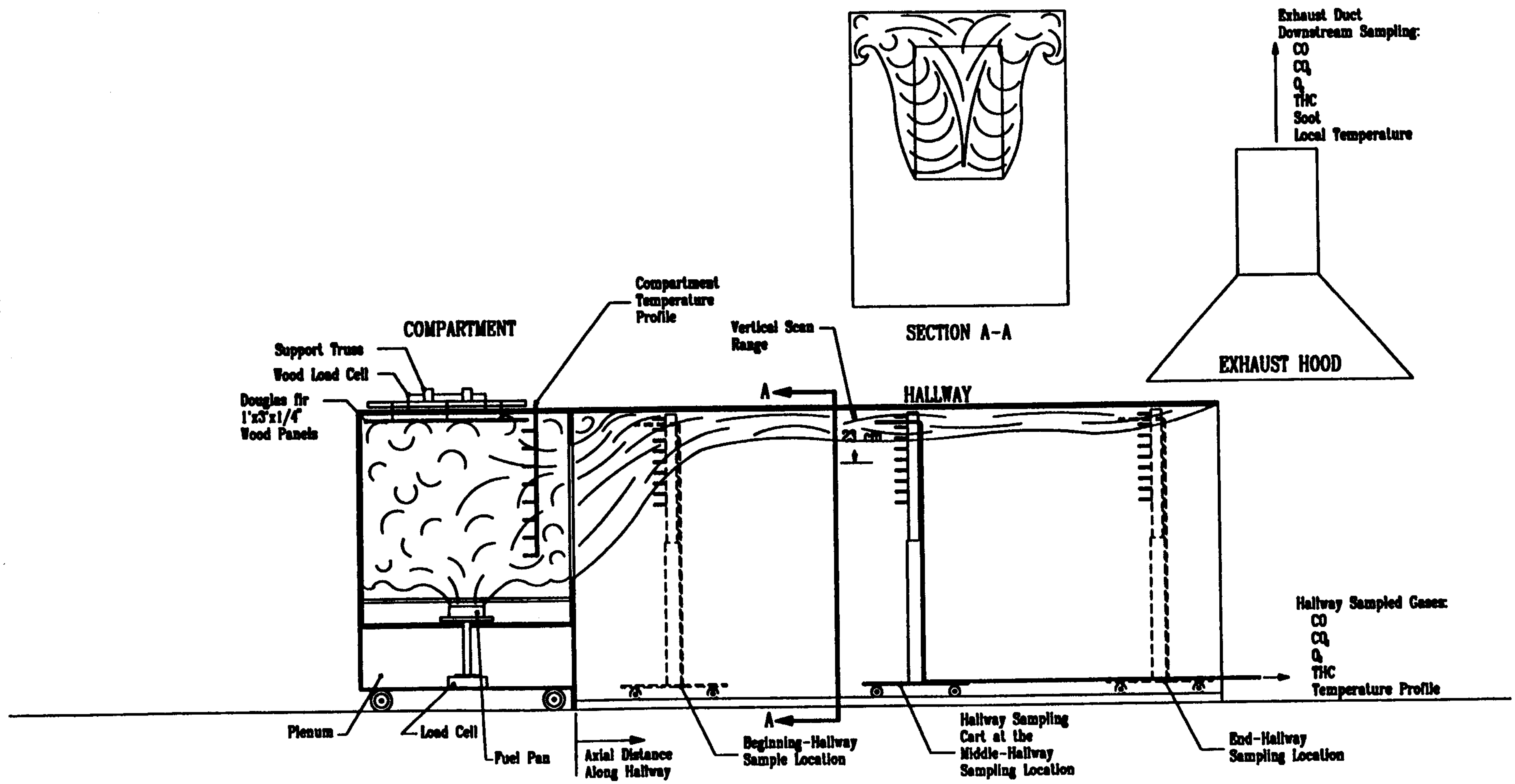


Figure 39. A side view of the fire facility showing the wooden ceiling and its weighing apparatus located on top of the compartment.

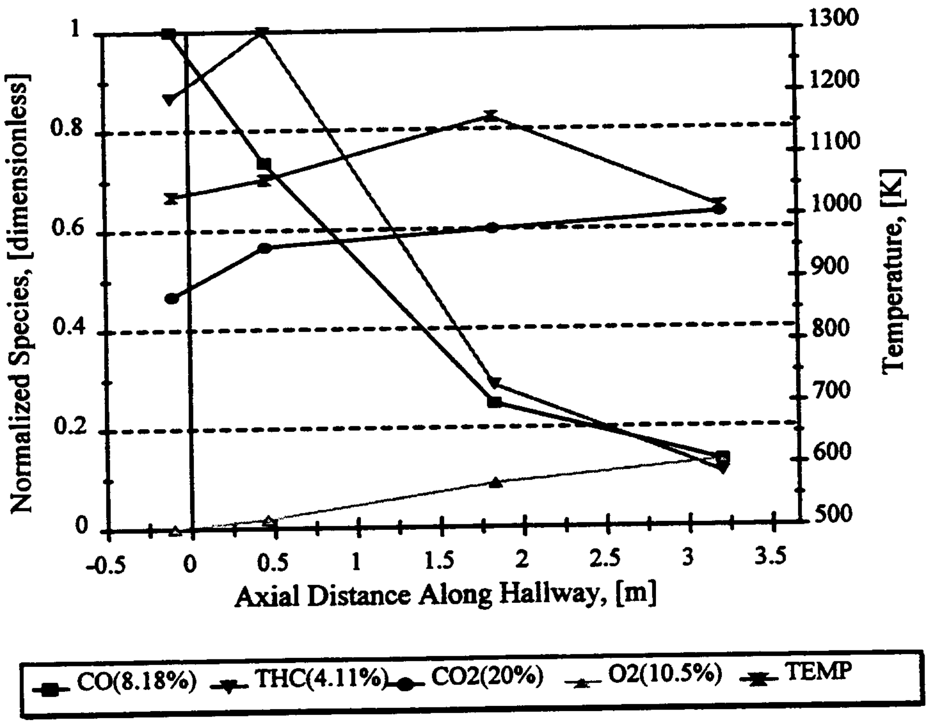


Figure 40. An axial profile of the upper-layer gases within the hallway, including the levels at the front of the compartment, are shown for the "door case" with a wooden ceiling and a (20/0) soffit combination.

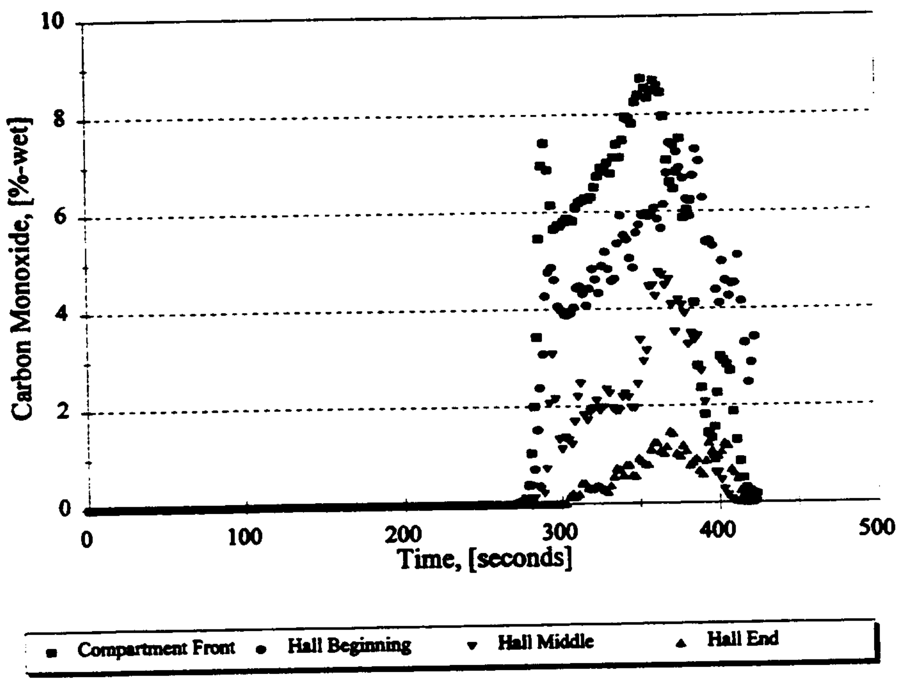
combustible ceiling case. A plot of the wet concentration of CO versus time for the four different sampling locations with a combustible ceiling is given in Figure 41a while the non-combustible ceiling case is shown in Figure 41b.. The THC level within the compartment is low and is suspected to be in error upon comparing it with other experimental THC level so the concentration reduction will have to be quantified at a later date. Figures 42a and b show the history of THC with time at the four sampling locations for the combustible and non-combustible ceiling within the compartment, respectively.

A combustible ceiling was then placed in the compartment with the plenum underneath open to the atmosphere, designated as the "window case". For this case, the 1200 cm^2 vent size was used and the liquid pool fires were burned in a 23 cm fuel pan. The larger fuel pan was used to get a heat release similar to that achieved in the door case. The average heat release for these pool fires was 485 kW which is again lower than the heat release with a non-combustible ceiling due to energy necessary for the wood to undergo pyrolysis. The average heat release of the wood ceiling was 748 kW. All heat releases are slightly lower than those in the "door case". The results of an axial profile for the "window case" with a combustible ceiling are shown in Figure 43. Again, CO and THC are oxidized down the entire length of the hallway and the flame length was longer than the hallway resulting in the flame extending up into the fume hood. The flame in the "window case" extended further up into the fume hood than what was seen in the "door case". Again, the temperatures within the hallway became higher as they were transported down the first part of the hallway. In the "window case", the temperature profile data showed that the hallway peak temperature of approximately 1225°K occurred approximately 1.8 m away from the compartment. This shift in the location of the peak temperature to a point further downstream than that seen in the "door case" is attributed to the less efficient air entrainment of the "window case". The temperature at the end of the hallway for the "window case" is higher than that inside the compartment and at the beginning of hallway. There was almost a nonexistent concentration of O_2 in the upper-layer of the hallway demonstrating, again, that the entrainment of air for the "window case" is not as efficient as the "door case". The concentration reduction in CO from the front of the compartment to the exit of the hallway is 69% which corresponds to values of 7.85%-wet at the front of the compartment and 2.4%-wet at the end of the hallway. The wet concentration of CO at the different sampling positions is plotted with time for both the combustible and non-combustible ceiling case in Figures 44 a and b, respectively. THC experienced a similar reduction of 82% which is equivalent to a 7.79%-wet level at the front of the compartment and a 1.41%-wet level at the end of the hallway. These concentrations are slightly higher than those results obtained with a non-combustible ceiling. This is clearly seen in Figures 45 a and b where the THC are plotted versus time for the four different sampling locations.

5.0 FUTURE WORK

During the next year (1994-95) several aspects of exhaust gas formation, transport and oxidation will be addressed, as well as modifications to the facility.

The first task which will be accomplished is altering the compartment-hallway



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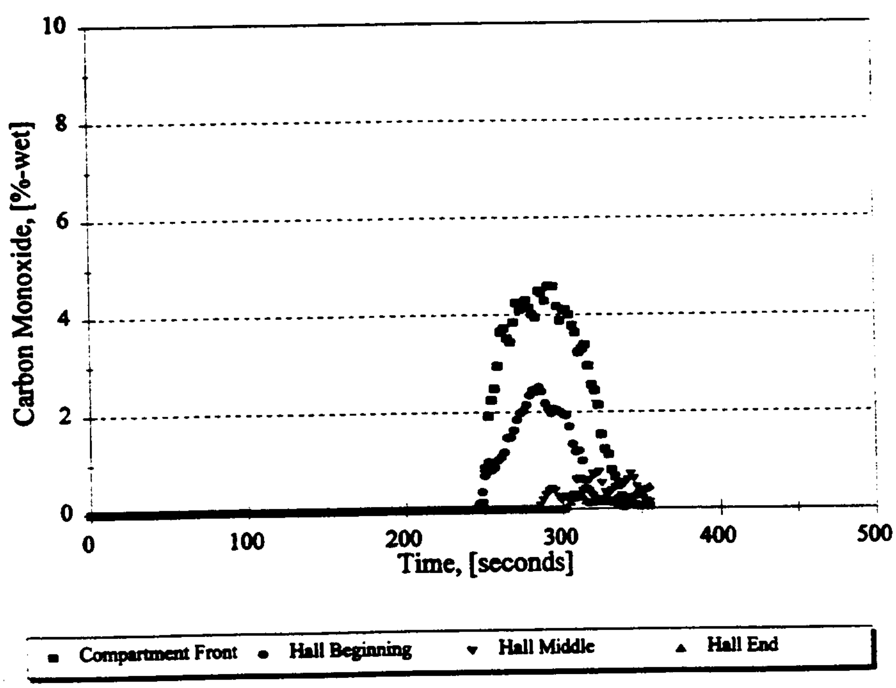
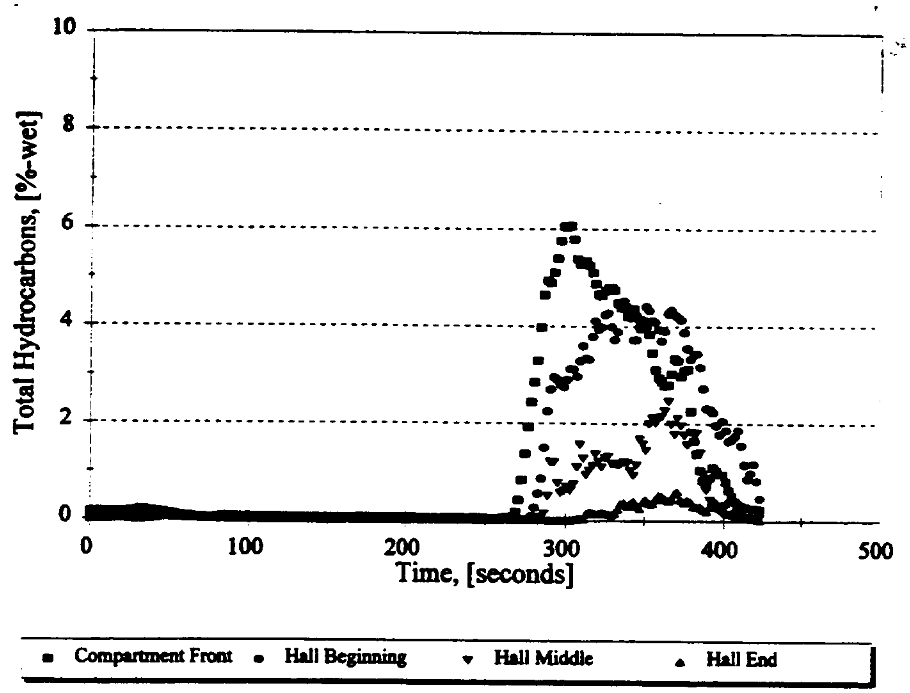


(b)

Figure 41. The time plots of the wet concentrations of CO (a) with a wooden ceiling and (b) without a wooden ceiling for the "door case" and a soffit combination of (20/0).



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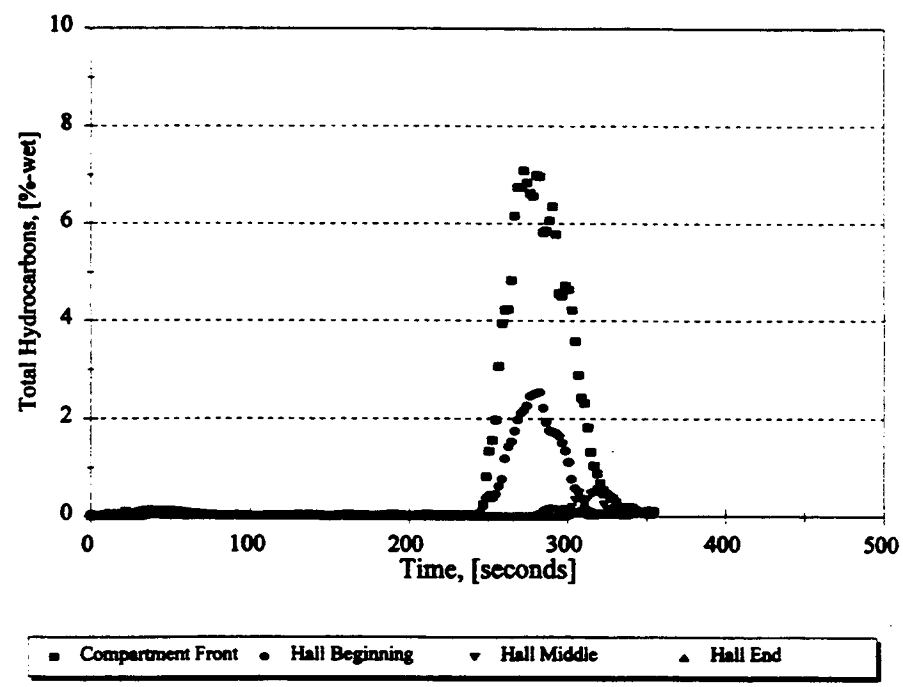

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Figure 42. The time plots of the wet concentrations of THC (a) with a wooden ceiling and (b) without a wooden ceiling for the "door case" and a soffit combination of (20/0).

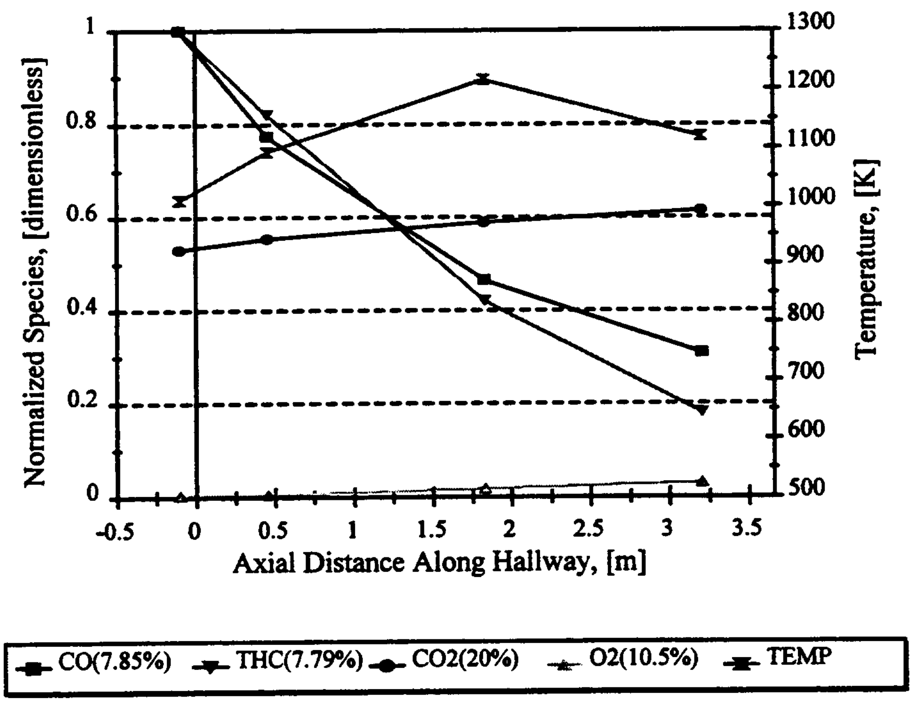
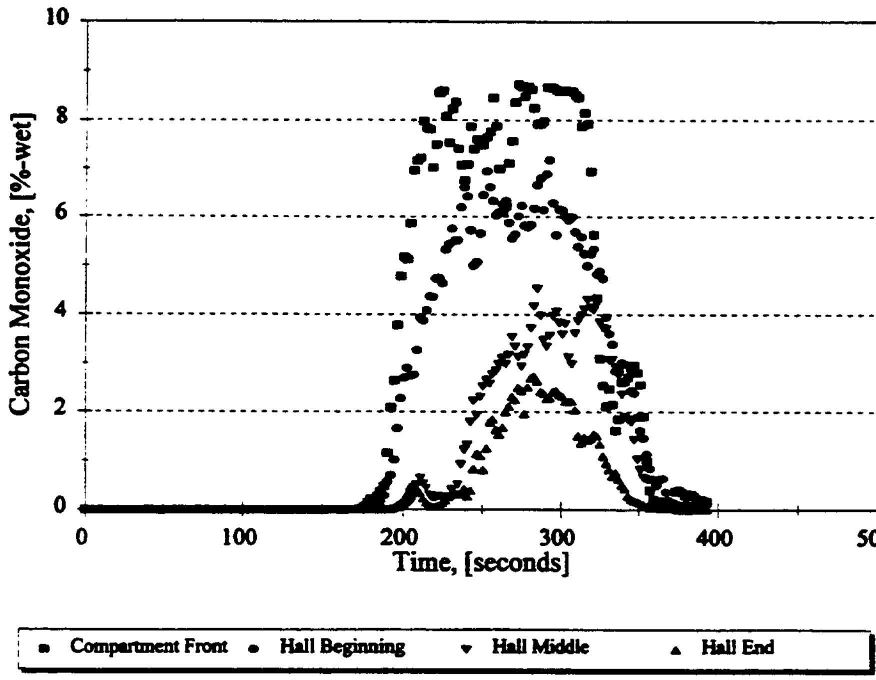


Figure 43. An axial profile of the upper-layer gases in the hallway, including the levels at the front of the compartment, for the "window case" with a wooden ceiling and a (20/0) soffit combination.



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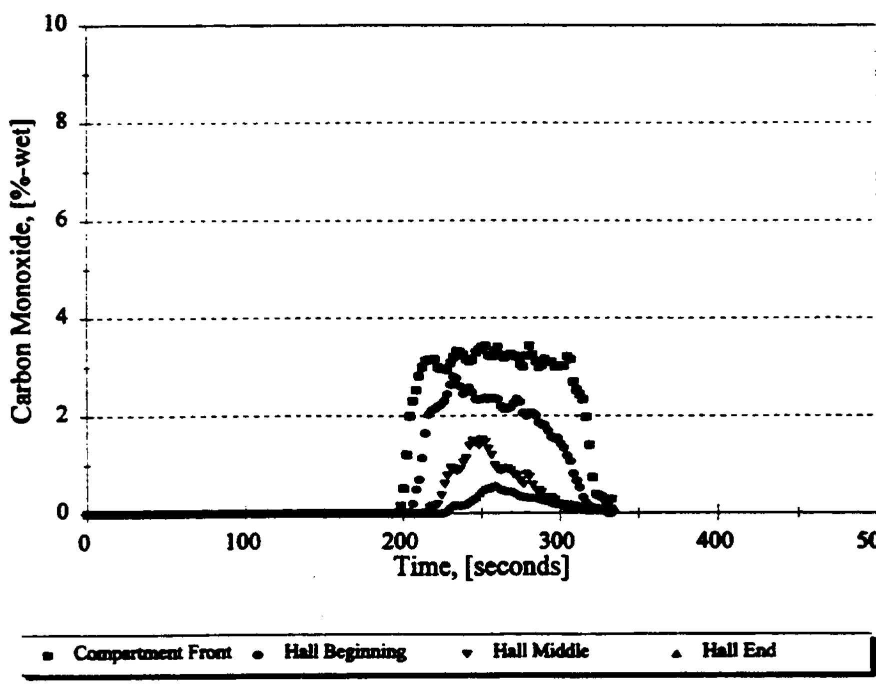
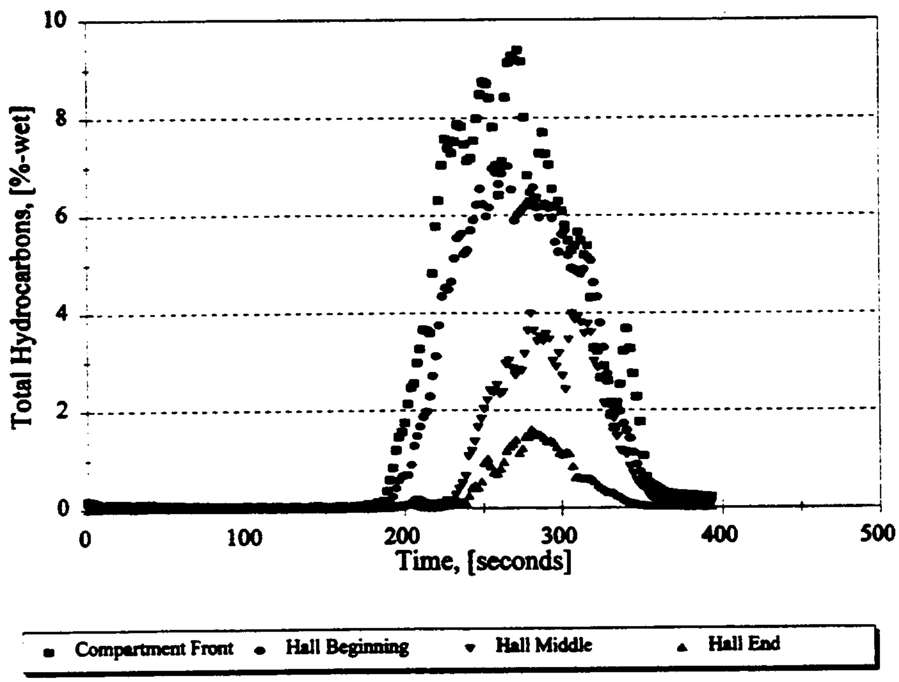


(b)

Figure 44. The time plots of the wet concentrations of CO (a) with a wooden ceiling and (b) without a wooden ceiling for the "window case" and a soffit combination of (20/0).



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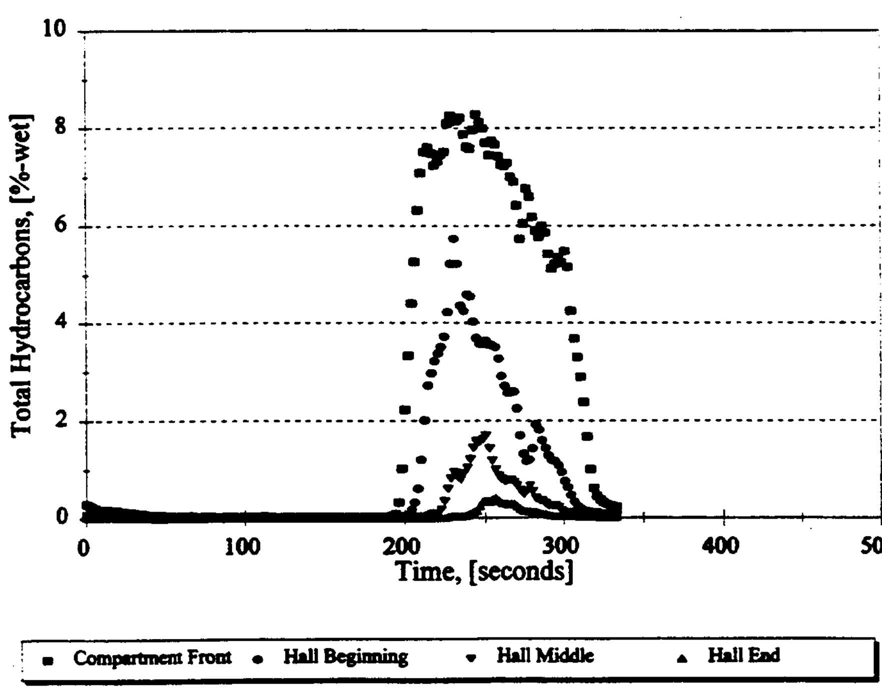


(b)

Figure 45. The time plots of the wet concentrations of THC (a) with a wooden ceiling and (b) without a wooden ceiling for the "window case" and a soffit combination of (20/0).

orientation. The two other orientations to be studied are the side-end configuration and the side-middle configuration, seen in Figure 46 a and b, respectively. The side-end configuration will be experimentally analyzed first followed by the side-middle configuration. For the side-middle configuration, an additional section of hallway will be added so there will be a sufficient amount of ceiling to keep the ceiling jet within the hallway. The effects of the four soffit combinations utilized in the current experimental configuration will be investigated for both of the new compartment-hallway orientations. These experiments will be conducted in the new hallway apparatus.

Before beginning these experiments, thermocouples will be placed every twelve inches along the ceiling of the hallway and will be used to estimate the flame length in each test. Correlations between the flame length and the oxidation of CO within the hallway are believed to exist and a more accurate measurement of the flame length needs to be made. Currently, the flame length along the ceiling is estimated using the video recordings of the tests. The measure of the flame length will aid in the estimation of the entrainment into the exhaust gases and will allow for comparison between work done by Hinkley et al. (1984) and Alpert (1972).

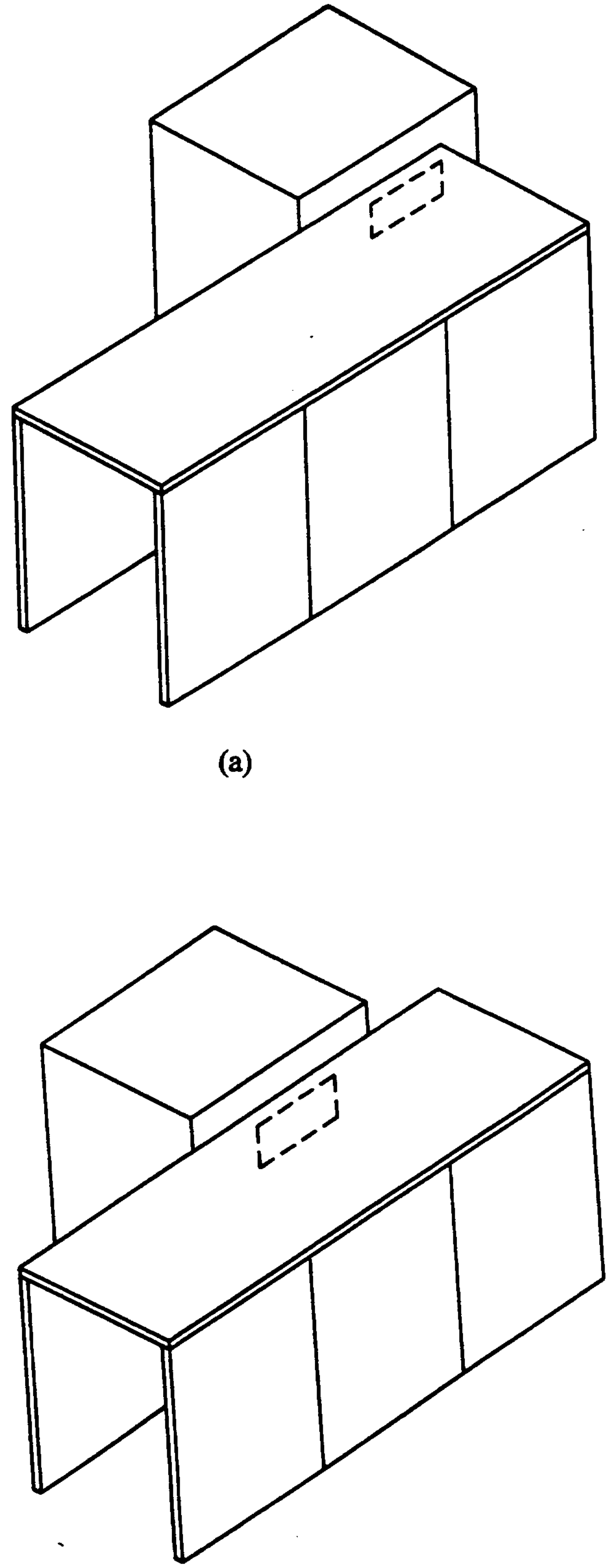
The automated fuel supply will be used when the side-end orientation, seen in Figure 46 a., is present. The automated fuel supply had not been used to this point due to the lack of durability of the old hallway. With the new hallway intact, the steady state time of each test can be extended for as long as desired.

The automated sampling cart will enable the sampling of gases at various locations within the hallway during a single test. This will reduce the number of experiments which needs to be run and will ensure that the data points creating an axial, vertical or horizontal profile within the hallway are for the same test. More refined profiles, which were previously time consuming and difficult to obtain experimentally, will also become possible.

An estimation of the entrainment of air into the hallway flame will also be undertaken using the experiments where external burning does not occur. In these cases, changes in the level of CO_2 within the hallway is caused by the entrainment of air into the upper-layer and can be used for comparison between different soffit combinations and vent areas.

Upon the completion of the investigation of the two compartment-hallway configurations, burner experiments within the hallway will be performed. In experiments by Hinkley et al. (1984), Alpert (1972) and others not listed, the burner was placed on the floor of the hallway so a buoyant jet rose vertically until it impinged upon the ceiling and was deflected down the length of a hallway. The difference between these experiments and the ceiling jets studied in this investigation is the vertical plume which is responsible for the largest amount of entrainment into the combustion gases. With the burner mounted on the wall near the ceiling of the corridor, experiments will be performed to examine the external burning ceiling jets contained within the hallway. The advantage of the burner experiments over the compartment experiments is that flow rates and the stoichiometry are controllable.

Finally, the measurement of soot within the corridor upper-layer will be done using a laser extinction system. The deposit of soot on the access windows will be corrected by injecting an inert gas, possibly N_2, across the surface of the window. The location of the



(a)

(b)

Figure 46. The (a) side-end and the (b) side-middle compartment-hallway configurations.

soot measurements within the hallway will at first be manual but will eventually be automated to enable vertical profiles of the upper-layer within the hallway.

6.0 PERSONNEL

During the past year, two graduate students and fifteen undergraduate students have participated on this project. In addition to the experimental results obtained, numerous improvement projects have been performed in the past year.

Mr. David S. Ewens completed his Masters of Science in February of 1994 and was responsible for performing all of the experiments with various soffit combinations. Mr. Brian Y. Lattimer took over the project in January of 1994 after aiding Mr. Ewens with the majority of the soffit combinations which were performed during this year of the investigation. Mr. Lattimer is currently working towards his Ph.D.

Brad Bumgarner, Larry Eget, Dan Couchman, Mike Ruby (also on one of the automated sampling cart design teams), Mike Monier and Matt Finn have all aided in the experimentation process. In addition to aiding the two graduate students with experiments, most of the undergraduates performed small research projects. The projects included a laser extinction system in the hallway, an automated fuel supply, a device for holding and weighing the wooden ceiling in the compartment, a measurement of flame length in the hallway and redesign of some aspects of the automated sampling cart.

Ten additional undergraduate students, two groups of five, designed a computer controlled sampling cart. One group was able to build their cart design which will eventually be integrated into the system.

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The overall scope of this research is to investigate the phenomena that control the generation and oxidation of compartment fire exhaust gases (particularly carbon monoxide, CO) which are transported down an adjacent corridor. Results of the first two years of the project are summarized. During the past year three hallway soffit combinations were investigated in order to characterize the effects of varying the fluid mechanics on the burnout behavior of combustion gases. The findings show that the addition of a soffit at the fire enclosure end of the corridor increased the degree of burnout, while adding a soffit at the exit of the corridor decreased the degree of oxidation. Soffits at both ends yielded an intermediate result. Varying the size of the opening into the corridor had no effects on the results. A set of experiments are also summarized in which fires were burned in an enclosure having a wood ceiling. This resulted in the generation of very high concentrations of CO in agreement with the findings of Pitts et al.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

carbon monoxide; ceilings; combustion gases; compartment fires; corridors; fire research; soffits; soot; toxic gases; wood

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