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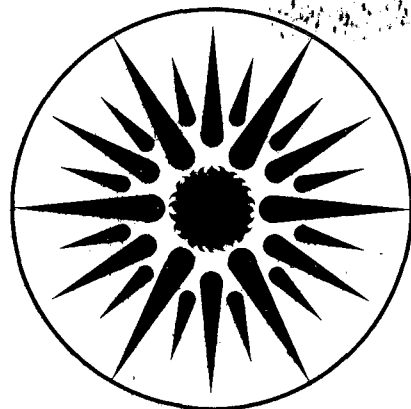
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Presented at the International Symposium on Characterization
and Toxicity of Smoke, Phoenix, AZ, December 5, 1988

The Use of Medium Scale Experiments to Determine Smoke Characteristics

C.M. Fleischmann, R.L. Dod, N.J. Brown, T. Novakov,
F.W. Mowrer, and R.B. Williamson

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THE USE OF MEDIUM SCALE EXPERIMENTS
TO DETERMINE SMOKE CHARACTERISTICS

by

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October 1988

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ABSTRACT

A series of medium-scale smoke experiments were conducted at the University of California, Berkeley. Representative fuels, such as wood, asphalt roofing shingles, and liquid hydrocarbons, were burned as medium scale fuel packages in the open, with no restriction on the ventilation. For some of the fuels, the experiments were also conducted in a burn room under limited ventilation conditions. The effects of different combustion conditions resulting from differences in fuel composition, geometry, and ventilation were determined.

Smoke emission factors measured for burning wood under well ventilated conditions were in the range of 0.1 to 0.3 percent, but under limited ventilation conditions they increased an order of magnitude to the 2 to 3 percent range. Under well ventilated conditions, the smoke emission factors measured for asphalt were in the 12 percent range and those for No. 2 fuel oil were in the 11 percent range. Burning in the compartment also affected the emission factors and smoke characteristics of fuel oil.

The results of the medium-scale experiments presented in this papers show that the smoke emission factors are not only dependent on the properties of a given fuel, but also on the environmental conditions under which the fuel was burned. Specifically, the influence of ventilation rate, fuel mass loss rate, temperature, and residence time are important. Although more research is required before a standardized medium scale fire test to measure smoke production can be developed, the need for such a test standard is clearly demonstrated by these results.

INTRODUCTION

The smoke from fires accounts for at least fifty percent of all fire deaths and billions of dollars in damage each year. In the last two decades significant advances have been made to improve our understanding of smoke movement and smoke characteristics, but we still lack the ability to predict the amount and the characteristics, both physical and chemical, of the smoke that is produced by fires. Yet a better understanding of the physical and chemical properties of smoke particles is important for many reasons. The toxicity of the smoke particles depends on their chemical composition, while their ability to penetrate into the human lung depends on the particle size distribution, a physical property. The atmospheric effects of smoke particles (such as radiative transfer, atmospheric residence times, and chemical reactivity) are also determined by both physical and chemical properties. Recent concerns with the global environmental effects of post nuclear fires have sparked a new interest in the amount and characteristics of smoke produced by fires.

The concept of "Nuclear Winter" has been postulated with a number of assumptions regarding the smoke produced by post-nuclear exchange fires^(1,2). The general premise is that following the use of nuclear weapons, sufficient smoke would be generated from fires and deposited in the atmosphere to cause a decrease in the incident solar energy reaching the Earth's surface. Such a change in the net radiative balance could cause global cooling. Whether Nuclear Winter would occur in the aftermath of a nuclear exchange depends largely on the quantity and nature of

smoke generated, its distribution in the atmosphere, and its optical characteristics.

Smoke is defined by ASTM E176 as "the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion"⁽³⁾. Using this definition, smoke can be separated into two prime components: (1) particulates and (2) gases. Particulates are the primary cause of reduced visibility and these may also have a physiological effect, such as increased heart rate of the occupants exiting from a burning structure⁽⁴⁾. Airborne particulates are the component of smoke which are responsible for activating smoke detection devices. Carbon monoxide, the principal gas for causing injury and death among occupants and fire service personnel, is one of many toxic gases contained in smoke.

Most of our current understanding of smoke has been derived from small scale experiments where the sample is either ignited by a pilot flame and allowed to burn freely, or it is exposed to a radiant energy source and undergoes smoldering combustion in a chamber of fixed volume. Typically, more smoke is produced under smoldering conditions; however, smoldering combustion is generally only a threat to the occupants in the room of origin and has little effect on other areas of the building. The piloted ignition tests use small samples which typically burn with a laminar flame lacking the turbulence, radiation, and ventilation characteristics present in actual fires.

This paper reports on experiments performed at the Fire Research Laboratory of the University of California at Berkeley aimed at characterizing the smoke produced from medium to full scale experiments and relate them to smoke measurements from bench scale experiments. The term "medium-scale" is used to characterize the 200 to 1000 KW fire experiments that produce flames a few meters in height. The term "full-scale" infers the use of a full scale room for the limited ventilation experiments. Though considered full-scale by the fire research community, these experiments are also used by the nuclear winter research community and therefore the term "medium-scale" is also being used throughout this paper. Both terms are in contrast to "bench-scale" experiments in which the flames are generally laminar and the rates of heat release are less than 20 KW.

Sixteen experiments were conducted on representative urban fuels including plywood, whole wood, asphalt roofing shingles, and #2 fuel oil. Smoke was characterized by the mass of airborne particulates, the size distribution of the particulates, and the carbon characteristics of the particulates, i.e., "graphitic", or "black", carbon and organic carbon. Mass loss and rate of heat release (RHR) were recorded during each experiment to characterize the combustion.

EXPERIMENTAL FACILITY

The experimental facility used to conduct the fire experiments is shown in Fig. 1. It consists of a 1,100 m³ (38,000 cu ft) "high-bay" room, a forced ventilation system, data acquisi-

tion facilities, and auxiliary sample preparation and storage area.

The ventilation system begins with a 3.0m x 3.0m (10 ft x 10 ft) canopy hood designed to capture the products of combustion generated during a fire experiment. The ventilation system is capable of transporting combustion products at a maximum rate of approximately $4 \text{ Sm}^3/\text{s}$ (8,000 SCFM). (Note that this flow is given in "standard" units, i.e., corrected for temperature). The canopy hood is connected to the exhaust fan by 0.61m (24 in.) diameter stainless steel ducting. The 0.92m (36 in.) diameter exhaust fan is driven by a 2 horse power AC motor, and the flow rate of the exhaust system is controlled by a solid state, AC motor controller.

The experiments reported here were either conducted on a 2.4 m x 2.4 m (8 ft x 8 ft) platform directly under the hood or in a 2.4 m x 2.4 m x 2.4 m (8 ft x 8 ft x 8 ft) "burn room" which is connected by an opening to another room 2.4 m x 3.7 m x 2.4 m (8 ft x 12 ft x 8 ft) which has a doorway under the hood. The burn room, which is constructed of a steel frame with steel stud walls, rests on a fire resistant floor that is elevated above the floor of the laboratory to permit instrumentation to be located below the burn room. The walls and ceiling of the room can be built to simulate different types of construction. During these experiments, the small burn room was lined with ceramic fiber insulation blankets while the outer larger room was lined with gypsum wallboard. The location of the platform and the burn room are shown in Fig. 1. The burn room and ventilation system are

capable of sustaining postflashover fires of several megawatts for up to one half hour duration.

EXPERIMENTAL PROCEDURE

During these 16 experiments, the fire and smoke were characterized by measuring the rate of heat release, the fuel mass loss rate and the smoke emission factors. The rate of heat release was determined using oxygen depletion calorimetry⁽⁵⁾. This method for determining the heat release rate is based on the assumption that all carbonaceous fuels release approximately the same amount of heat per unit mass of oxygen consumed (13.1 MJ/kg). The oxygen concentration was measured using a Beckman paramagnetic oxygen analyzer. Carbon monoxide concentration was also measured for all the experiments and in later experiments, such as the #2 fuel oil and the second asphalt experiments, carbon dioxide concentration was also measured. The gas concentration measurements were performed by extracting gas samples from the exhaust stream for analysis. Values of gas concentrations and duct flow conditions were recorded every 5 seconds by a laboratory minicomputer. Flow rates in the exhaust stream were determined using a bidirectional low-velocity probe, as described by McCaffrey and Heskestad⁽⁶⁾, which is accurate to within 10%.

The fuel mass loss during burning was measured using a Toledo scale Model 8132 which was, depending on the experiment, placed under the platform or the burn room. The output from the scale was recorded in real time using the computer controlled data acquisition system.

Aerosol particulate sampling for this series of experiments was conducted primarily from the exhaust duct at a point approximately 2 m (6 ft) downstream of the straightening vanes. Sampling probes were inserted at this point to accommodate the impactor and a stacked-filter pair. Further sampling was conducted in Exps. 3 - 16 by placing a sampling probe in the plenum directly above the hood. Another stacked-filter pair was used to collect the plenum samples. The plenum samples were then used to provide qualitative information regarding changes in the particulate carbon content and morphology which could potentially occur during the 0.3 to 0.5 sec transit of the duct to the primary sampling ports.

Several experiments, i.e., solid wood under ventilation limited conditions, asphalt roofing, and liquid hydrocarbon, produced such heavy smoke that dilution was necessary to avoid clogging of the impactor. This was accomplished by inserting into the impactor probe line a chamber through which continuously filtered air was recirculated to provide the impactor with only 1/10 of the duct particle concentration. The decision whether to use the dilution chamber was made prior to each experiment based on the expected smoke production.

The impactor used for these studies was a Pilat Mark 5 Cascade Impactor manufactured by the Pollution Control Systems Corp. All the filters used were 47 mm diameter quartz fiber. Sample mass was determined for each filter and impactor stage using a Cahn Model 4700 electrobalance.

The carbon content for each filter and impactor sample was determined by combustion of the sample in oxygen and then measuring the resulting CO₂ with a CO₂ Coulometer, (Coulometrics, Inc., Model 5010⁽⁷⁾). Further characterization of the carbon content in the filter and impactor samples was obtained using thermal evolved gas analysis (EGA) for carbon. This technique has been used to characterize collected aerosol carbon particles by type, i.e., "organic", "black", or "carbonate" carbon^(8,9). All the samples analyzed in this study showed a dominant black carbon peak and no carbonate, allowing for a clear differentiation between black and organic carbon. The sampling procedure and reliability of the method used in this study is discussed in greater detail by Dod, et al.⁽¹⁰⁾

EXPERIMENTS

Sixteen experiments were conducted on representative urban fuels. In six of the experiments, Douglas fir plywood was burned in a parallel plate geometry, as shown schematically in Fig. 2. The fuel geometry, one of the two idealized cases presented by Babrauskas and Williamson⁽¹¹⁾, represents the condition in which the fuel specimens create their own environment, independent of the greater surroundings. The nominal separation distance between the plywood sheets was 0.15 m (0.5 ft) for all the plywood experiments, except for Exp. 2 where the separation distance was reduced to 0.10 m (0.33 ft). A catch pan was not provided in Exps. 1 and 2, thus allowing the burning mass that fell away to be included in the fuel mass loss. This was corrected in the

remaining experiments by using a wire mesh catch basket. A propane-fired gas flame was used to ignite the plywood faces and was extinguished after the fuel specimen reached a self sustaining stage of burning. For Exps. 1-5, 5 ply CDX grade Douglas fir plywood which was 1.3 cm (0.5 in.) thick was used. For Exp. 6, 3-ply Douglas fir plywood which also was 1.3 cm (0.5 in.) thick, but had a thicker veneer, was burned. Experiment 6 could be thought of as being an intermediate step between Exps. 1-5 where plywood samples were used and the whole wood experiments described below.

For the whole wood experiments, the specimens were burned in a wood crib geometry. Wood cribs have been used for a long time as a fuel for fire research because of their good reproducibility. Heat confinement within the wood cribs and radiation between the burning surfaces allow sticks of substantial cross section to burn efficiently. Each crib weighed 28 kg and was made of kiln-dried Douglas fir whole wood sticks 3.6 cm x 3.6 cm x 45.0 cm (1.4 in. x 1.4 in. x 18.0 in.) arranged in 15 layers of 6 sticks. The spacing between each layer was 4.8 cm (1.9 in.) to yield a lattice work box with rectangular faces of the dimensions given in Table I. The ignition of each crib was accomplished by burning heptane in a 0.3 m (1.0 ft) diameter pan located on the platform beneath the crib. Smoke emission measurements were not started until the heptane had been completely consumed. In experiment 7, a single wood crib was burned in the open with unrestricted ventilation. For Exp.7, the mass loss rate of the

crib was governed by the crib porosity, as defined by Thomas⁽¹²⁾.

In Exps. 8 and 9, three wood cribs were burned in the burn room in order to investigate the effects of the compartment on the smoke production. The compartment had a single opening (window) 0.76 m by 1.0 m (2.5 ft by 3.3 ft) centered horizontally on the wall leading to the outer room with the top of the opening located 2.0 m (6.7 ft) above the floor, see Fig. 1. This opening was small enough to force the fire to burn under limited ventilation conditions, i.e. the fuel mass loss rate was controlled by the window opening.

In two experiments, asphalt roofing shingles were burned in an angular geometry, as shown in Fig. 3. This configuration represents the burning of a roof with the impingement of an external flame. The parallel non-combustible Kaowool material was used to increase the radiation feedback to the fuel surface which helped to sustain the burning of the roofing material after the propane flame had been extinguished.

For the liquid hydrocarbon fuel experiments, #2 fuel oil was burned. The fuel oil was burned in a circular pan 56 cm (22 in.) in diameter and 28 cm (11 in.) high. A pool fire is a typical geometry for both liquid hydrocarbon fuels and solid hydrocarbon fuels in a horizontal configuration. In each experiment, except for Exp. 13, 8.9 cm (3.5 in.) of fuel was floated on top of 19.1 cm (7.5 in.) of water. The water was used as a "filler" to reduce the total amount of fuel required. In Exp 13, 2.5 cm (1.0 in.) of fuel was floated on 25.4 cm (10 in.) of water. Because of the high ignition temperature of fuel oil, 250

ml (8.5 oz) of heptane was floated on the surface of the fuel to augment ignition. Smoke emission measurements were performed after the heptane had burned. For Exps. 12 and 13, a single pan was burned on the platform in the open. As a simple method for scaling the fire, two pans were burned in the open in Exps. 14 and 15. The two pans were placed tangent to one another. For Exp. 16, a single pan was placed in the burn room as described above. The burn room was again used to investigate the effects of the compartment on the hydrocarbon fires. In this experiment the fire was not ventilation limited. A summary of the sixteen experiments is given in Table 1.

EXPERIMENTAL RESULTS

Parallel Plywood Sheets

In Exps. 1 through 6, plywood sheets were burned in a parallel plate geometry of the dimensions given in Table 1. The plies of wood were attached to each other by a layer of adhesive that burned differently from the wood. In these experiments, a decrease in the heat release rate could frequently be observed in the period during which a second ply was being ignited from the backside of the most recently burning layer of veneer. A typical heat release rate curve for this geometry is shown in Fig. 4 where the RHR curve for Exp. 3 is shown. Note the decrease in heat release rate at 11 minutes which occurred when the second ply was being ignited.

The emission factors for all the experiments are given in Table 2 and are compared graphically in Fig. 5. With the

exception of Exp. 2, the emission factors for the first 5 experiments were remarkably similar and seemed quite independent of minute-to-minute variations in the heat release rates. The measured particulate carbon emission factors for these experiments were nearly identical ($0.17 \pm 0.01\%$), indicating the degree of reproducibility which can be achieved for specimens burning under similar conditions, see Fig. 6. In Exp. 2 identical plywood sheets were used, but they were configured with a 10 cm (4 in.) gap between them, causing the fire to have more restricted ventilation than during the other five 5-ply plywood experiments. This reduction in ventilation explains the large value for the measured emission factors in Exp. 2. The results of the 3-ply and the 5-ply experiments are not expected to be identical since the 3-ply fuel has thicker veneer layers and contains less adhesive. This may be the reason that the fuel in Exp. 6 burned in a manner between the 5-ply plywood and whole wood.

Wood Cribs

Experiment 7 involved burning a single wood cribs in the open under well-ventilated conditions. Figure 7 is a plot of the rate of heat release versus time. Ignition of the crib is accomplished in approximately 3 minutes. Sampling for smoke particles occurred between 7.5 and 16.5 minutes, and for most of this period, burning is nearly steady-state with an average heat release rate of 230 KW.

The next two experiments, Exps. 8 and 9, involved burning three wood cribs in an interior room ventilated only by a window.

This type of combustion is characteristic of a post flash-over fire. Reproducibility of the combustion characteristics in the two experiments is extremely good. Measurements of mass loss of the fuel during both of these experiments indicate that the burning was steady state. Mass loss during the 25 minute period following ignition was 73 kg including the mass of the cribs and the heptane ignition fluid. Figure 8 shows the RHR curve for Exp. 9 whose heat of release curve is nearly identical to that for Exp. 8, which is not shown. Following the combustion of the heptane, the rate of heat release increased from 600 to 1000 KW. The spike in the rate of heat release, shown in Fig. 8, corresponds to the burning of paper from the gypsum wall board in the exterior room.

The emission factors for the wood crib experiments are compared graphically in Fig. 9. Ventilation limited conditions caused an order of magnitude difference in the smoke production. There was a difference in the sampling times between Exps. 8 and 9. Experiment 8 included the last 2 to 3 minutes of its maximum heat release rate while in Exp. 9 the sampling was terminated just after the spike in the heat release rate. The sampling times are shown in Table 2. The difference in the sampling time resulted in an increase in the emission factors which indicates an increase in the smoke production.

Asphalt Shingles

Experiments 10 and 11 involved burning asphalt shingles in a configuration designed to simulate roof burning as a result of

direct impingement of an external flame. During the asphalt shingle experiments, pieces of the specimen often melted, dripped, and burned in the catch pan underneath. Both samples ignited in three minutes, and each specimen underwent steady state burning as evidenced by the nearly constant slopes of the individual mass loss curves. The two experiments did have different burning rates: 0.36 kg/min for Exp. 10, and 0.45 kg/min for Exp. 11. The rate of heat release for Exp. 10, shown in Fig. 10, decreased during the experiment. A similar behavior was also seen in Exp. 11. This decrease may be due, in part, to the burning of the cellulosic material used for lining the shingles.

In Figure 11 the emission factors for the asphalt experiments are shown graphically. Burning of asphalt roofing shingles produced the largest emission factors observed in this series of experiments. The smoke particulates were in excess of 10% of the consumed fuel mass, nearly two orders of magnitude greater than those observed for the wood fires burning under similar ventilation conditions. Particle collection for Exp. 10 was initiated earlier and was continued for a period 50% longer than for Exp. 11. It is interesting to note that the increased sampling time for Exp. 10 caused an increase in the emission factors of less than 10% in the organic carbon and non-carbon; yet the black carbon emission factor increased more than 30%.

Liquid Hydrocarbons

In Exps. 12 and 13, a pan of #2 fuel oil was burned in the open with no restriction on the ventilation. The RHR curve for

Exp. 13. is shown in Fig. 12. The combustion characteristics for all the fuel oil experiments are summarized in Table 3. The values in Table 3 are averaged over the steady state burning period. The mass loss rate recorded for Exps. 12 and 13 is lower than the reported mass loss rate for large tank fires $0.039 \text{ kg}/(\text{m}^2\cdot\text{sec.}) (\pm 0.003)^{(13)}$. However, the mass loss rate for this pan size is governed by radiation feedback from the flame. The flames were considered optically thin, and optically the pool fires usually have lower mass loss rates. The emission factors for all the #2 fuel oil experiments can be compared graphically by examining Fig 13. For Exps. 12 and 13, the total emission factor is over 10%, with the black carbon emission factor accounting for over 70% of the total particulate.

In Exps. 14 and 15 two pans were burned in the open with no restriction on the ventilation. The RHR curves for Exp. 14 is shown in Fig. 14, and an increase in the mass loss rate occurs (Table 3) which is most likely due to the increased radiation to the fuel surface from the adjacent pan. The most interesting result of the two pan experiments is the reduction in the emission factors as compared with those of the single pan experiments burning in the open. Reproducibility of the emission factors and the combustion characteristics for both the one and two pan experiments is quite good, as seen in Fig. 13 and Table 3.

Experiment 16 was conducted with one pan in the burn room with a single window. During this experiment, the fire reached flashover conditions within the room of origin, and this in-

creased the radiation feedback to the fuel surface. The increased radiation contributed substantially to the increase in mass loss rate noted for oil burning in the compartment. In addition to the higher mass loss rate, the net heat of combustion was also found to be slightly higher than that of the single pan experiments in the open. This apparent increase in the calculated heat of combustion is believed to be a result from the increased residence time and more complete burning of the pyrolyzates at the elevated temperature within the room. This elevated temperature allows many of the unburned pyrolyzates to burn within the room before being quenched in the plume. The increase in the rate of heat release is larger than the increase in the mass loss rate because more of the volatilized fuel burns in the compartment.

The compartment had a significant effect on the smoke emission factors. Emission factors are reduced by more than a factor of two in the compartment. The most pronounced effect was on the black carbon emission factor, which was decreased by nearly a factor of four when compared to the single pan experiments in the open. The organic carbon emission factors were nearly identical. The non-carbon emission factor was larger in the burn room than in the single pan open-burn experiments. These changes in emission factors are clearly shown in Fig. 13.

DISCUSSION AND CONCLUSION

The most important result of the experiments described above is the considerable influence of the compartment on the produc-

tion of smoke. As shown in Fig. 9, the smoke emission factors measured for wood cribs burning in the compartment were more than an order of magnitude higher than those burning in the open. In addition, the smoke from the compartment fire was thick and black, similar in appearance to the smoke produced by burning plastic or oil. For the fuel oil experiment, the compartment had the opposite effect. In the experiment conducted in the compartment, the smoke production was significantly reduced from those conducted in the open, as seen in Fig. 13. It is, therefore, important to analyze the combustion and ventilation characteristics of the compartment burning experiments to account for the seemingly different results. In the compartment, the rate of air inflow to the compartment can be approximated by

$$\dot{m} = 0.52wH^{3/2}$$

where w is the width of the compartment opening and H is the height¹⁴. The mass stoichiometric ratio for wood burning is 5.7. The fire is ventilation limited for wood if the mass burning rate of wood is equal to

$$\dot{m} = (0.52/5.7)wH^{3/2}.$$

For our compartment, $wH^{3/2}$ is $0.76m^{5/2}$ yielding an $\dot{m} = 0.068$ kg/s which is identical to the value measured for Exp. 9 and very close to the value measured for Exp. 8. (0.071 kg/s). Thus the wood cribs burning in the compartment were ventilation limited. In contrast, the oil fires in the compartment were not. Assuming a stoichiometric ratio of 14.7, the measured fuel mass loss rate of 0.054 kg/m²s is approximately 1/2 the value computed for ventilation limited conditions. For wood crib burning in the

compartment, the emission factors were larger because of the incomplete combustion characteristics of the environment. In contrast, the emission factors for the oil decreased in the compartment because of the higher temperature and increased residence time of the pyrolyzates within the compartment, which resulted in more complete combustion and substantial soot burn-out.

These results are also important in the context of the nuclear winter hypothesis. Wood is one of the major building materials used in the United States. It is reasonable to assume that large quantities of wood would burn, under both restricted and unrestricted ventilation conditions, in post nuclear fires. The results of the asphalt roofing shingles demonstrate the significant impact a single material might have on the urban smoke production in the post nuclear environment. The smoke emission factors found for asphalt roofing shingles, averaged for the two experiments, was over 12% with 90% being black carbon.

Further research is necessary in order to more accurately quantify the amount of air required to reduce the smoke production within a compartment. The next series of experiments should include: 1) Wood cribs in the burn room where the mass loss rate is not limited by the size of the window, 2) Hydrocarbon pool fires in the compartment where the window is small enough to control the fuel mass loss rate.

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REFERENCES

- (1) Turco, R. P., Toon, O. B., Ackerman, T. P., Pollack, J. B. and Sagan, C., Science, Vol. 222., 1983, p. 1283.
- (2) Turco, R. P., Toon, O. B., Ackerman, T. P., Pollack, J. B. and Sagan, C., Scientific American, Vol. 251, 1984, p. 33.
- (3) American Society for Testing and Materials. Committee E-5 on Fire Standards, "E 176-86: Standard Terminology Relating to Fire Standards" in "ASTM Fire Test Standards," 2nd ed., Philadelphia, 1988, pp. 116-120.
- (4) Jin, T., Proceedings of the 4th Joint Panel Meeting of the UJNR Panel on Fire Research and Safety, Building Research Institute, Ministry of Construction, Tokyo, 1979.
- (5) Parker, W. J., "Calculations of the Heat Release Rate by Oxygen Consumption for Various Applications", NBSIR 81-2427-1, Gaithersburg, MD, National Bureau of Standards, Center for Fire Research, 1982.
- (6) McCaffrey, B. J., and Heskestad, G., Combustion and Flame, Vol. 26, 1976, p. 125.
- (7) Huffman, E. W. D., "Performance of a New Carbon Dioxide Coulometer," Microchemical Journal, Vol. 22, 1977, pp. 567-573.
- (8) Dod, R. L., and Novakov, T., "Application of Thermal Analysis and Photoelectron Spectroscopy for the Characterization of Particulate Matter," in Industrial Applications of Surface Analysis, eds. L. A. Casper and C. J. Powell, American Chemical Society, Washington, 1982, pp. 397-404.
- (9) Novakov, T., "Microchemical Characterization of Aerosols," in Nature, Aim and Methods of Microchemistry, Springer Verlag, Vienna, Austria, 1981, pp. 141-165.
- (10) Dod, R. L., Brown, N. J., Mowrer, F. W., Novakov, T., and Williamson, R. B., "Smoke Emission Factors from Medium Scale Fires: Part 2," Aerosol Science and Technology, in press
- (11) Babrauskas, V., and Williamson, R. B., "Post-Flashover Compartment Fires: Basis of a Theoretical Model," Fire and Materials, Vol. 2, No. 2, 1978, pp. 39-53.
- (12) Thomas, P. H., "Fire in Enclosures," Building Research Establishment Current Paper, CP 30/74, Fire Research Station, Borehamwood, U.K., 1974.
- (13) Babrauskas, V.: "Estimating Large Pool Fire Burning Rate," Fire Technology, Vol. 19, 1983, pp. 251-261.

(14) Drysdale, Dougal, "An Introduction to Fire Dynamics", John Wiley and Sons, 1985, PP. 310-311.

FIGURES

- Figure 1 Schematic Diagram of Experimental Facility Used in this Work.
- Figure 2 Schematic Diagram of the Parallel Plate Apparatus Used for the Plywood Experiments.
- Figure 3 Schematic Diagram of the Angled Parallel Plate Apparatus Used for the Asphalt Roofing Shingle Experiments.
- Figure 4 Rate of Heat Release Curve for Experiment #3.
- Figure 5 Emission Factors for all the Experiments.
- Figure 6 Emission Factors for the Plywood Experiments.
- Figure 7 Rate of Heat Release Curve for Experiment #7.
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- Figure 9 Emission Factors for the Whole Wood Experiments.
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- Figure 11 Emission Factors for the Asphalt Roofing Shingles Experiments.
- Figure 12 Rate of Heat Release Curve for Experiment #13.
- Figure 13 Emission Factors for the Fuel Oil Experiments.
- Figure 14 Rate of Heat Release Curve for Experiment #14.
- Figure 15 Rate of Heat Release Curve for Experiment #16.

TABLES

- Table 1 Summary of Experimental Variables.
- Table 2 Emission Factors From Duct Total Filters for all the Experiments.
- Table 3 Summary of Combustion Characteristics for the Fuel Oil Experiments.

TABLE 1--Summary of Variables in All the Experiments

EXPERIMENT NUMBER	MATERIAL	VENTILATION	SPECIMEN	
			HEIGHT (meters)	WIDTH
1	plywood	open	1.83	1.22
2	plywood	open	1.83	1.22
3	plywood	open	1.83	1.22
4	plywood	open	1.83	1.22
5	plywood	open	1.22	1.83
6	plywood	open	1.83	1.22
7	wood crib	open	0.62	0.47
8	3 wood cribs	room	0.62	0.47
9	3 wood cribs	room	0.62	0.47
10	asphalt	open	1.86	1.22
11	asphalt	open	1.86	1.22
12	1 pan #2 fuel oil	open	0.56 dia	
13	1 pan #2 fuel oil	open	0.56 dia	
14	2 pan #2 fuel oil	open	2x 0.56 dia	
15	2 pan #2 fuel oil	open	2x 0.56 dia	
16	1 pan #2 fuel oil	room	0.56 dia	

TABLE 2--Emission Factors From Duct Total Filters

DATE	EXPT #	FUEL	TOTAL M	EMISSION FACTORS				SAMPLING TIME
				MASS-C	TOTAL C	BLACK C	ORG. C	
6/13/86	1	plywood		.00%	.16%	.13%	.03%	1:20 to 7:15
7/ 9/86	2	plywood	.24%	.00%	.23%	.17%	.06%	3:22 to 10:22
7/14/86	3	plywood	.17%	.02%	.15%	.12%	.04%	1:20 to 11:32
7/16/86	4	plywood	.19%	.03%	.16%	.13%	.04%	1:20 to 10:35
7/22/86	5	plywood	.20%	.01%	.18%	.13%	.05%	1:30 to 11:30
9/ 2/86	6	plywood	.14%	.04%	.10%	.09%	.01%	4:30 to 11:30
9/ 5/86	7	1 crib	.09%	.01%	.08%	.05%	.02%	4:20 to 13:50
9/16/86	8	3 cribs room	1.96%	.55%	1.41%	1.12%	.29%	3:30 to 14:25
10/ 7/86	9	3 cribs room	3.60%	.49%	3.11%	2.57%	.54%	4:00 to 14:30
8/15/86	10	C roofing	13.94%	2.05%	11.89%	10.03%	1.85%	1:15 to 13:25
7/21/87	11	C roofing	10.22%	1.86%	8.35%	6.23%	2.12%	2:00 to 9:00
6/ 5/87	12	1 pan oil	11.65%	2.08%	9.57%	8.78%	.78%	2:00 to 9:00
7/ 7/87	13	1 pan oil	10.95%	1.48%	9.47%	8.86%	.61%	5:00 to 13:00
7/ 9/87	14	2 pans oil	8.42%	.56%	7.86%	7.27%	.59%	3:30 to 8:30
7/16/87	15	2 pans oil	7.61%	.58%	7.02%	6.50%	.53%	4:30 to 9:00
8/ 5/87	16	1 oil - room	5.06%	2.43%	2.63%	1.97%	.66%	7:00 to 17:00

(carbon in expts. 10 & 11 is from inspector sums)

(sampling times are from time of ignition)

Table 3--Summary of Combustion Characteristics for #2 Fuel Oil Experiments

Experiment Number	\dot{m}'' [kg/(m ² m ² sec)]	RHR [KW]	h_c [MJ/kg]
12	0.027	240	36
13	0.032	290	37
14	0.040	710	37
15	0.037	680	37
16	0.054	570	43

Values are averaged over steady state burning period.

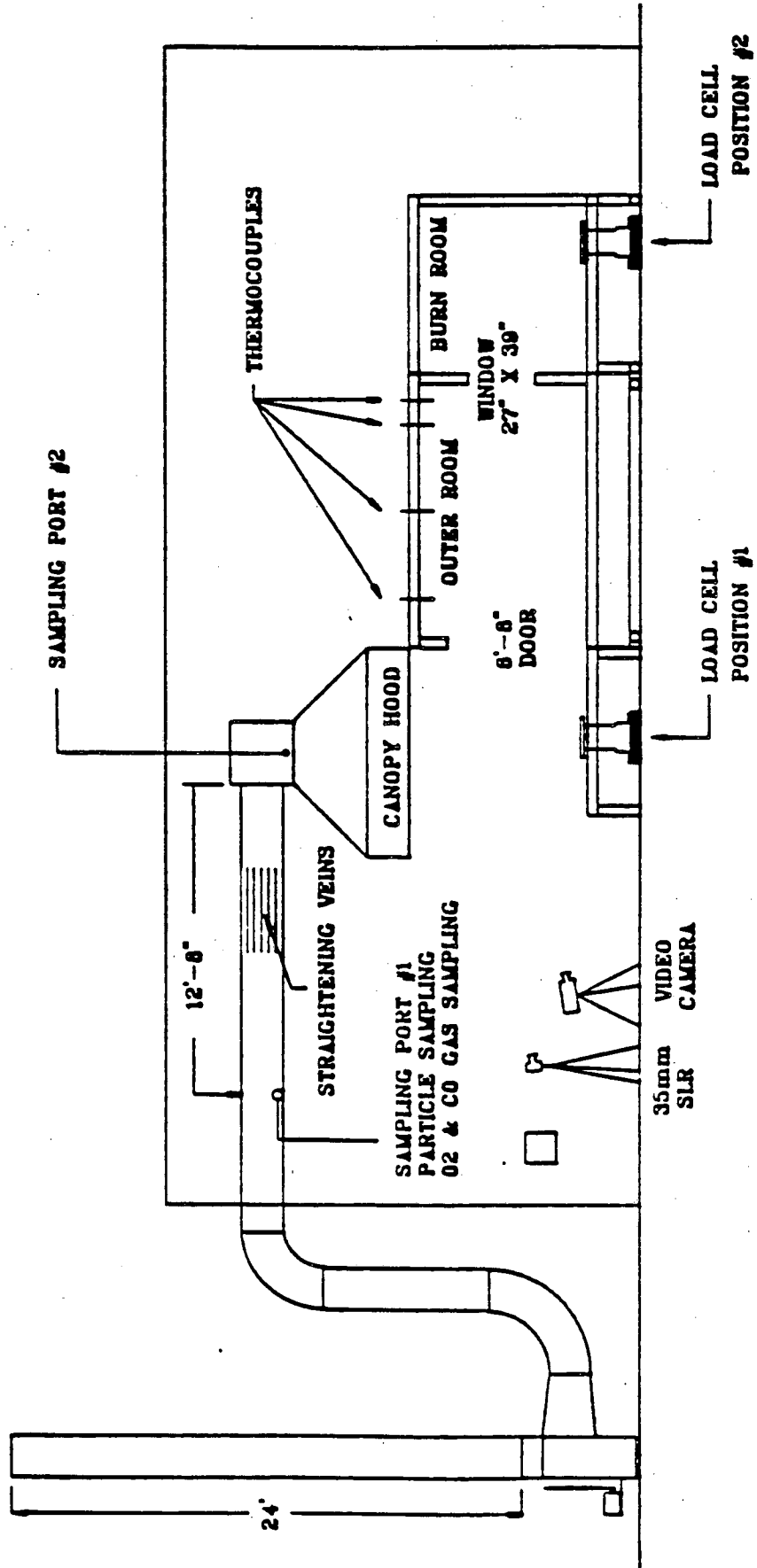


Fig. 1

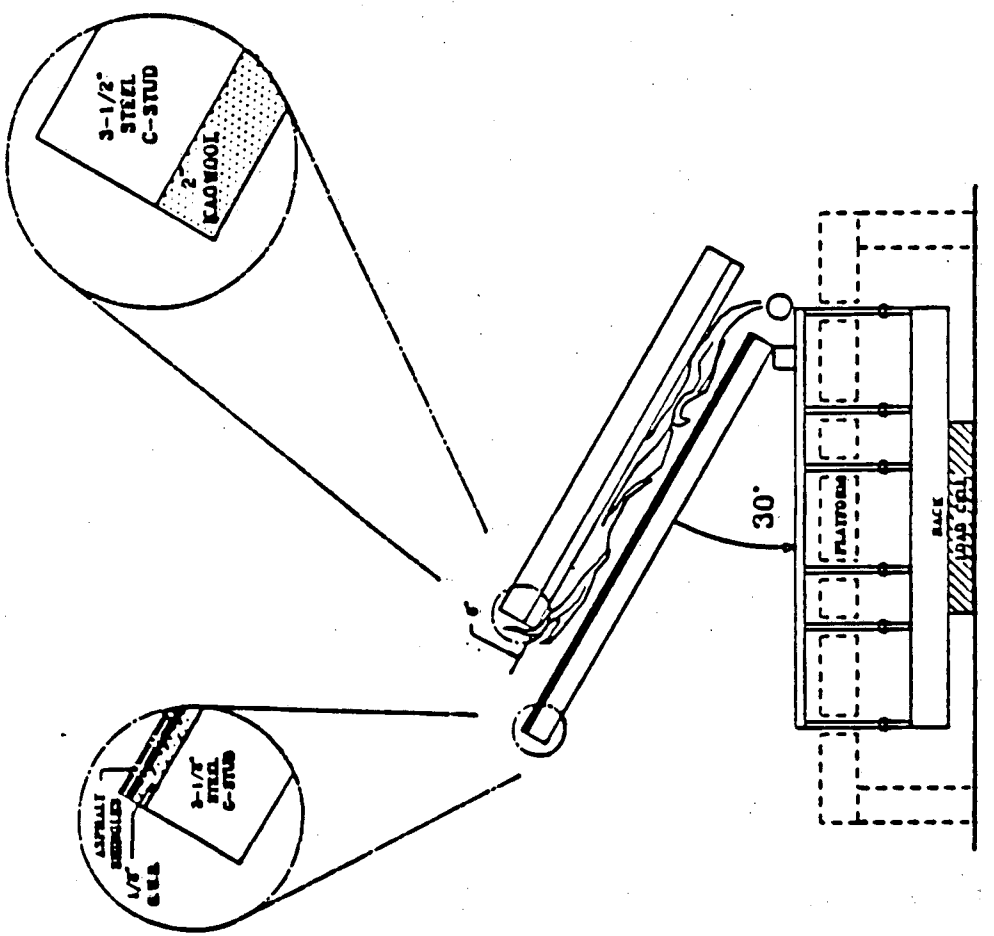
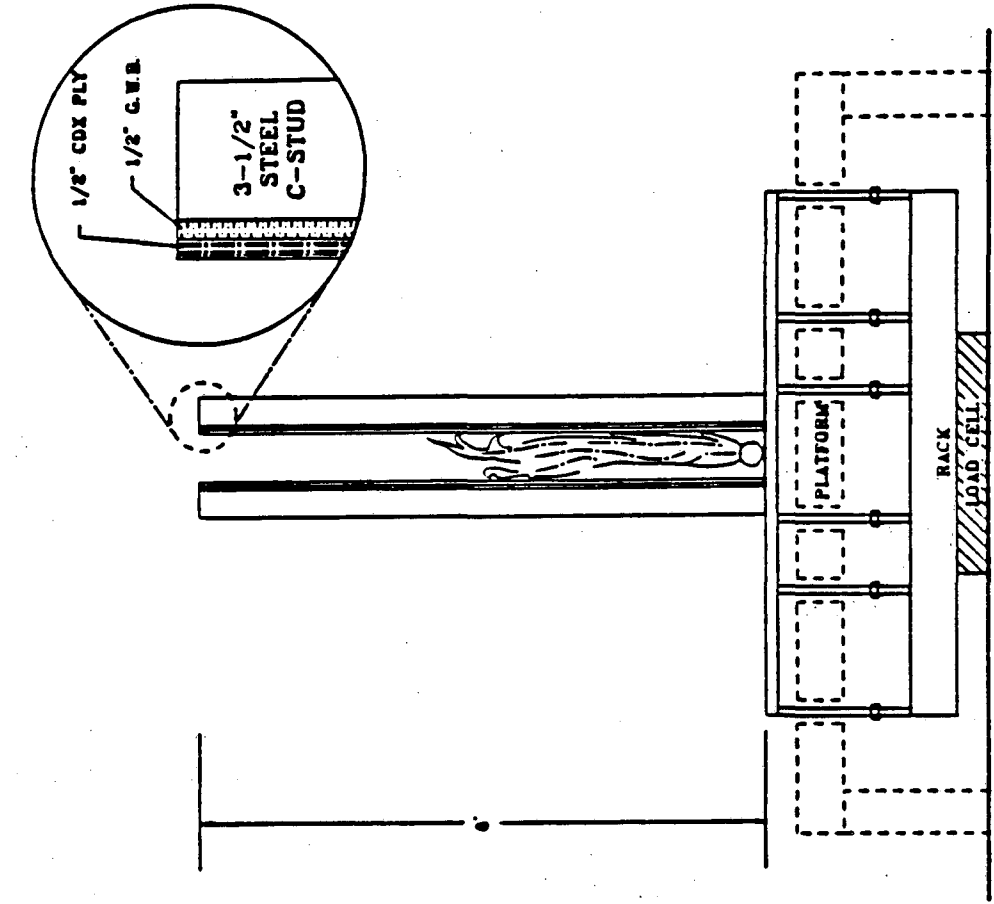


FIG. 3

FIG. 2

EXP. 3 PARALLEL PLYWOOD PLATES RATE OF HEAT RELEASE

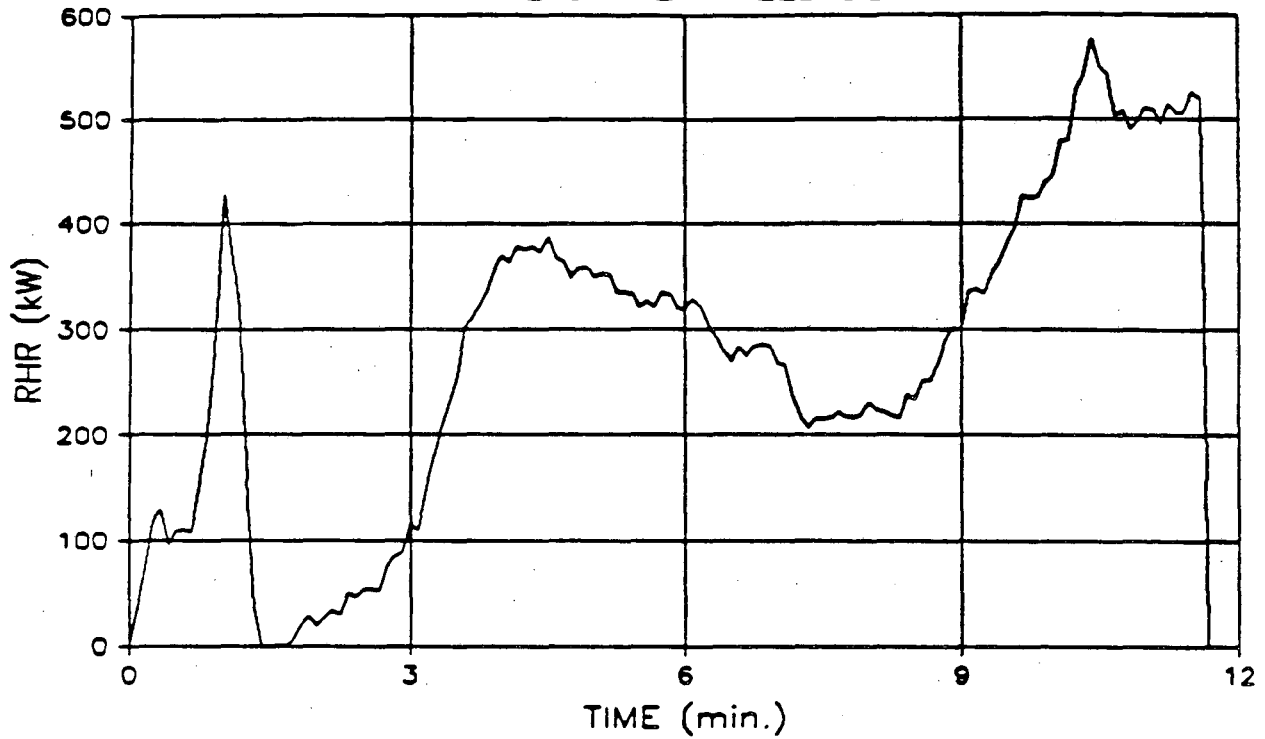


Fig. 4

SUMMARY OF EMISSION FACTORS ALL EXPERIMENTS

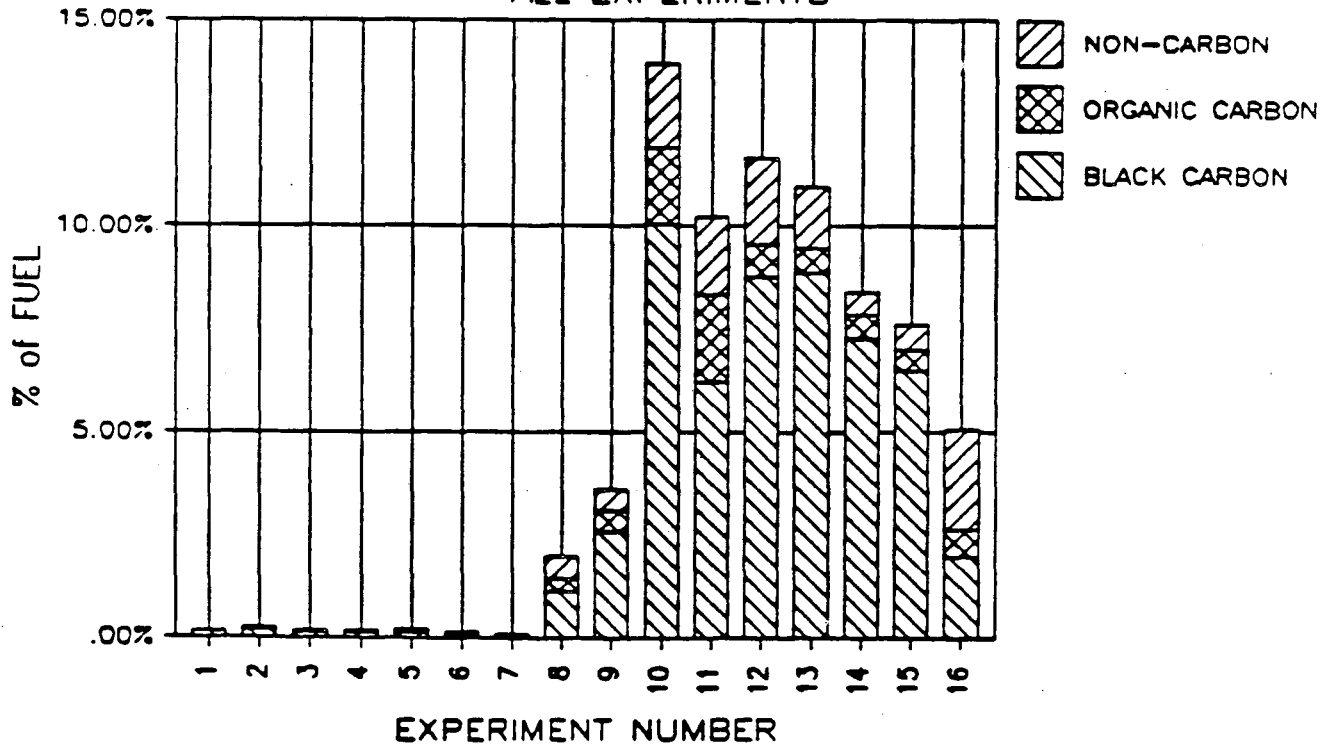


Fig. 5

SUMMARY OF EMISSION FACTORS PLYWOOD EXPERIMENTS

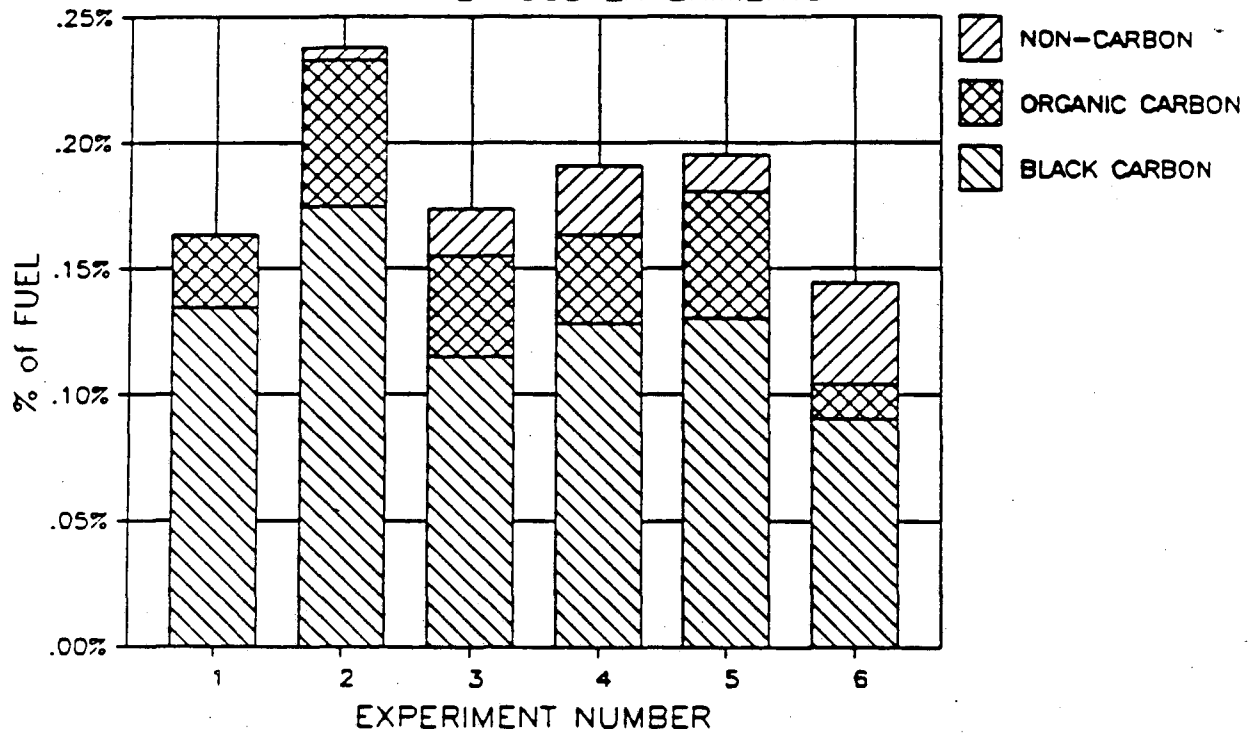


Fig. 6

EXP. 7 SINGLE CRIB IN THE OPEN RATE OF HEAT RELEASE VERSUS TIME

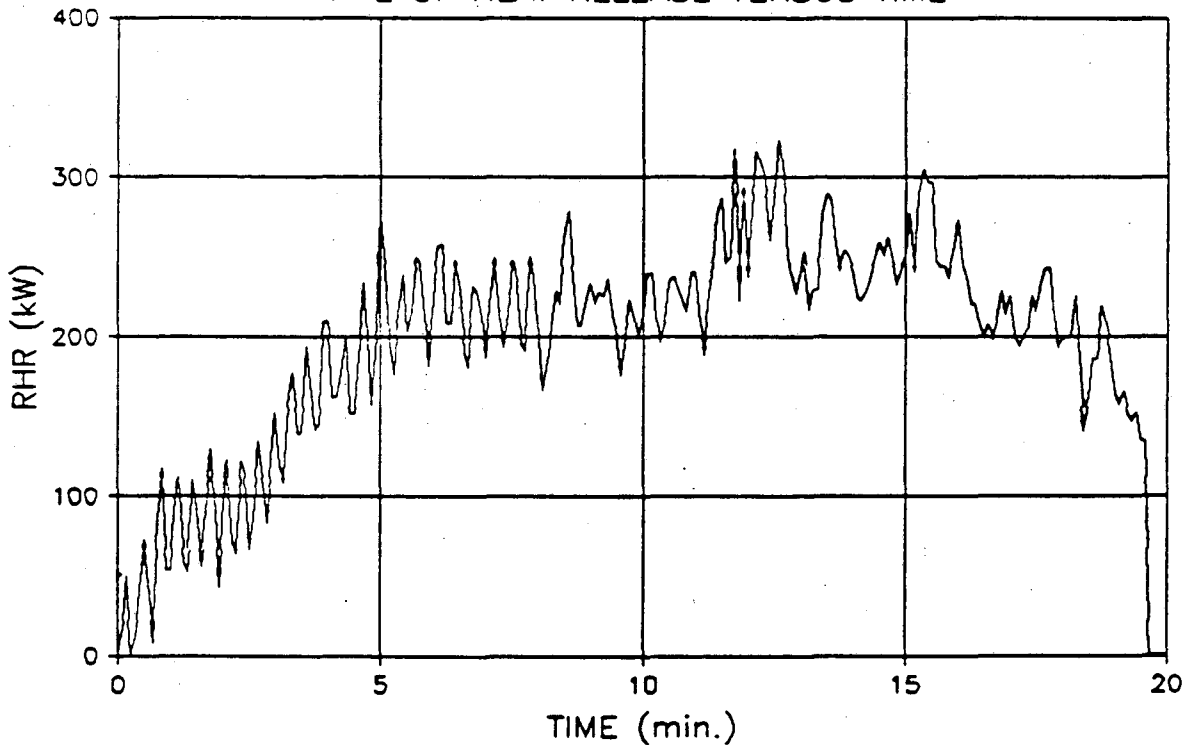


Fig. 7

EXP. 9 THREE CRIBS IN THE BURN ROOM RATE OF HEAT RELEASE VERSUS TIME

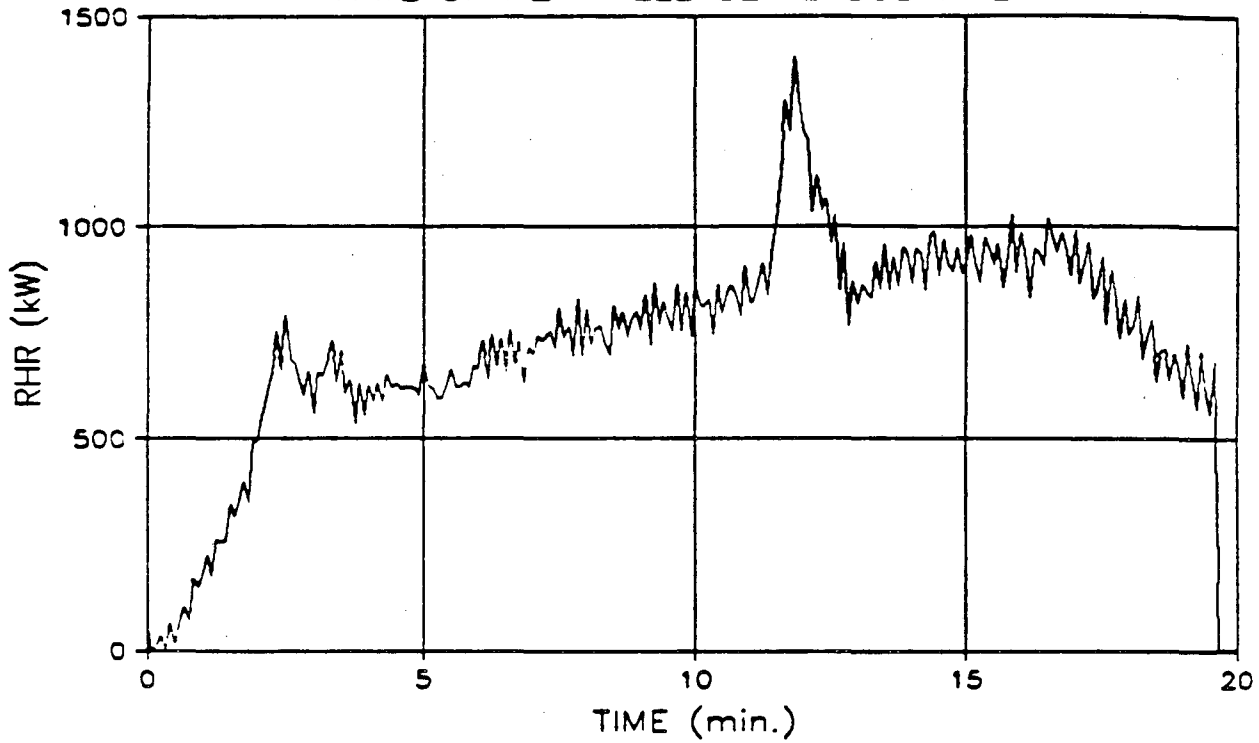


Fig. 8

SUMMARY OF EMISSION FACTORS WHOLE WOOD EXPERIMENTS

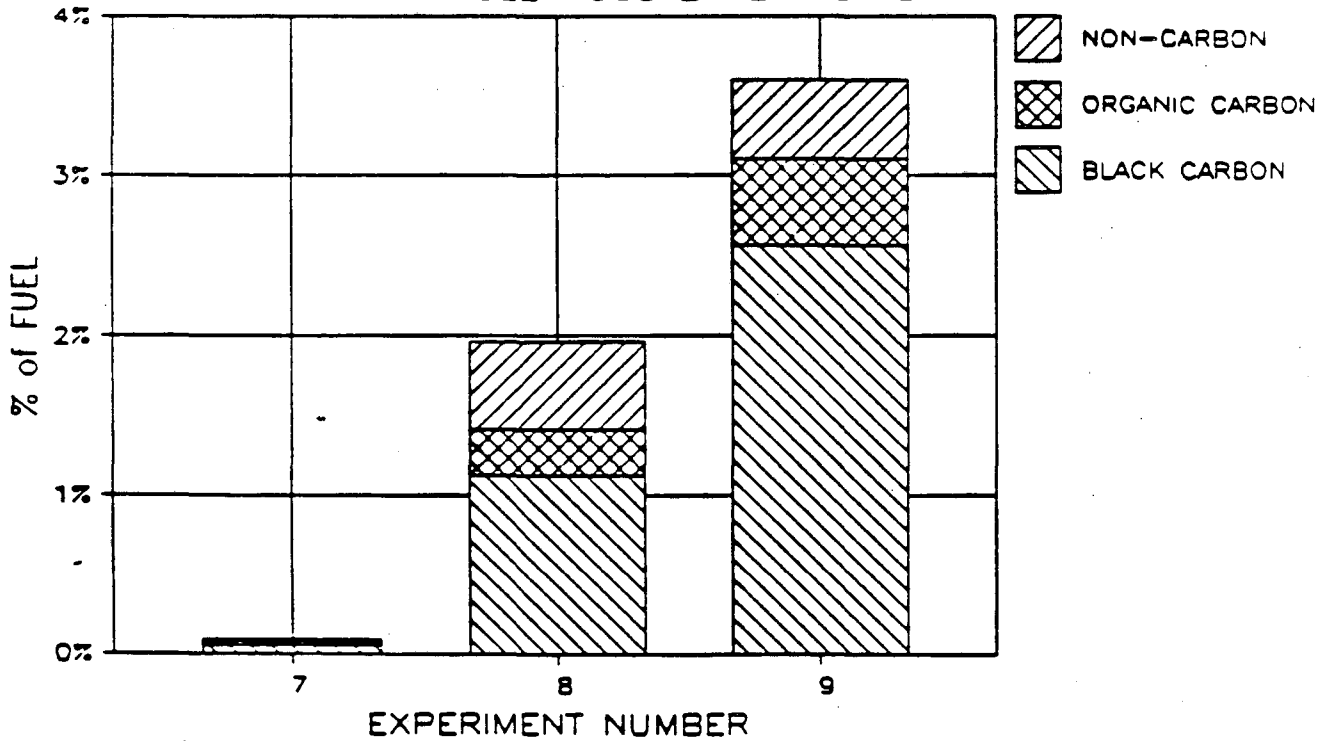


Fig. 9

EXPERIMENT 10 ASPHALT ROOFING SHINGLES RATE OF HEAT RELEASE VERSUS TIME

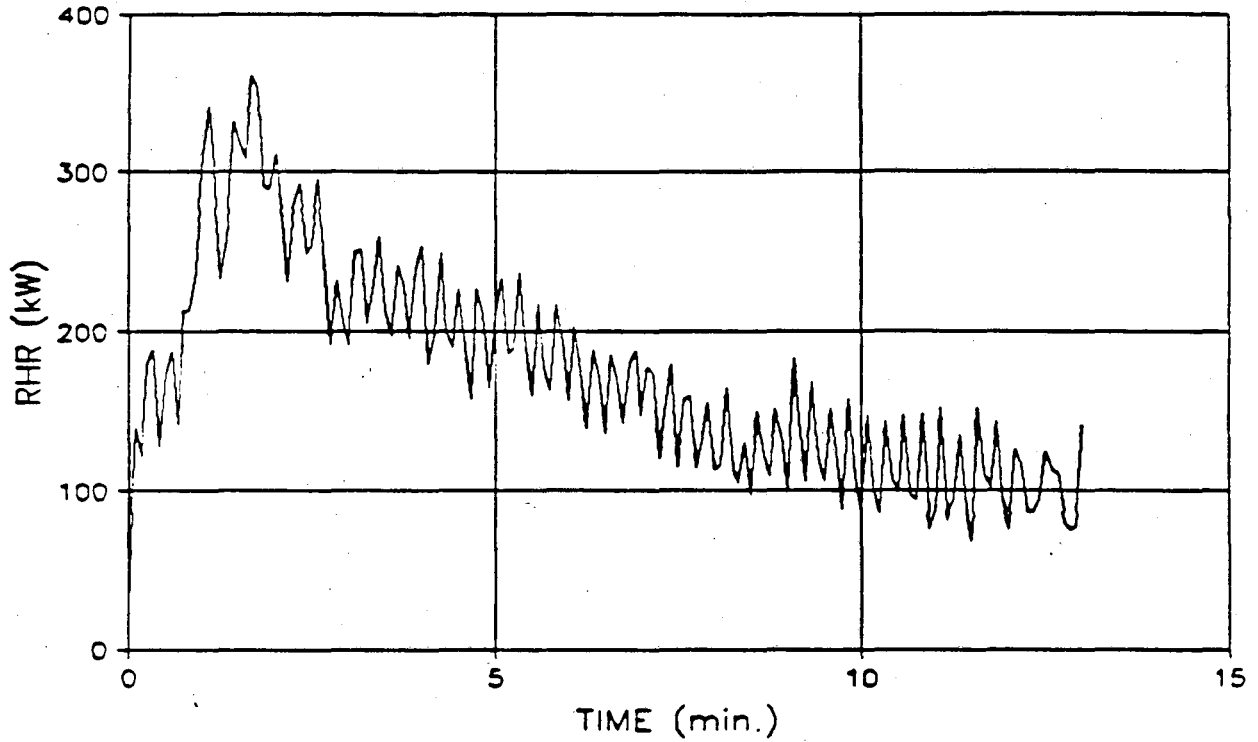


Fig. 10

SUMMARY OF EMISSION FACTORS ASPHALT ROOFING SHINGLES

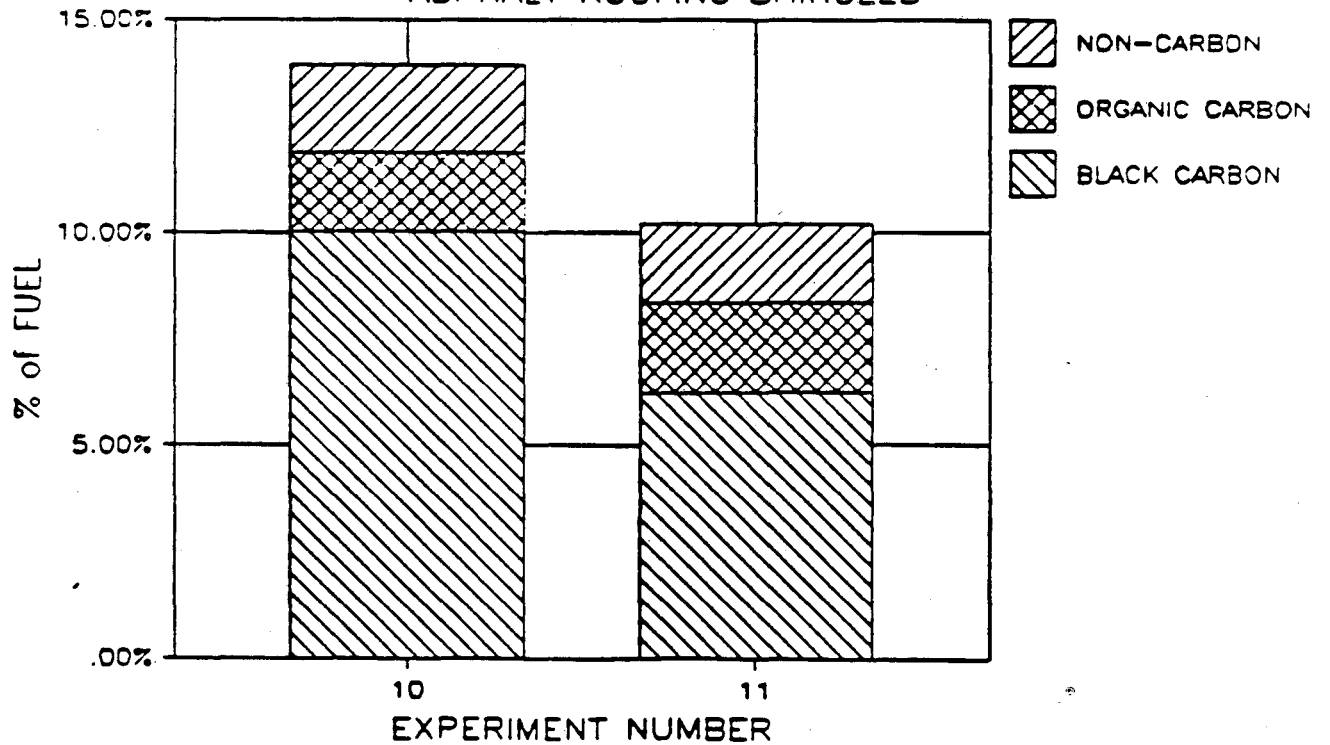


Fig. 11

EXP. 13 ONE PAN IN THE OPEN RATE OF HEAT RELEASE VERSUS TIME

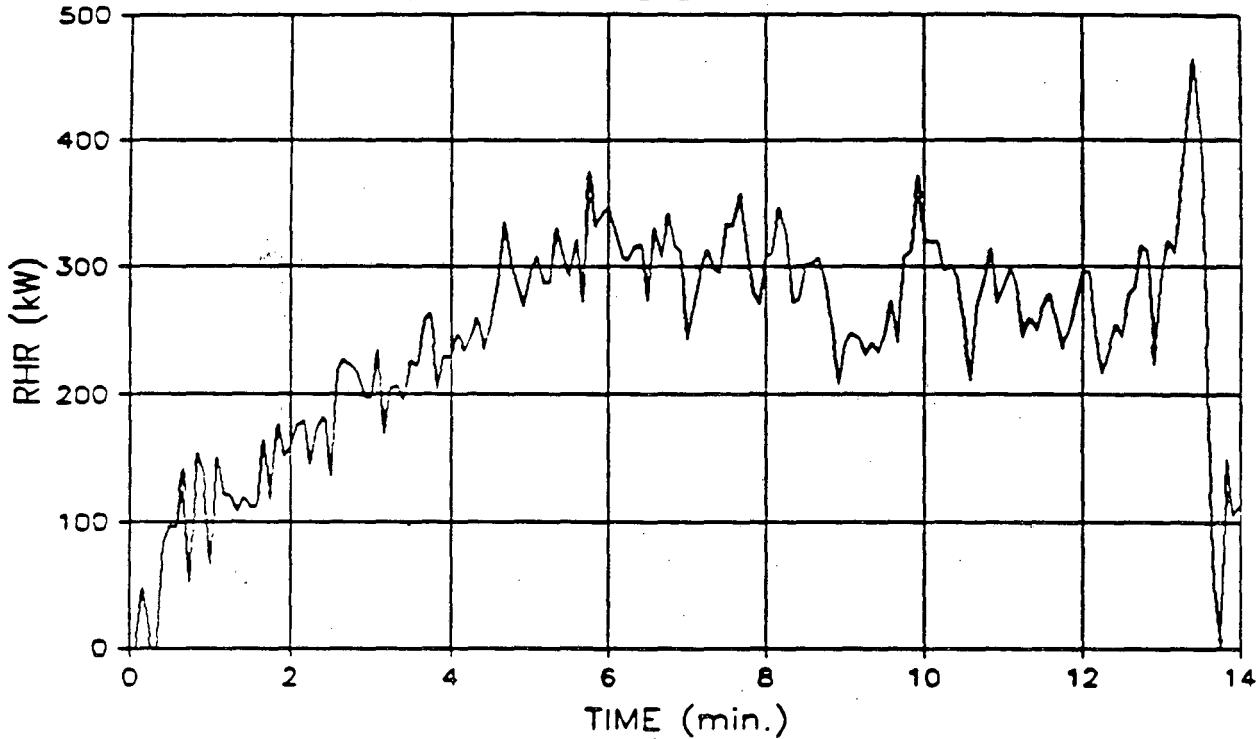


Fig. 12

SUMMARY OF EMISSION FACTORS #2 FUEL OIL EXPERIMENTS

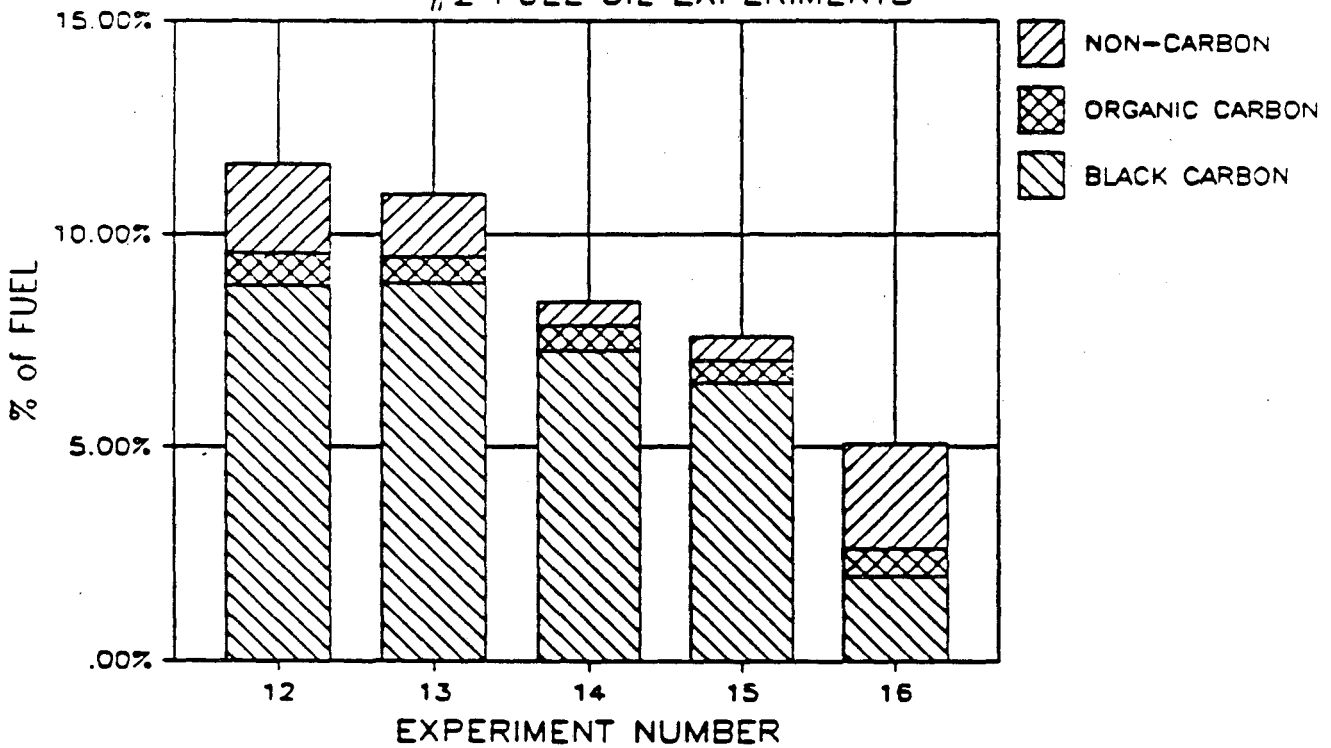


Fig. 13

EXP. 14 TWO PANS IN THE OPEN RATE OF HEAT RELEASE VERSUS TIME

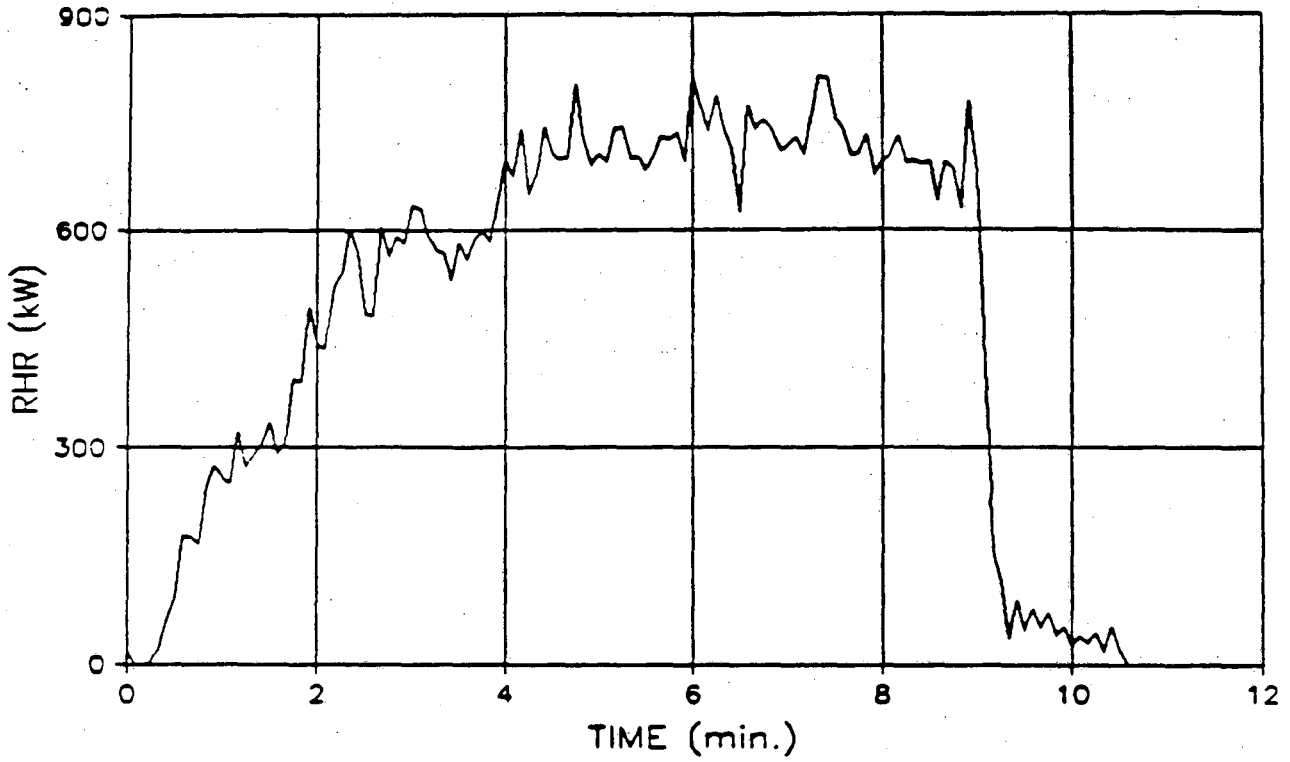


Fig. 14

EXP. 16 ONE PAN IN BURN ROOM RATE OF HEAT RELEASE VERSUS TIME

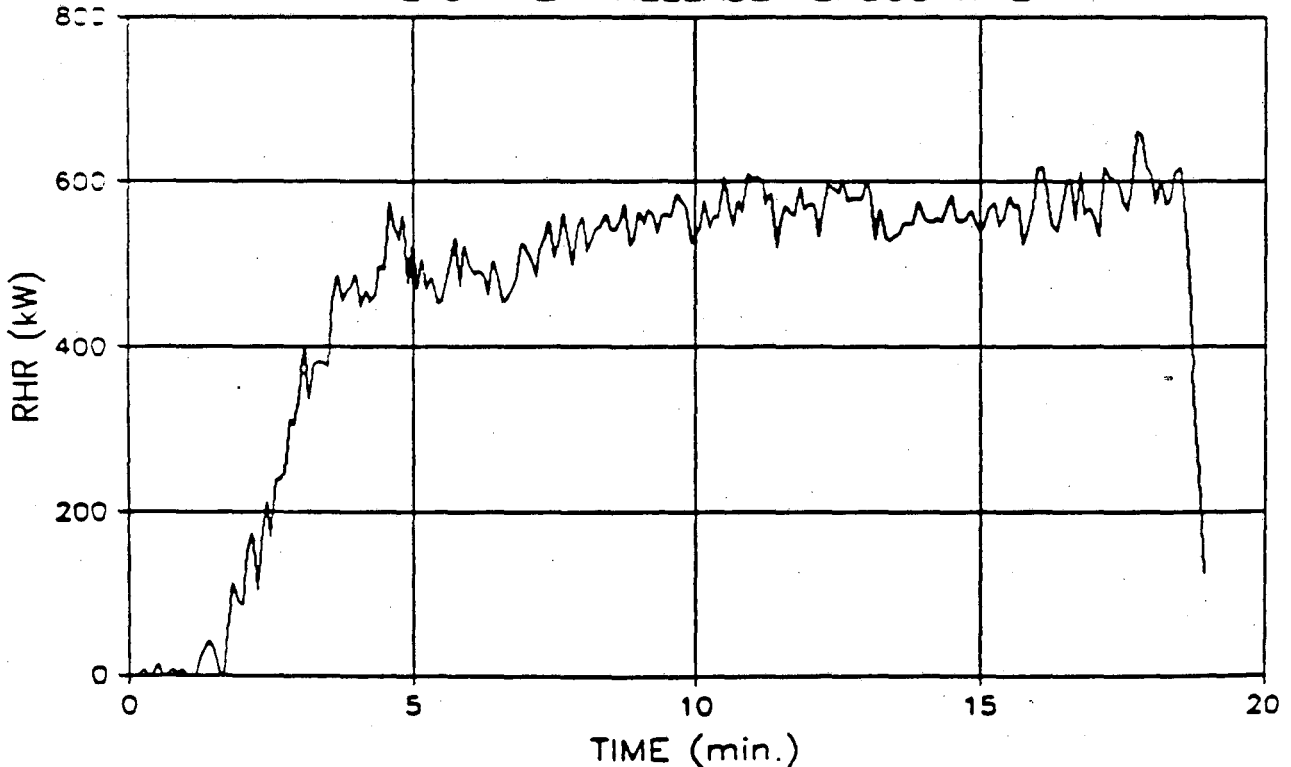


Fig. 15

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