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# Smoke and Carbon Monoxide Formation from Materials Tested in the Smoke Density Chamber

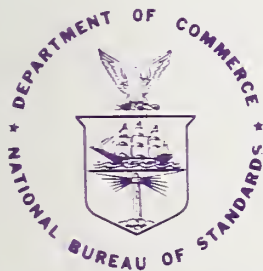
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Institute for Applied Technology  
National Bureau of Standards  
Washington, D. C. 20234

October 1975

Final Report



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U S. DEPARTMENT OF COMMERCE  
NATIONAL BUREAU OF STANDARDS



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# SMOKE AND CARBON MONOXIDE FORMATION FROM MATERIALS TESTED IN THE SMOKE DENSITY CHAMBER

Thomas Y. King<sup>1</sup>

The effects of physical and chemical factors on the smoke and carbon monoxide generated by burning polymers and red oak in the NBS Smoke Density Chamber are reported.

Smoke and carbon monoxide formation was found to depend on irradiance level and oxygen concentration in the chamber. Smoke optical density correlations with particulate mass density showed that the ratio of these two varied with material composition and burning conditions.

Key words: Carbon monoxide; electrostatic precipitation; heat flux; oxygen depletion; particulate mass; scanning electron microscope; smoke.

## 1. INTRODUCTION

The most important consideration during a fire is life safety. Smoke, toxic gases, ease of ignition, heat release, and flame spread are some of the factors which can contribute to a fire hazard. All of these factors should be considered in the final assessment of a material's potential hazard. In past years, studies dealing with smoke and noxious gas production from burning materials were considered less significant than ignition and flame propagation studies. Statistics show that inhalation of products of combustion from the sustained burning of materials is a contributing factor in a large number of fire deaths. Poor visibility caused by the smoke compounds the problem since it impedes escape for the victim and causes him to remain in the fire environment for longer periods of time.

The density of smoke and concentration of toxic gases present at any given time in an actual fire depends on variables such as the amounts and types of materials burned, heat exposure conditions, air temperatures, air velocities, enclosure volumes and dimensions, and ventilation. Many of these variables are interrelated and time dependent. In order to evaluate and compare the smoke generating potential of different materials it is necessary to control as many of the variables as possible.

This paper presents the results of smoke and carbon monoxide measurements from burning selected materials under various controlled fire environments in a smoke density chamber.

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<sup>1</sup>The author was a Research Associate at the National Bureau of Standards, Washington, D.C. when the work reported here was performed.

## 2. THEORETICAL ASPECTS

Smoke can be defined as solid or liquid particulate matter in suspension arising from the burning or decomposition of any material. Smoke is most commonly measured in terms of its light attenuation in a photometer. This method assumes the application of Bouguer's or Beer's law to the attenuation of light by the smoke, and results are given as optical density rather than light absorption or transmittance. Foster [1]<sup>2</sup> has described the relationship:

$$I = I_0 e^{-KeB}$$

where (I) is the transmitted light intensity, (I<sub>0</sub>) is the incident light intensity, (Ke) is the extinction area coefficient, and (B) is a function of mass concentration (c), particle mass mean radius (a), density (d), and optical light path length (s), as given by:

$$B = \frac{3cs}{4ad}$$

The extinction area coefficient (Ke) can be defined in terms of the absorption cross section area (A) and scattering cross section area (S), so that  $Ke = \frac{S + A}{\pi a^2}$ . The optical density (D) then can be described by:

$$D = \log_{10} \frac{I_0}{I} = \frac{KeB}{2.303} \tag{1}$$

$$\text{or } D = \frac{\left(\frac{S + A}{\pi a^2}\right) \left(\frac{3cs}{4ad}\right)}{2.303} = \frac{3cs(S + A)}{4\pi a^3 d (2.303)} \tag{2}$$

For systems with nonuniform particle size, such as smoke, (S) and (A) are expressed as complicated functions of particle size distribution, refractive index, and wavelength of incident light.

Smoke measurements can also be expressed in terms of specific optical density (D<sub>s</sub>) in which light path length (L), chamber volume (V), and exposed specimen surface area (A<sub>1</sub>) are taken into consideration. Equation (1) then becomes:

$$D_s = D \left(\frac{V}{A_1 L}\right) = \left(\frac{V}{A_1 L}\right) \log_{10} \frac{I_0}{I} = \left(\frac{V}{A_1 L}\right) \frac{KeB}{2.303}$$

<sup>2</sup>Numbers in brackets correspond with the literature references listed at the end of this paper.

$D_s$ , being dimensionless, allows direct comparison of smoke densities regardless of chamber volume, light path length, and exposed specimen surface area, provided other parameters remain constant.

### 3. EXPERIMENTAL DETAILS

#### 3.1. Smoke Density Chamber

Data reported in this paper were obtained from measurements in the National Bureau of Standards Smoke Density Chamber [2]. This is a  $0.51 \text{ m}^3$  ( $18\text{-ft}^3$ ) enclosed chamber in which a vertically positioned photometer with  $0.9 \text{ m}$  path length measures the amount of light attenuation (or scattering) by the smoke. The smoke emanates from burning a vertical specimen  $3$  by  $3$  inch and with a  $2\text{-}9/16$  inch square exposed surface area. The specimen can be exposed to heat under either flaming or non-flaming (smoldering) conditions. In the standard test method the specimen surface is exposed to a heat flux of  $2.5 \text{ W/cm}^2$  ( $2.2 \text{ Btu/s/ft}^2$ ) from a radiant source (electrically heated) with or without a piloted ignition source consisting of a 6 jet air-propane burner. The wall temperature of the chamber is maintained at  $35 \pm 2 \text{ }^\circ\text{C}$  at the start of the test. The specific optical smoke density is dependent upon specimen variables of thickness and density, the exposed sample area being constant as defined by the specimen holder.

Normally, in routine testing, only the maximum specific optical smoke density ( $D_m$ ) is reported. The recorded maximum specific optical smoke density is corrected by subtracting the photocell residue reading from the  $D_m$  after the test has been terminated and the chamber exhausted. The rate of increase of  $D_m$  and the time to reach a specific  $D_m$  value may also be of interest.

Carbon monoxide (CO) concentration was recorded simultaneously with the smoke density using an infrared analyzer connected in line to the top of the chamber. Results are reported as volume concentration in parts per million (ppm). In these studies flow rates from the chamber to the analyzer were maintained at about  $1 \text{ liter/min}$  by using a critical orifice under vacuum. A dry ice trap and filter assembly was necessary to remove most of the smoke ahead of the analyzer. The sample line dead volume resulted in a delayed time response of approximately  $30 \text{ s}$  to reach 95% of the steady-state value. The carbon monoxide curves reported were not corrected for this factor.

#### 3.2. Test Materials

The five materials used in this study (table 1) were: red oak, rigid polyvinyl-chloride, plasticized polyvinyl-chloride, acrylonitrile-butadiene-styrene (ABS), and polystyrene.

Table 1. Materials Studied

Material	Abbreviation	Approximate Thickness		Approximate <sup>*</sup> Density	
		(in)	(mm)	(lb/ft <sup>3</sup> )	(kg/m <sup>3</sup> )
Rigid Polyvinylchloride	R-PVC	0.023	0.58	77.3	123.7
Plasticized Polyvinylchloride	P-PVC	0.022	0.56	80.6	129.0
Acrylonitrile-Butadiene-Styrene	ABS	0.031	0.79	57.4	91.8
Red Oak	Red Oak	0.045	1.14	39.6	63.4
Polystyrene	Polystyrene	0.026	0.66	65.0	104.0

\* Density measurements were calculated from the approximate thickness and weights of the actual samples.

In order to compare the smoke and carbon monoxide generating potentials of these particular materials, several sample design criteria were used:

1. Samples were compared at similar weights (approximately 4.15 grams average) since total smoke and carbon monoxide depend upon the weight of sample combusted, especially in the case of non-charring materials.
2. The samples used in the study contained no fillers or flame retardants and a minimum of other components necessary for fabrication. This permitted a better comparison of the data resulting from the basic polymer rather than from the many additives possible; in practical applications, additives could comprise a large percentage of the actual composition and have a significant effect on the results.
3. Sample thickness and weight were relatively small to meet the following criteria:
  - a. The heat transfer into the sample and resultant smoke generation would not be restricted by excessive char formation. The time for particulate deposition to occur during the buildup stage was thereby limited.

- b. Oxygen depletion would be minimized in the chamber by burning a relatively small sample.
- c. The burning characteristics of the material resulting from variable sample densities would be minimized for thin compared to thick samples.

#### 4. SMOKE AND CARBON MONOXIDE GENERATION

Factors which can govern a material's tendency to smoke include: composition, density, weight, thickness, heat flux, airflow, oxygen availability, pressure, surface characteristics, and geometry. This study was conducted primarily to obtain data on the relative concentration of smoke and carbon monoxide generated from the 5 typical materials and to determine if a relationship exists between smoke optical density and carbon monoxide formation for various materials under a range of exposure conditions.

##### 4.1. Sample Probe Position

Since the chamber is equipped with a vertically arranged photoelectric cell and light source to eliminate errors in measurements due to smoke stratification, it was necessary to determine what effect smoke stratification might have on carbon monoxide measurements made at a single location in the chamber. It was conceivable that due to convective heat flow patterns smoke and hot gases would tend to concentrate at the top of the chamber before mixing. To determine whether this occurred, carbon monoxide was monitored at the top, middle, and bottom of the chamber. Carbon monoxide produced from red oak and rigid PVC samples was measured at these three positions under flaming conditions, as shown in figure 1. Results indicated that a significant carbon monoxide concentration gradient existed only during the first few minutes of the test. After this initial time period concentration was essentially uniform throughout the chamber under these conditions.

##### 4.2. Material Composition

The relationship between simultaneous smoke (dotted curves) and carbon monoxide (solid curves) measurements with time for the five materials burned under non-flaming ( $2.5 \text{ W/cm}^2$ ) exposures is shown in figure 2. Curves shown are averages of three separate determinations and are approximations of the actual curves recorded, since data points were plotted every 2 minutes for smoke and 2.5 minutes for carbon monoxide.

Results indicate that the four plastic materials generated carbon monoxide very slowly (2-3 ppm/min) at a constant cumulative rate over the time interval defined under these test conditions. Since there were substantial differences, in certain cases in maximum smoke densities,

but little differences in the rates of CO buildup, the detection of a simple correlation between smoke density and carbon monoxide concentration for different materials appears doubtful. The six-fold difference in maximum smoke density between rigid and plasticized PVC was attributed to the large contribution of the plasticizer to the smoldering smoke evolution. The magnitude of this difference, however, may change with plasticizers of different chemical composition and physical properties.

Compared to the plastics, red oak liberated large quantities of carbon monoxide under non-flaming burning conditions. The relatively rapid rate of CO generation (approximately 80 ppm/min) occurred concurrently with the onset of glowing combustion.

Figure 3 illustrates similar curves for the five materials burned under flaming conditions. Under this exposure, the rate of carbon monoxide generation from the pilot burners (~5-6 ppm/min) was subtracted from actual measured CO curves. With the exception of red oak, generally more smoke and CO were produced under flaming, compared to smoldering, conditions. In most cases, the maximum carbon monoxide levels for red oak and ABS reached a plateau after the maximum smoke density had been reached, which was consistent with the observation that little char remained at that point. For rigid and plasticized PVC, the CO concentration continued to increase well after the maximum smoke density was attained, which apparently resulted from slow oxidation of the remaining char.

The carbon monoxide curve for polystyrene was not typical of those previously described. The melting and dripping characteristics of the material when burned caused a substantial portion of the sample to flow into a holding pan at the base of the sample holder. Delayed ignition of this material resulted in a second burning stage and accounts for the erratic shape of the CO curve.

#### 4.3. Heat Flux

In an actual fire a material is subjected to a broad range of irradiance levels, from pre-ignition to flashover. Studies relating smoke density and carbon monoxide concentration to variations in thermal flux levels for the five materials were made under flaming and non-flaming exposure conditions.

Under flaming exposures, the radiant heat flux from the electric heater was varied from 0 to approximately 4.2 W/cm<sup>2</sup> with the same pilot burner exposure. Irradiance levels under non-flaming conditions were typically 1.0, 2.5, and 4.2 W/cm<sup>2</sup>. (A more efficient radiant heater assembly was used to attain the 4.2 W/cm<sup>2</sup> irradiance level.) A Gardner thin foil air-cooled radiometer was used to calibrate the heater at flux levels ranging from 1.9 to 3.1 W/cm<sup>2</sup>, while a water-cooled thin foil radiometer was used for calibrations at 1.0 and 4.2 W/cm<sup>2</sup>.

In figure 4, the average maximum specific optical smoke densities (uncorrected) are shown at various irradiance levels under flaming conditions for the five materials. At a relatively high heat flux ( $\sim 4.2$  W/cm<sup>2</sup>) the plastic materials tested generate similar smoke densities under this particular test configuration. Total weight loss after a 20-minute period ranged from 93 - 99%. At the lower irradiance levels smoke density is strongly dependent upon material composition. The largest change in maximum smoke generation occurred at heat fluxes ranging from 2.0 to 3.0 W/cm<sup>2</sup> for polystyrene and rigid PVC. ABS reached the highest smoke buildup at about 3.0 W/cm<sup>2</sup>, and a further increase in radiant flux level resulted in an apparent lowering of the maximum smoke density. Variations in irradiance levels had little effect on smoke density for red oak samples under these conditions. The results for materials such as polystyrene which melt and drip when burned should be qualified since they are strongly dependent upon the physical properties of the sample and test geometry.

The averaged carbon monoxide curves for ABS, plasticized PVC, red oak, rigid PVC, and polystyrene at the various heat fluxes under flaming exposures are shown in figures 5-9. The rate of carbon monoxide formation for all materials tested is increased with successively higher irradiance levels. After this initial period of rapid CO generation, concurrent with observed rapid burning and smoke production, further carbon monoxide formation probably depends upon the nature and amount of char remaining after flaming combustion and the total heat flux level (including the contribution from the burner flames) of the particular test. For example, the total CO generated by burning ABS at different irradiance levels (fig. 5) tends to converge after 8 minutes. At the higher heat fluxes and temperatures, more smoke is produced with little char remaining, accounting for the rapid leveling of the CO buildup after  $D_m$  is reached. The converse occurs at the lower irradiance levels, and the carbon monoxide concentration after an extended period of time can be as high or higher than that obtained at the higher irradiance levels at similar times, probably due to the slow formation of CO from oxidation of the char.

Under non-flaming conditions the five materials show a similar increase in  $D_m$  with higher irradiance levels (fig. 10). The curves shown here are based on limited data. Red oak and rigid PVC produced substantially less smoke density, over the range of heat flux levels explored, than ABS, plasticized PVC, or polystyrene.

Carbon monoxide formation was negligible for all materials tested at a 1.0 W/cm<sup>2</sup> radiant flux level over a 40-minute period. At 4.2 W/cm<sup>2</sup> the averaged carbon monoxide curves (fig. 11) do show appreciable differences in the tendency of the plastic materials to form carbon monoxide. The induction period of between 4 to 6 minutes before the CO concentration is measurable suggests that CO formation is linked to char oxidation rather than smoke production, since a significant amount of smoke generated occurs in all cases prior to any measurable carbon monoxide. Furthermore, the relative ranking of the plastics based on carbon monoxide concentration at any given time (R-PVC > P-PVC, ABS > polystyrene) might be expected if one assumes a similar ranking for the amount of char remaining at any given

time. Some CO contribution from the oxidation of smoke and decomposition products in close proximity to the radiant heat source also is possible. At 4.2 W/cm<sup>2</sup>, red oak produced larger quantities of carbon monoxide at a more rapid rate (~280 ppm/min), and the induction period was shorter (~30 s).

#### 4.4. Weight Loss

Although the initial weight of the samples in the previous studies was similar, the total weight loss was found to depend upon the composition of the material and the thermal exposure conditions. In table 2 the average percent total weight loss occurring after a 20 minute period and initial average sample weights (grams) are shown for the five materials at various irradiance levels under flaming conditions.

Table 2. Average Percent Total Weight Loss\* (Flaming Exposure)

	0 W/cm <sup>2</sup>	1.0 W/cm <sup>2</sup>	1.9 W/cm <sup>2</sup>	3.1 W/cm <sup>2</sup>	4.2 W/cm <sup>2</sup>
R-PVC	(4.30) 16.5	(4.19) 61.1	(3.97) 72.6	(3.92) 85.6	(4.19) 93.4
ABS	(4.38) 36.6	(4.00) 74.9	(4.00) 82.1	(4.47) 94.4	(4.11) 97.9
P-PVC	(4.08) 39.5	(4.00) 71.5	(4.12) 83.2	(3.95) 90.4	(4.02) 94.5
Red Oak	(4.04) 41.5	(4.01) 73.3	(4.32) 79.6	(4.13) 87.6	(4.05) 94.8
Poly-styrene	(4.00) 20.0	(3.92) 45.7	(3.96) 69.3	(4.01) 91.4	(3.99) 98.5)

(Range 3.92 - 4.47 g, av 4.08 g)

[Initial sample weight av (g) given in parenthesis.]

\*The heading gives irradiance levels from the electric heater in W/cm<sup>2</sup>. In the first case where the value is 0 W/cm<sup>2</sup> the radiance heater was off with only the pilot burners ignited.

While total weight loss increases with irradiance level, the data give no indication of the relationship between smoke density and weight loss rate. Others [3] have shown through continuous weight loss measurements in the chamber that for certain materials, the smoke density for a given mass loss of sample is greater in the latter stages of sample consumption. The early degradation products, because of their physical and chemical nature, could have less tendency to obscure a light beam path than a similar weight of degradation products generated later in the combustion process.

#### 4.5. Oxygen Depletion

Another important factor affecting smoke and carbon monoxide generation in a developing fire is oxygen depletion. In some large-scale fire



tests it is not uncommon for the oxygen level to drop to such a low value that the fire is extinguished.

The volume of the smoke chamber was designed [4] so that sufficient oxygen would be available for complete combustion of most specimens. To determine general trends, smoke and carbon monoxide concentrations from the five materials were evaluated under an artificially oxygen depleted chamber atmosphere. Nitrogen was used to purge the chamber and the oxygen concentration was monitored continuously (paramagnetic oxygen analyzer) until a desired 15% oxygen level was obtained. The sample was attached by a spring clip to a dummy blank located in front of the radiant heater so that it could be positioned in front of the heater at the desired time without opening the chamber. Thermal radiation was blocked from the sample during purging by means of an aluminum foil shield positioned between the radiant heater and the sample. Under flaming exposures, the pilot burners were ignited prior to purging the chamber.

Comparison of the resultant smoke and carbon monoxide measurements at normal (21% O<sub>2</sub> initially) and oxygen lean (15% O<sub>2</sub> initially<sup>3</sup>) chamber atmospheres are shown in figures 12-16 for plasticized PVC, rigid PVC, ABS, red oak, and polystyrene, respectively, under flaming conditions. By reducing the oxygen level in the chamber, the duration of flaming combustion for all materials was noticeably reduced, as expected. The times at which the maximum smoke densities were reached were usually increased. Although more data over a range of oxygen levels are necessary, some general observations can be made. For those materials which generate similar maximum smoke densities under standard flaming and non-flaming burning conditions (e.g., plasticized PVC and polystyrene), artificially reducing the oxygen in the chamber to an initial 15% level initially does not appear to change the maximum smoke density significantly although the time to reach this value is lengthened. For materials which have considerably higher maximum smoke densities under flaming compared to non-flaming exposures (e.g., rigid PVC and ABS), burning similar samples in an oxygen deficient atmosphere appears to result in a significant reduction of the maximum smoke density.

Carbon monoxide concentrations were found to be similar or lower initially at the lower chamber oxygen level, but were enhanced in all cases after this initial burning period.

## 5. SMOKE MASS DENSITY VERSUS OPTICAL DENSITY

Smoke particulates present a dual fire hazard -- visual obscuration and particulate inhalation by potential victims. Optical density measurements appear to be sufficient for relating to visual obscuration, but little has been reported on smoke concentration in terms of mass density, another useful parameter to characterize "quantity of smoke."

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<sup>3</sup>The oxygen concentration was not measured after the start of the test. During the test the oxygen concentration fell below the 15% level due to consumption by the burning sample as well as by the pilot burners.

Correlations between smoke mass density and optical density were studied in the smoke chamber using both gravimetric filtration and electrostatic precipitation as collection techniques. All smoke was sampled at the midpoint of the side wall of the chamber opposite the photometer. For smoke samples composed primarily of carbonaceous soot, a 0.6 micron (average pore diameter) millipore PVC filter was employed to collect the larger particle size mass fraction. An electrostatic mass monitor [5] was used as a backup for the smaller particles and/or condensable liquid droplets which might pass through the filter. For smoke generated under non-flaming (smoldering) type conditions (consisting primarily of suspended liquid droplets); and red oak under flaming conditions (consisting of both solid and liquid particulate matter), the electrostatic mass monitor was the sole collection technique. This latter technique has several advantages over filtration methods. Smoke mass is continuously monitored by a shift in resonance frequency of a small quartz plate which collects smoke on its surface. Smoke in the sampling stream is deposited electrostatically on the quartz plate, thus changing the mass of the plate. The resonance frequency of the plate is proportional and very sensitive to the mass of the plate. A smoke deposition rate on the order of 0.1 mg/min can be easily detected. Measurements were made under steady-state conditions after the maximum optical smoke density had been reached. With collection by filtration, a 1.0 liter/min critical orifice was used and the smoke was sampled over a 5-min period after reaching the maximum density. The average optical density had to be determined over this 5-min time period. Because of problems with moisture absorption, it was necessary to allow the smoke on the filter paper to approach a steady weight during micro-weighing.

A comparison of optical smoke densities (per metre path length) versus smoke mass densities (milligram per cubic metre) for the five materials under flaming and non-flaming conditions is shown in figure 17. Initial sample weights were varied by changing the sample area exposed while keeping thickness constant, to obtain a range of optical densities in the chamber. With the exception of red oak, ABS, and polystyrene under non-flaming burning conditions, smoke mass density appeared to be linearly related to optical density over the range explored. The observed cases of non-linearity are not fully understood. They might result from the particular properties of the pyrolysis products contributing to agglomeration [6] or backward light scattering. The ratio of particulate smoke to optical density, expressed as  $K$  (grams per cubic metre/optical density per metre) shown in table 3, indicates little difference among the materials which produce sooty smoke (ABS, R-PVC, P-PVC, and polystyrene) under flaming conditions. This implies that regardless of the initial composition of these materials, the same mass of carbonaceous smoke will provide similar light obscuration. Optical density/mass density relationships are affected substantially by burning conditions. For all five materials smoke generated under non-flaming conditions resulted in half the obscuration per unit mass of smoke than under flaming conditions. Comparison of the smoke mass density from red oak under smoldering exposures and from any of the plastics under flaming exposure at an arbitrary 0.2 optical density per metre value shows that there is approximately a four-fold mass difference at the same optical density.

Table 3. Ratio of Particulate Smoke Mass to Optical Density - K Factors ( $\frac{\text{Grams per Cubic Metre}}{\text{Optical Density per Metre}}$ )

Material	Exposure	Collection Techniques	K Factor
ABS	Flaming	Gravimetric Filtration	0.27
Polystyrene	Flaming	Gravimetric Filtration	0.27
R-PVC	Flaming	Gravimetric Filtration	0.28
P-PVC	Flaming	Gravimetric Filtration	0.30
Red Oak	Flaming	Electrostatic Precipitation	<u>0.40</u>
		Average	0.30
P-PVC	Non-flaming	Electrostatic Precipitation	0.46
R-PVC	Non-flaming	Electrostatic Precipitation	0.52
ABS	Non-flaming	Electrostatic Precipitation	0.33-0.56*
Polystyrene	Non-flaming	Electrostatic Precipitation	0.38-0.52*
Red Oak	Non-flaming	Electrostatic Precipitation	<u>0.83-1.21</u>
		Average	0.60

\* approximate range

## 6. SMOKE PARTICULATE SIZE AND SHAPE

Smoke particle size to a large degree determines whether smoke is entrapped in the lungs, filtered out in the nose, or inspired and expired without depositing on the lung tissue [7]. Furthermore, particle size undoubtedly plays an important role in the optical density versus mass density relationships.

In this study, smoke particulate matter from the five materials was examined with a scanning electron microscope. Samples were prepared by electrostatic precipitation (aerosol sampler) [8] onto an electropolished titanium metal surface. By using a pulsed precipitating electric field in the sampler, smoke deposition on the metal surface was relatively uniform without preferential size separation.

Photographs of the particles from smoke generated under flaming burning conditions from rigid and plasticized PVC, red oak, ABS, and polystyrene are shown in figures 18-22, respectively. The smoke samples from the plastic materials under these burning conditions appeared as discrete spherical units forming chains or "stringers." Smoke from the red oak sample appeared as a mixture of solid particles and elliptical-shaped liquid residue. The diameter of the smoke particles varied widely, ranging from a fraction of a micron for monospherical particles up to 30 or more microns in diameter for the larger aggregates. Although a size distribution analysis was not felt to be within the scope of this study, estimates were made of the range of particle diameters assuming single, non-aggregated spherical units (table 4).

Table 4. Estimated Minimum Particle Diameters

Material	Estimated Minimum Diameter Range ( $\mu\text{m}$ )
R-PVC	0.1 - 0.4
P-PVC	0.1 - 0.2
Red Oak	0.2 - 0.7
ABS	0.1 - 0.3
Polystyrene	0.1 - 0.3

Similar attempts to evaluate smoke samples from these materials under non-flaming burning conditions proved unrewarding. The smoke samples were coated with a thin (~200 Å) layer of tin metal before microscopic examination to improve conductivity and to eliminate possibilities of interior microscopic contamination. The lack of particle definition upon examination indicated that the samples did not survive this treatment and suggested that the smoke generated under these conditions was primarily liquid.

## 7. CONCLUSIONS AND RECOMMENDATIONS

This project has been primarily of a basic nature. The materials studied were selected to represent a group of typical polymers rather than building materials and commercial products; the results are specific for the chemical composition and physical characteristics of these particular samples.

This study has demonstrated that the relationship between optical density and smoke mass density can change depending upon material composition and burning conditions. Because of this changing relationship, optical density and mass density of smoke should be evaluated jointly. Secondly, since there is no simple relationship between smoke density and carbon monoxide generation among materials of different composition, one cannot assume that a smoke density measurement gives a direct measure of the relative amount of carbon monoxide. Finally, as the oxygen concentration is depleted, combustion can change from a flaming to a smoldering mode. For those materials which produce less smoke under smoldering exposure conditions, the smoke density will probably be lower when the oxygen level is reduced. Potential fire hazard assessments will be more meaningful when these factors are taken into consideration.

## 8. ACKNOWLEDGEMENT

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FIGURE 1 PROBE POSITION AND CARBON MONOXIDE CONCENTRATION FROM RED OAK AND RIGID PVC (FLAMING EXPOSURE)

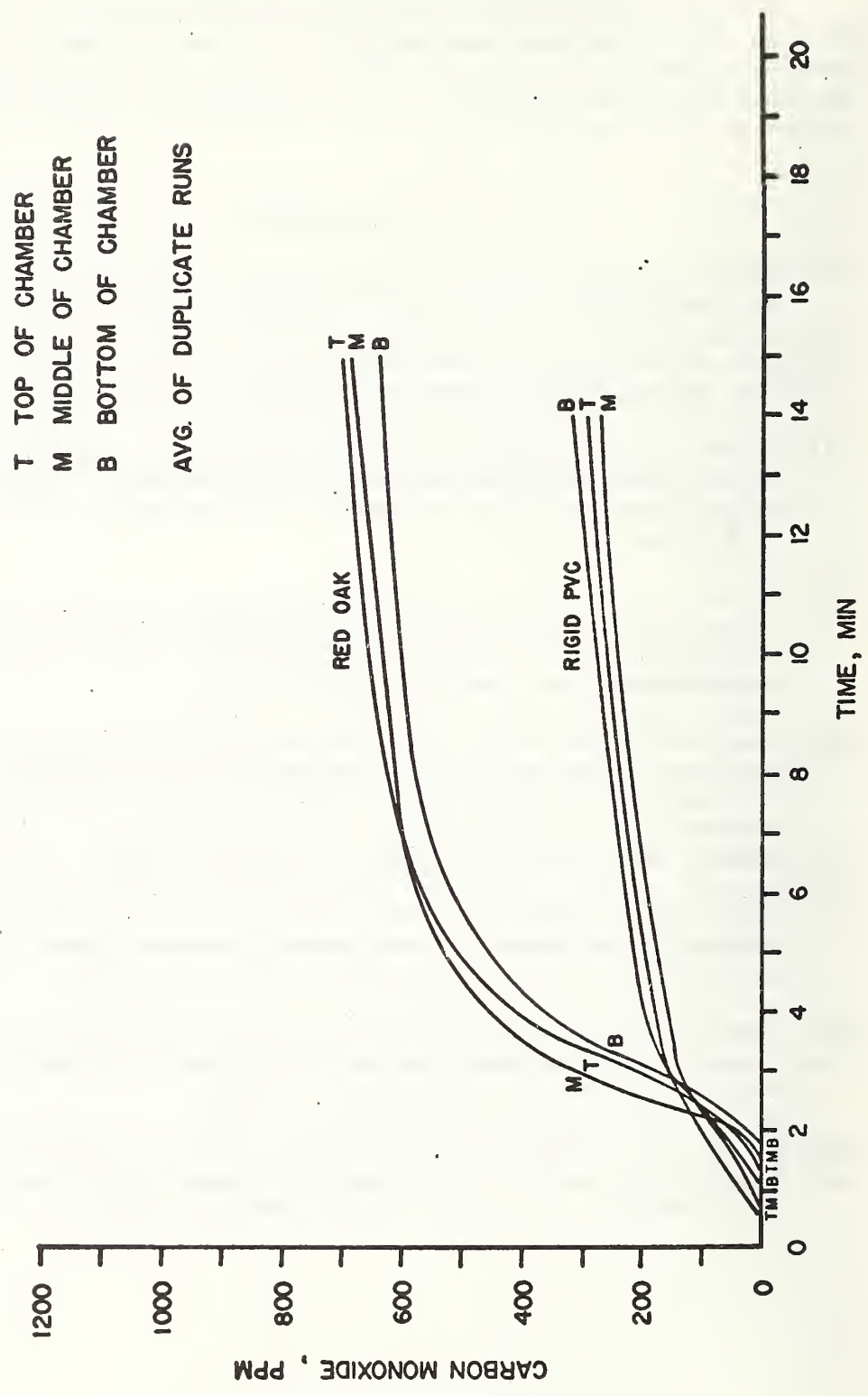


FIGURE 2 SMOKE AND CARBON MONOXIDE FROM VARIOUS MATERIALS

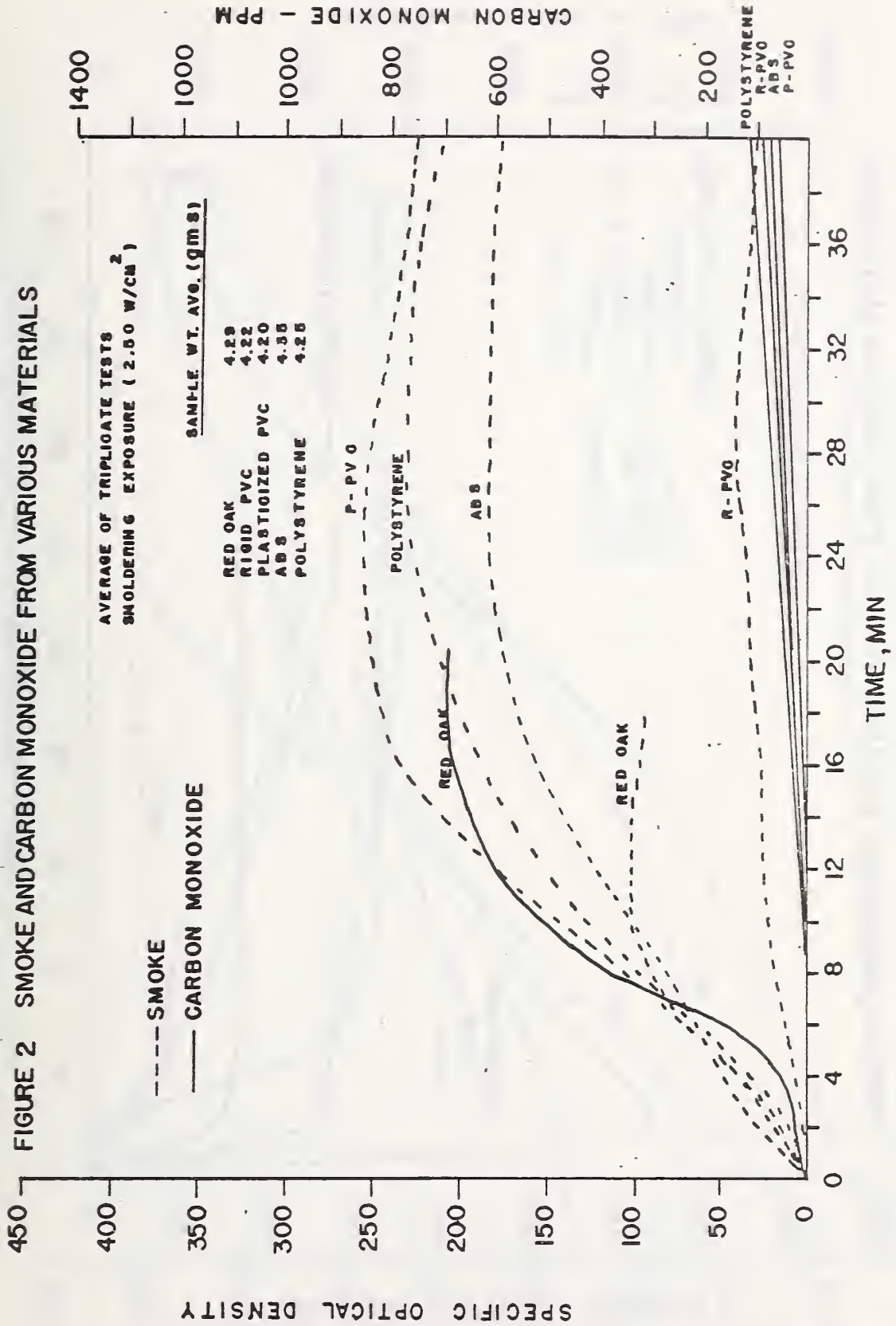


FIGURE 3 SMOKE AND CARBON MONOXIDE FROM VARIOUS MATERIALS

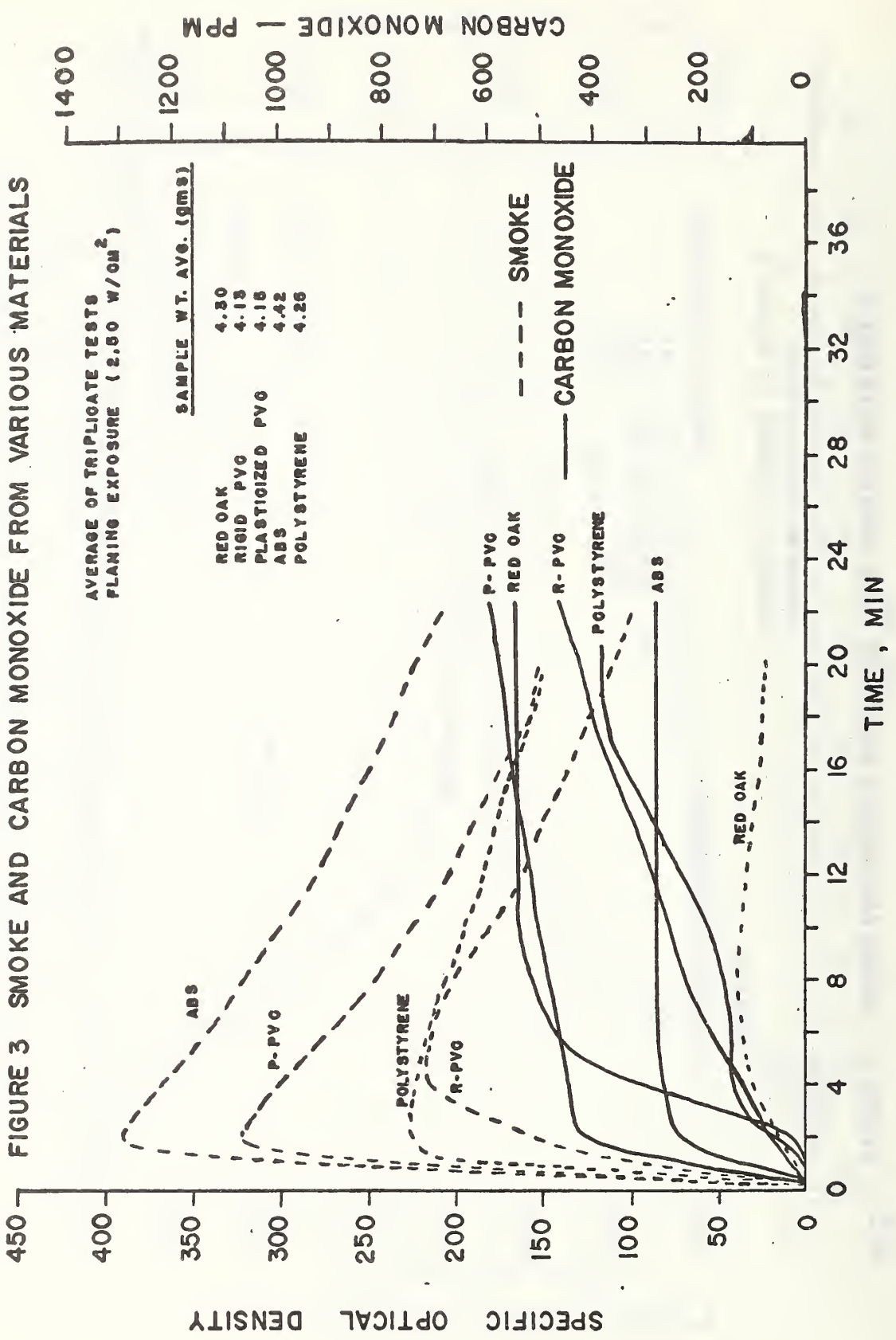




FIGURE 4 VARIATIONS IN MAXIMUM SPECIFIC OPTICAL DENSITY WITH IRRADIANCE LEVEL (FLAMING EXPOSURE)

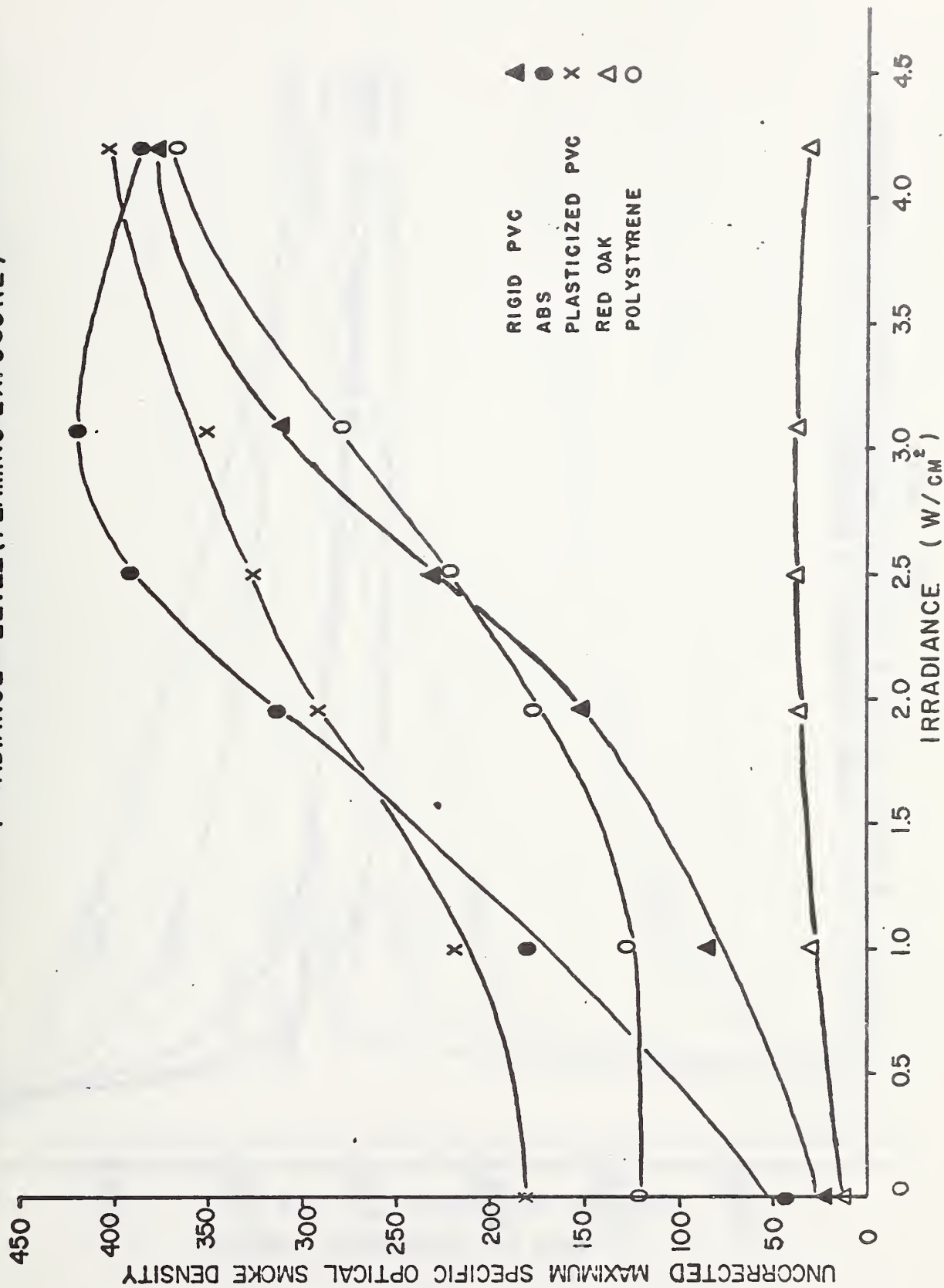


FIGURE 5 EFFECT OF HEAT FLUX ON CARBON MONOXIDE FORMATION  
ABS (FLAMING EXPOSURE)

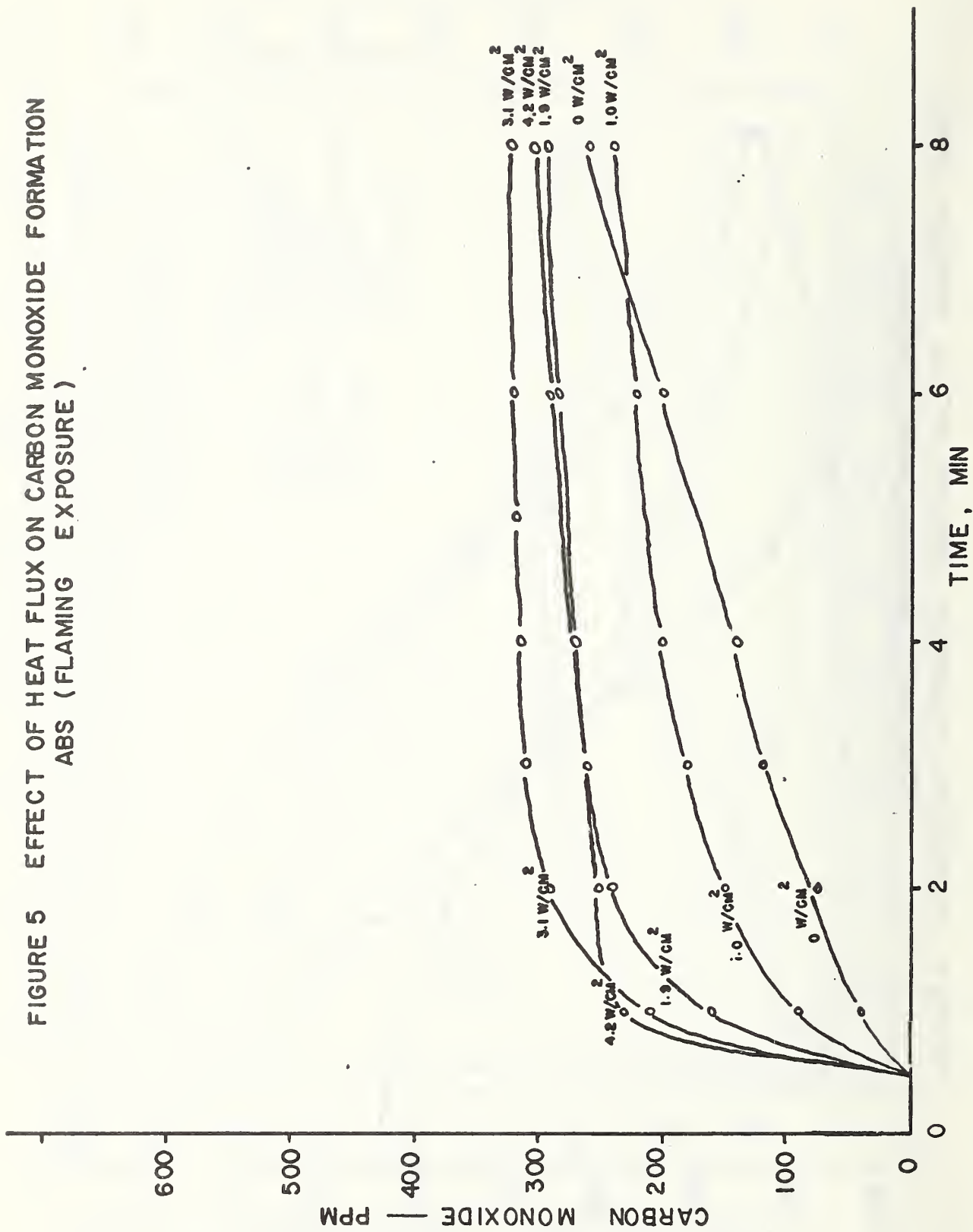


FIGURE 6 EFFECT OF HEAT FLUX ON CARBON MONOXIDE FORMATION  
PLASTICIZED PVC (FLAMING EXPOSURE)



FIGURE 7 EFFECT OF HEAT FLUX ON CARBON MONOXIDE FORMATION  
 RED OAK (FLAMING EXPOSURE)

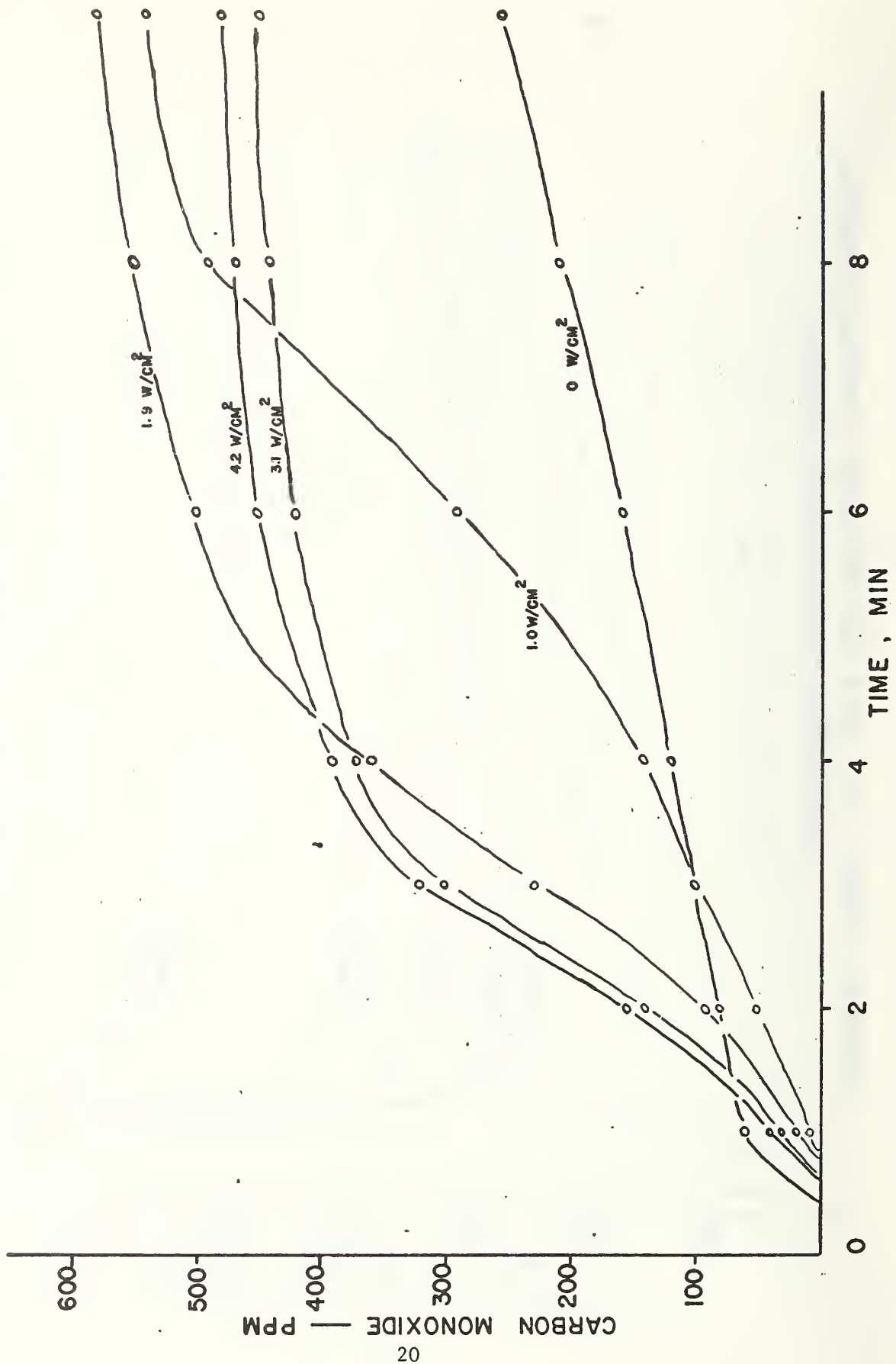


FIGURE 8 EFFECT OF HEAT FLUX ON CARBON MONOXIDE FORMATION  
POLYSTYRENE (FLAMING EXPOSURE)

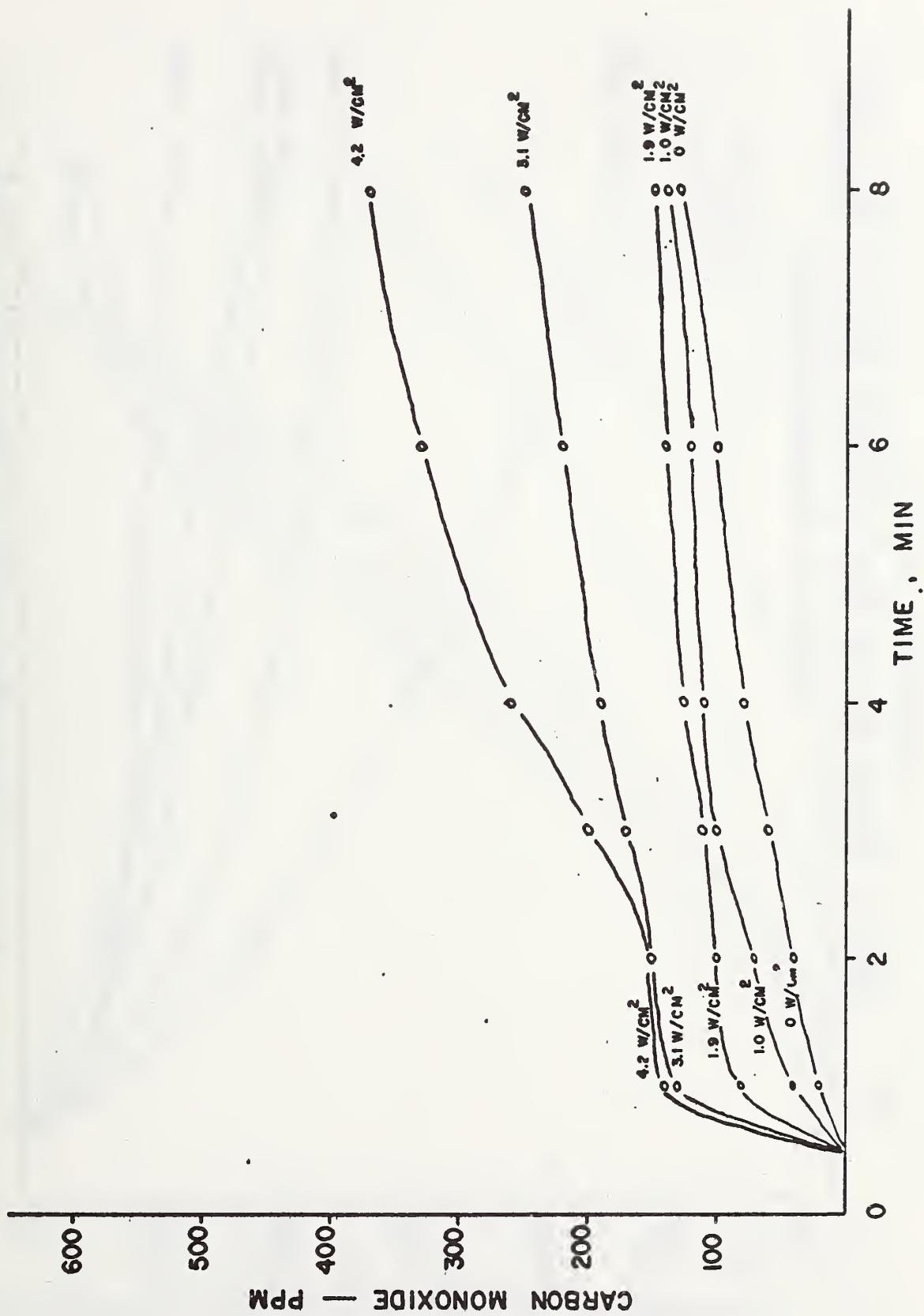


FIGURE 9 EFFECT OF HEAT FLUX ON CARBON MONOXIDE FORMATION  
RIGID PVC (FLAMING EXPOSURE)

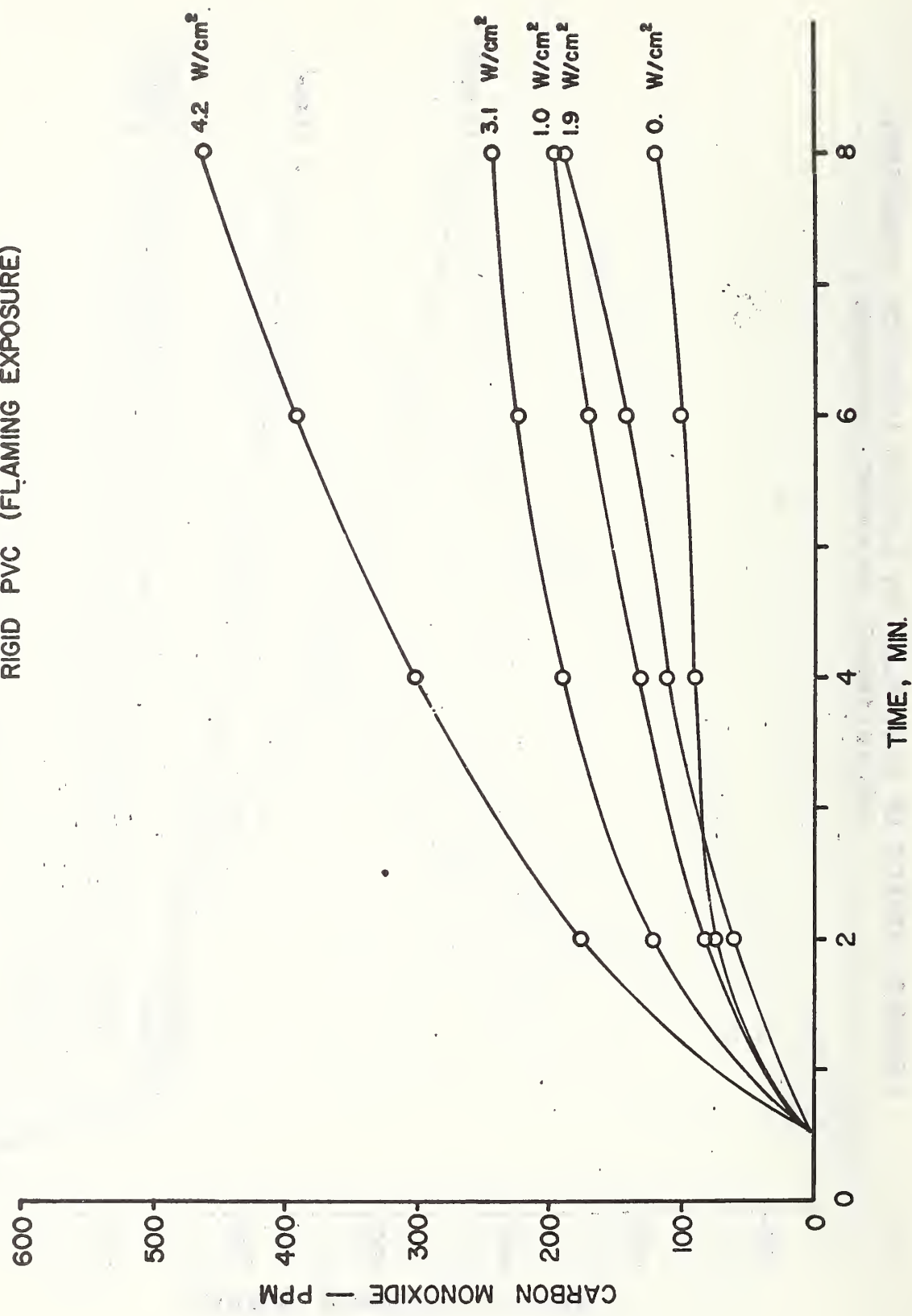


FIGURE 10 VARIATIONS IN MAXIMUM SPECIFIC OPTICAL DENSITY WITH IRRADIANCE LEVEL ( SMOLDERING EXPOSURE )

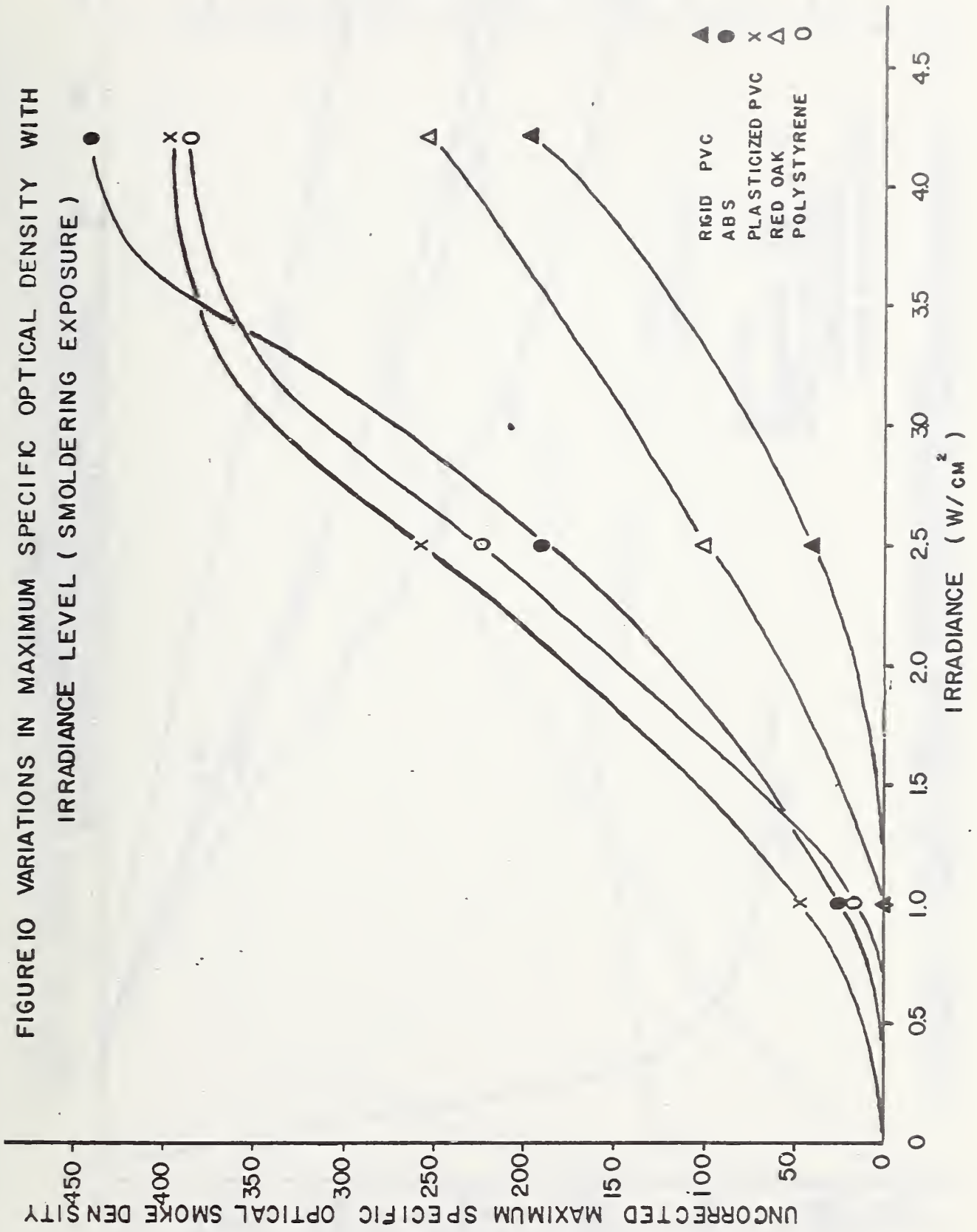


FIGURE II CARBON MONOXIDE FORMATION FOR VARIOUS MATERIALS AT 4.2 W/CM<sup>2</sup> (SMOLDERING EXPOSURE)

AVERAGE OF DUPLICATE TESTS

SAMPLE	WT. AVG. (GMS)
REDOAK	4.30
RIGID PVC	4.31
PLASTICIZED PVC	4.16
ABS	4.27
POLYSTYRENE	4.27

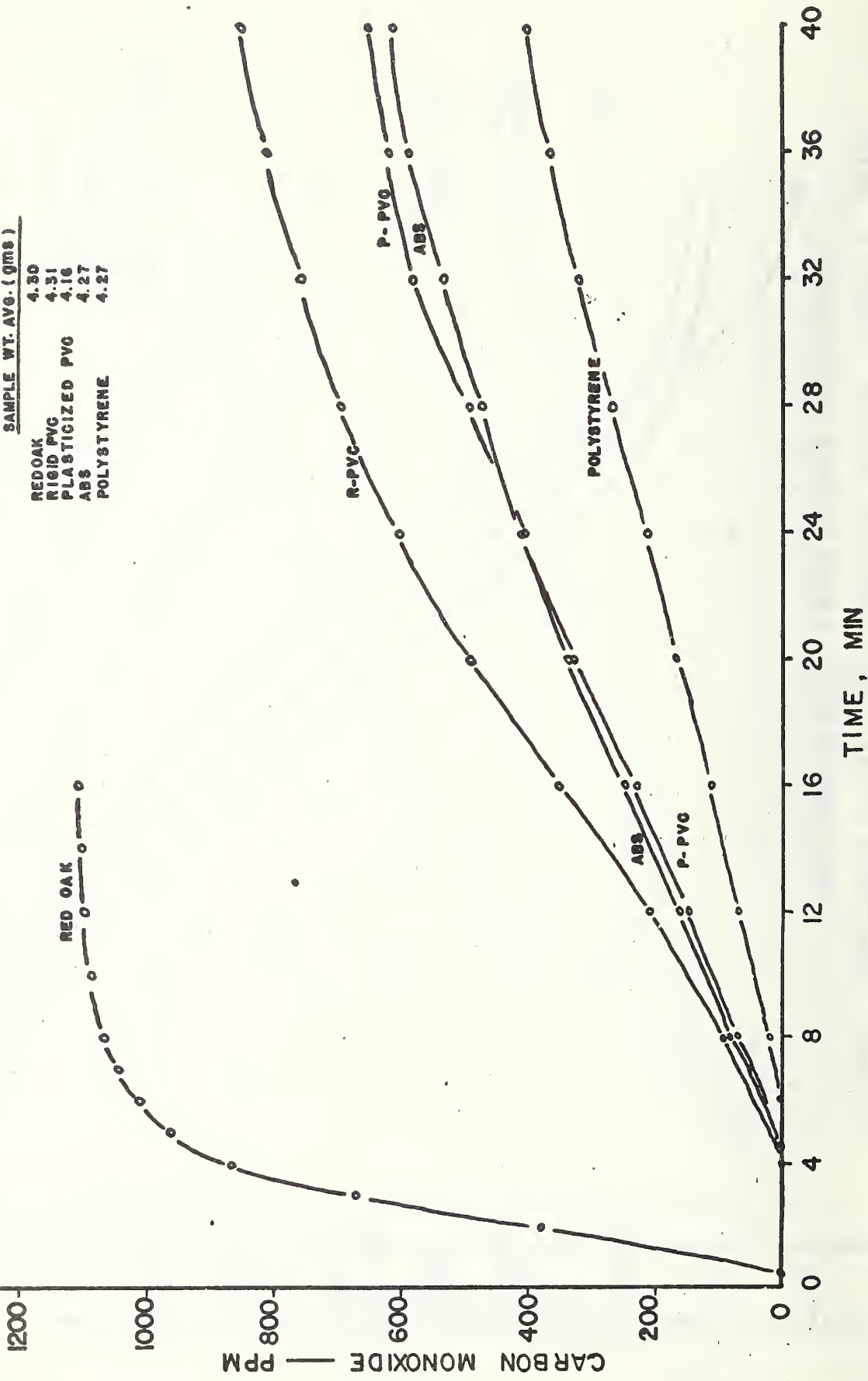




FIGURE 12 SMOKE AND CO VARIATIONS WITH CHAMBER OXYGEN PLASTICIZED PVC (FLAMING EXPOSURE)

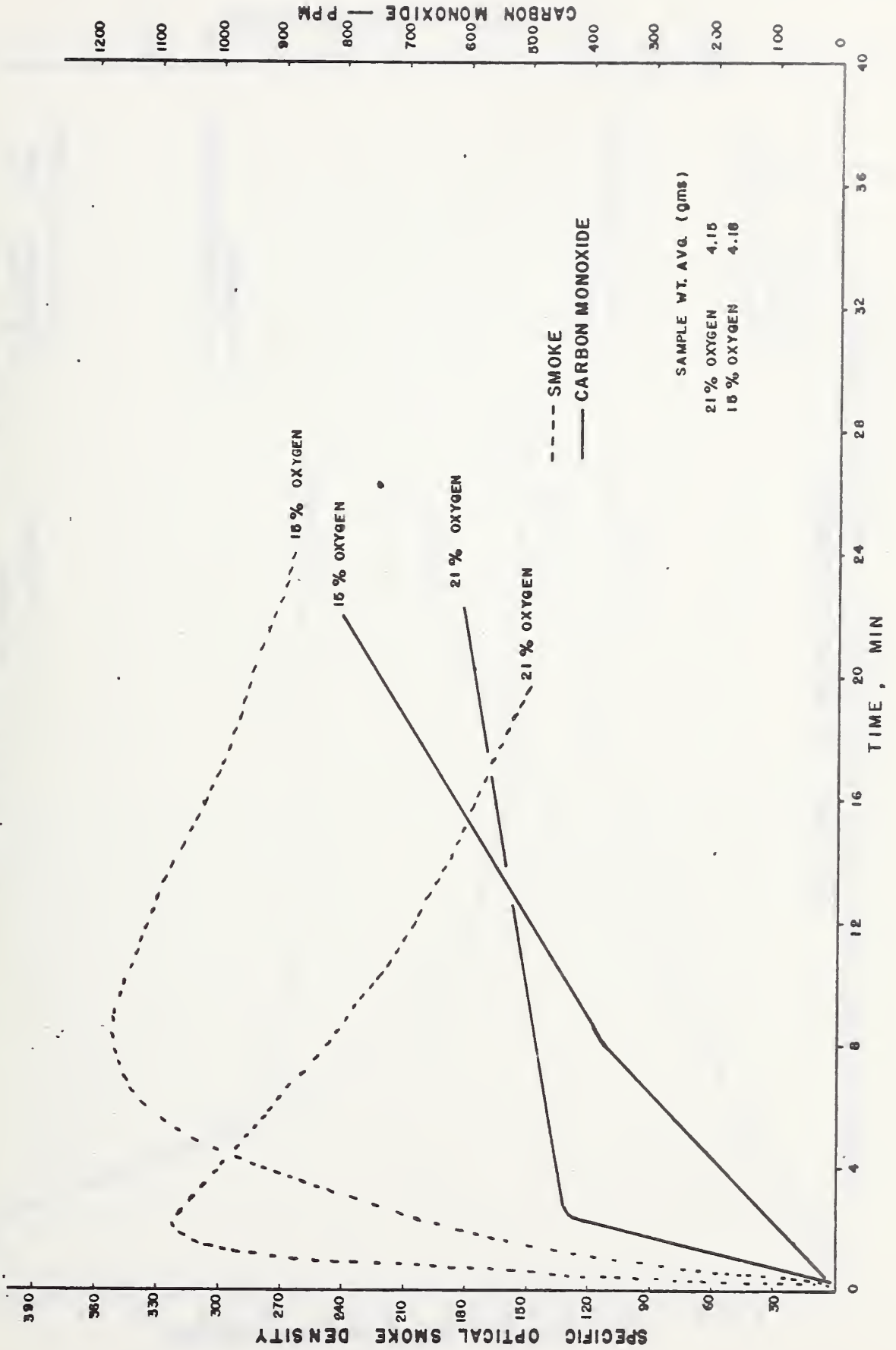


FIGURE 13 SMOKE AND CO VARIATIONS WITH CHAMBER OXYGEN  
 RED OAK (FLAMING EXPOSURE)

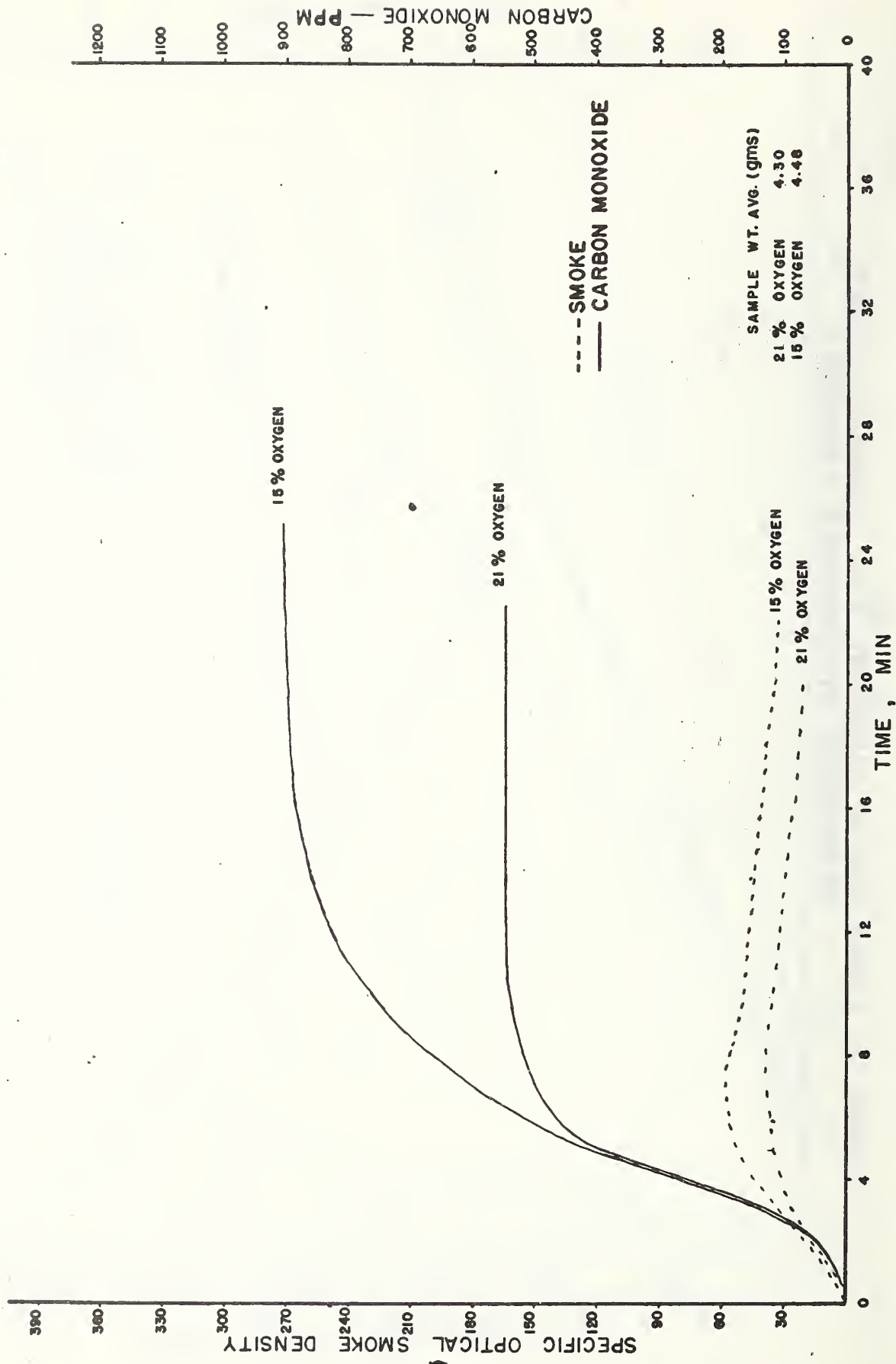


FIGURE 14 SMOKE AND CO VARIATIONS WITH CHAMBER OXYGEN  
RIGID PVC. ( FLAMING EXPOSURE )

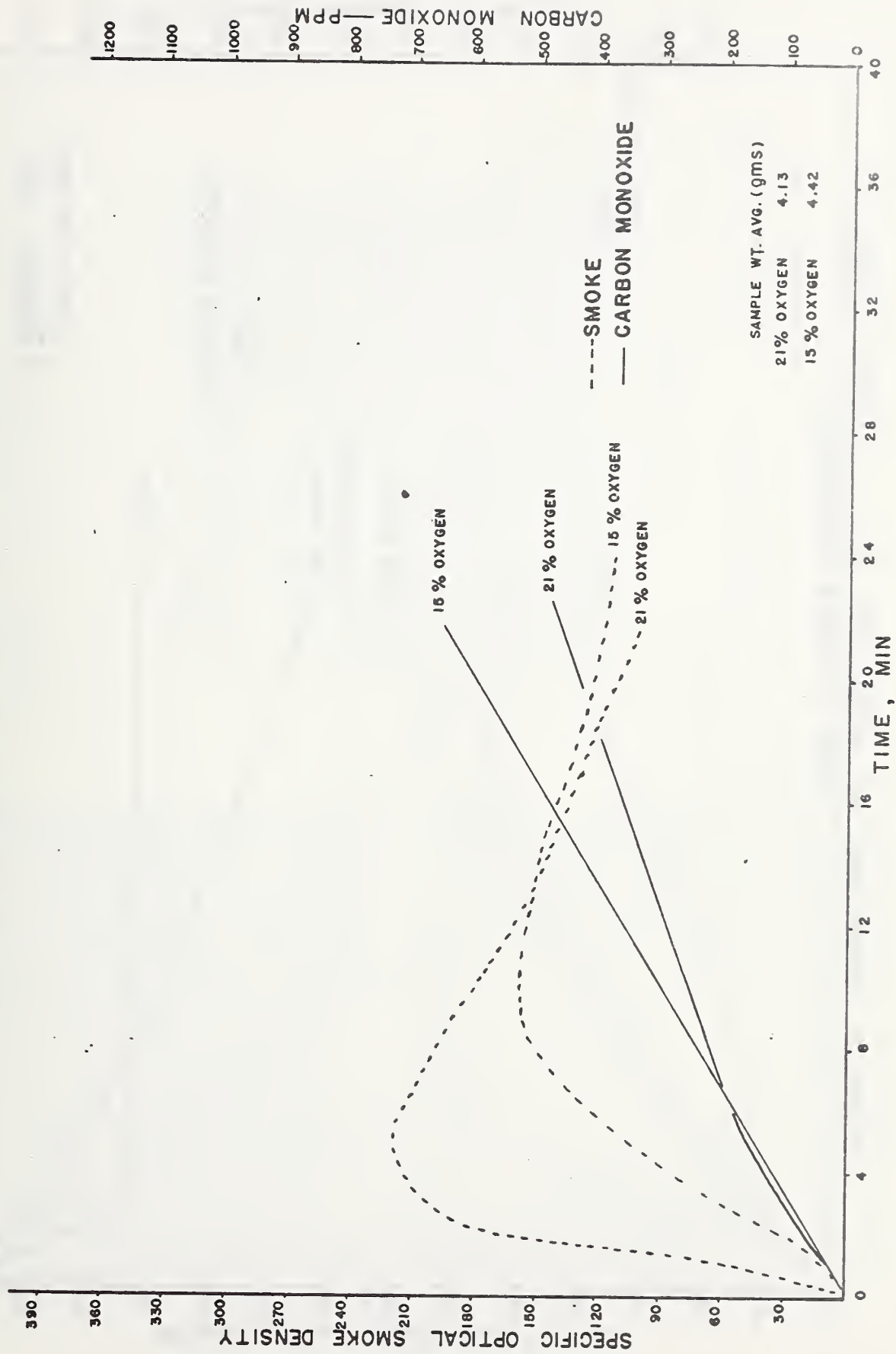


FIGURE 15 SMOKE AND CO VARIATIONS WITH CHAMBER OXYGEN ABS (FLAMING EXPOSURE)

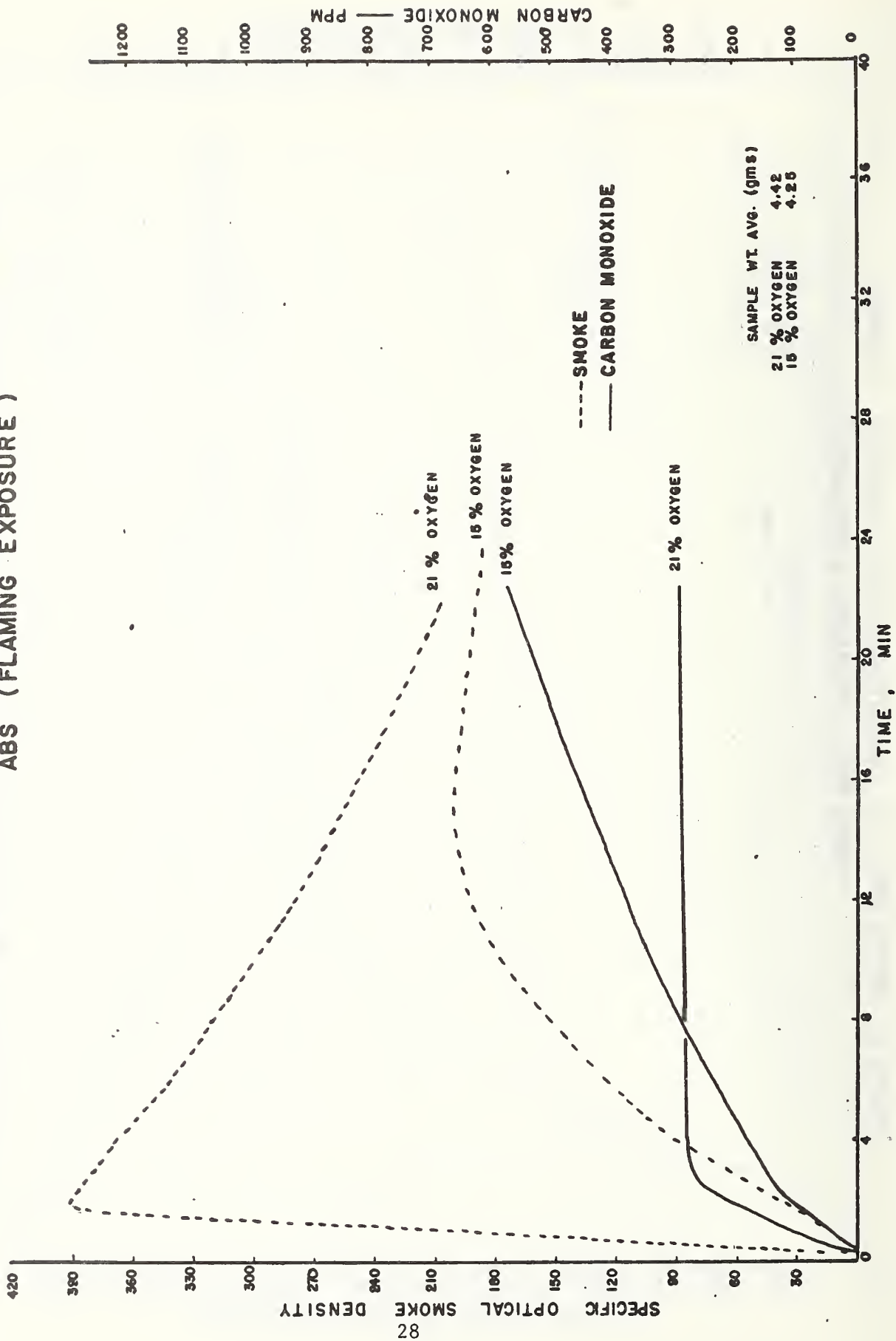
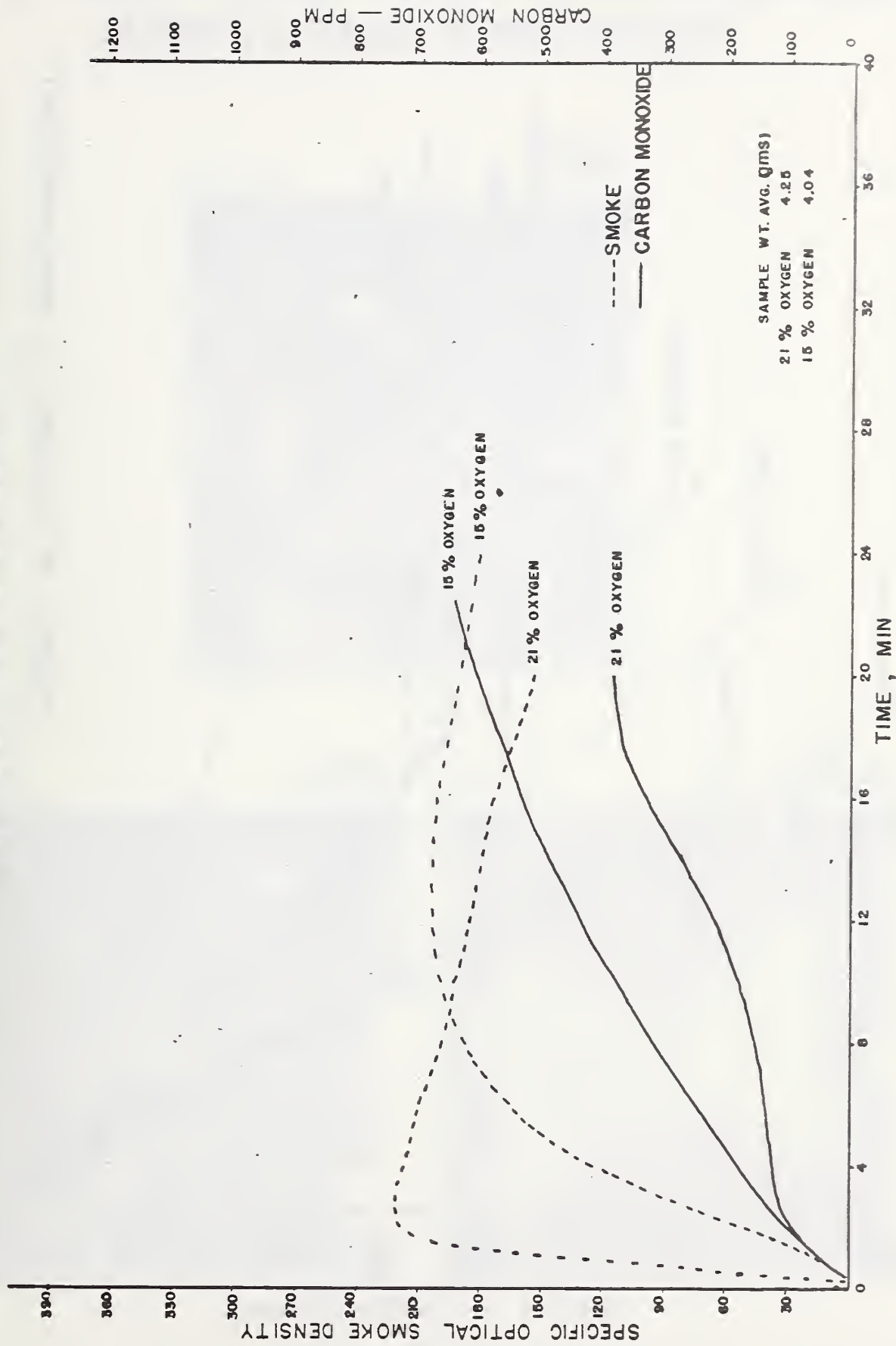


FIGURE 16 SMOKE AND CO VARIATIONS WITH CHAMBER OXYGEN  
POLYSTYRENE ( FLAMING EXPOSURE )



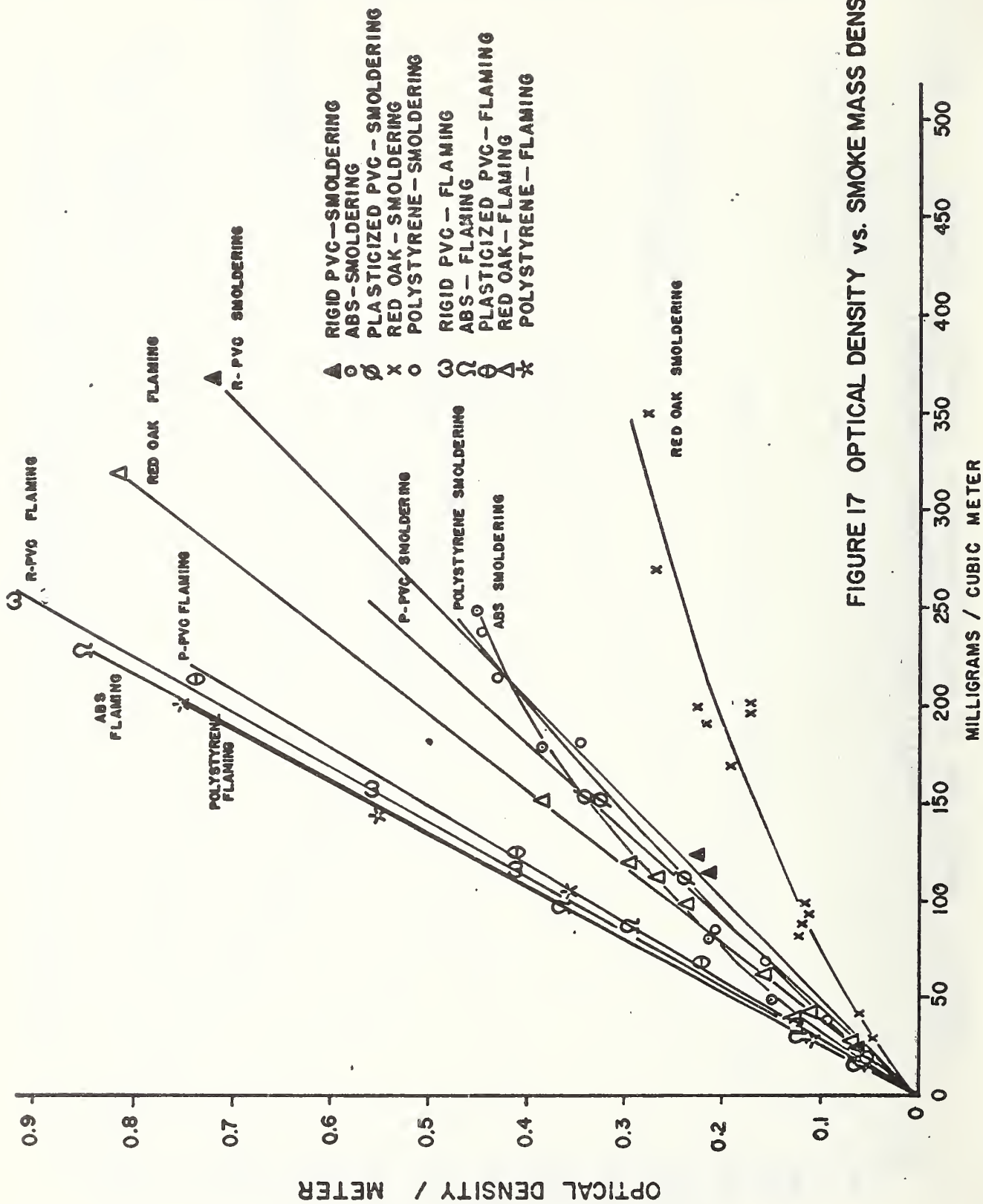
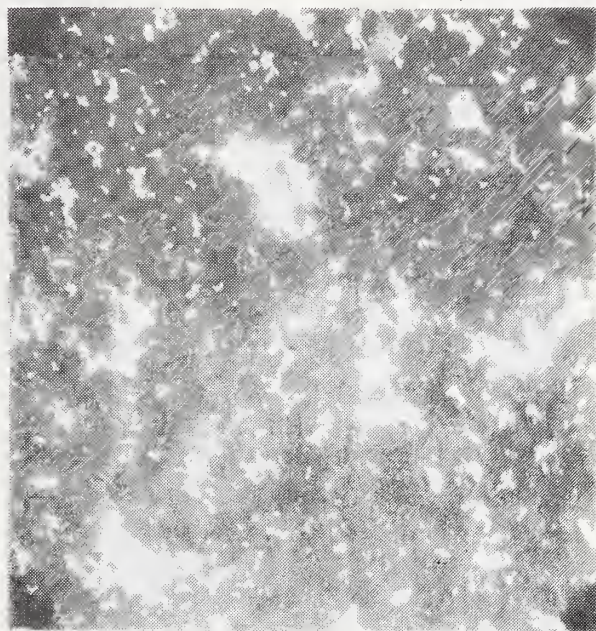


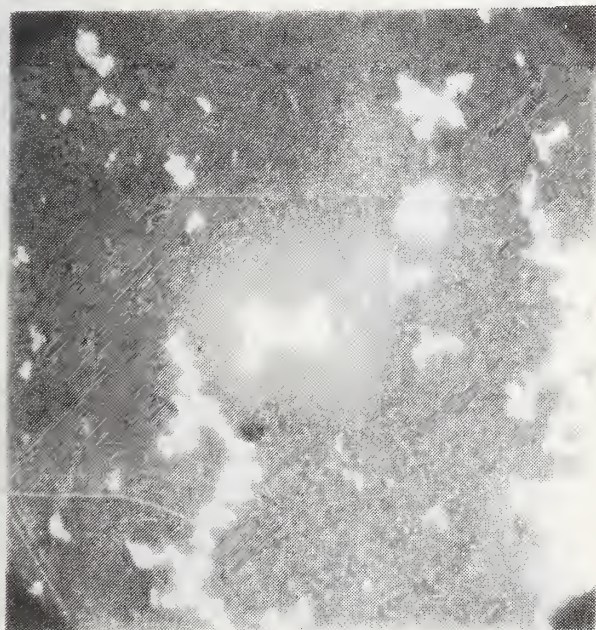
FIGURE 17 OPTICAL DENSITY vs. SMOKE MASS DENSITY

**FIG. 18 RIGID PVC 'FLAMING EXPOSURE' SMOKE PARTICULATE,  
SCANNING ELECTRON MICROPHOTOGRAPHS**

13.4  $\mu\text{m}$



3.4  $\mu\text{m}$

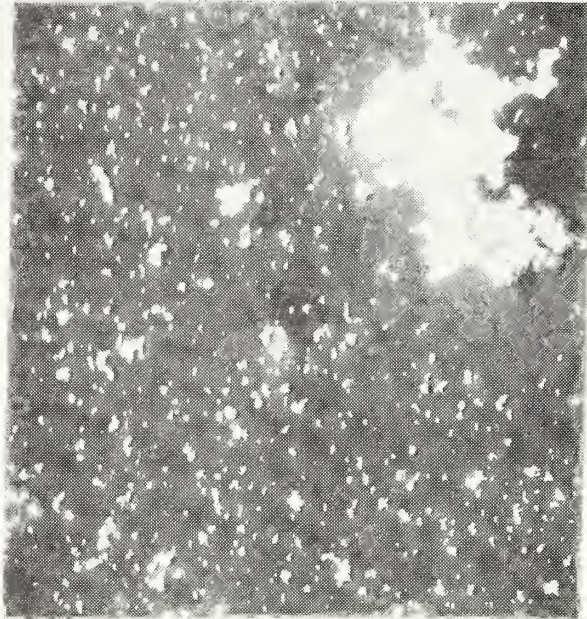


0.6  $\mu\text{m}$

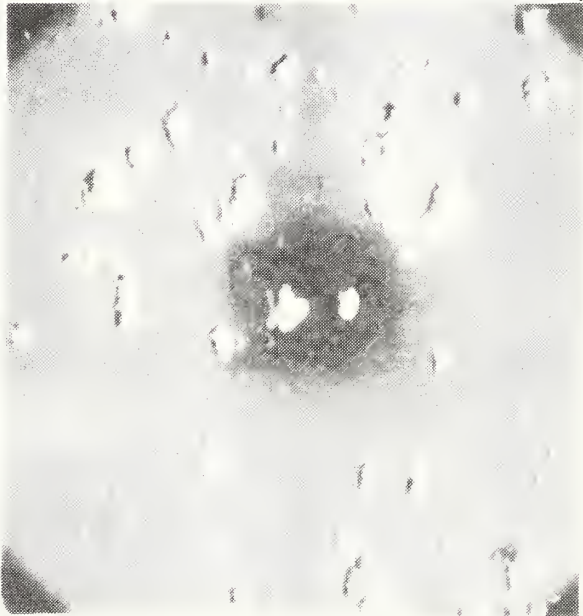


**FIG. 19 PLASTICIZED PVC 'FLAMING EXPOSURE' SMOKE PARTICULATE,  
SCANNING ELECTRON MICROPHOTOGRAPHS**

11.8  $\mu\text{m}$



3.0  $\mu\text{m}$



0.6  $\mu\text{m}$

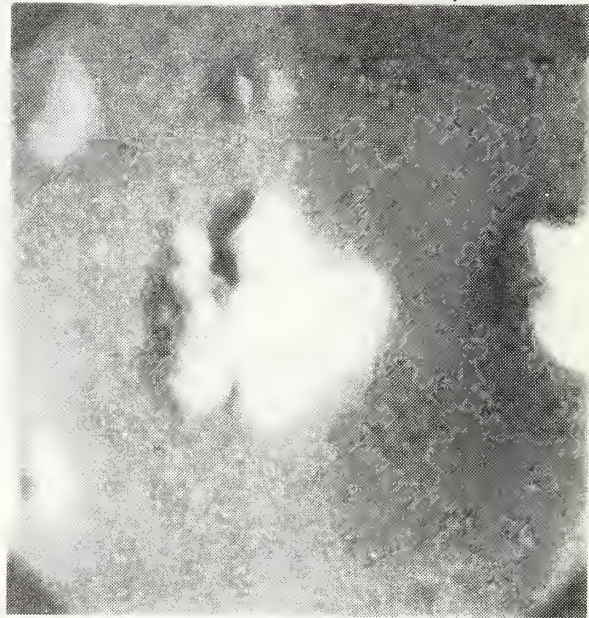
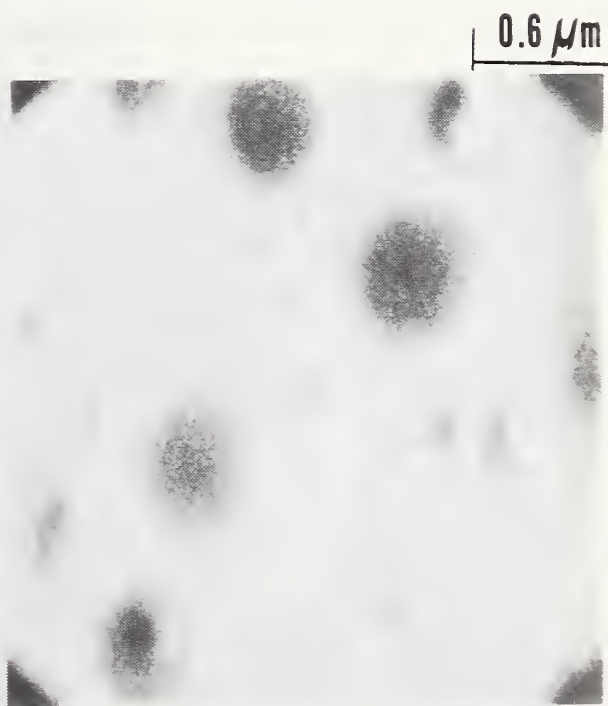
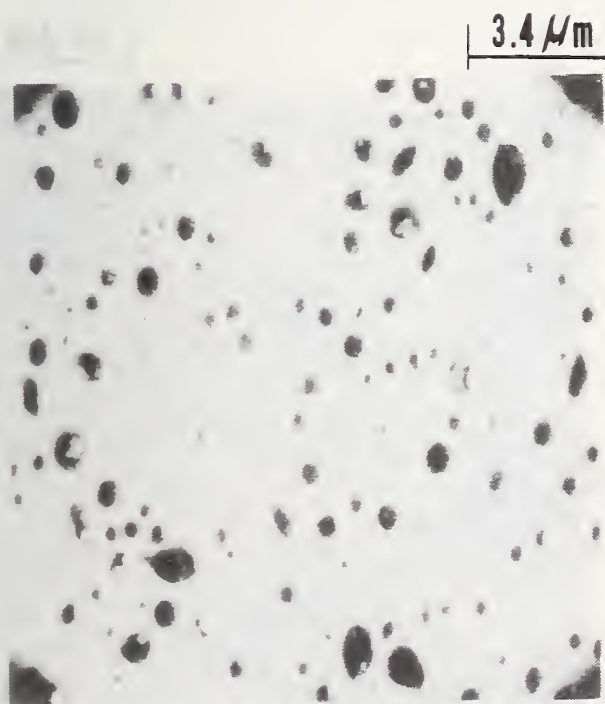
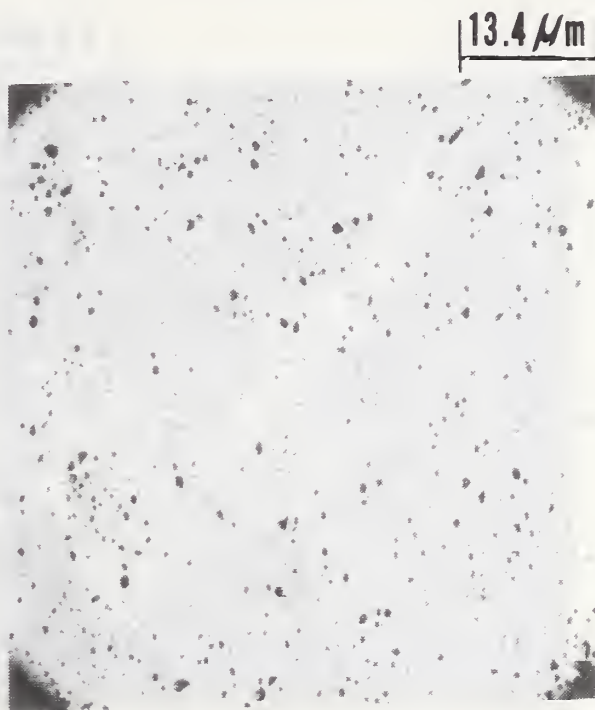
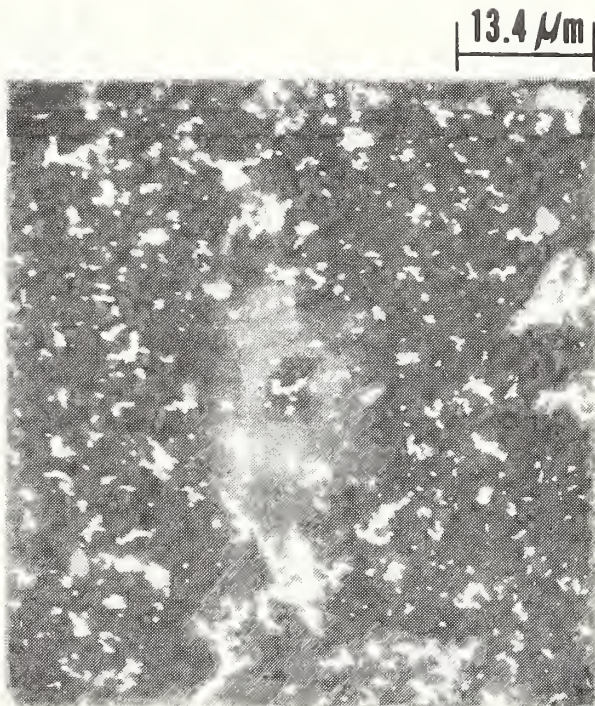
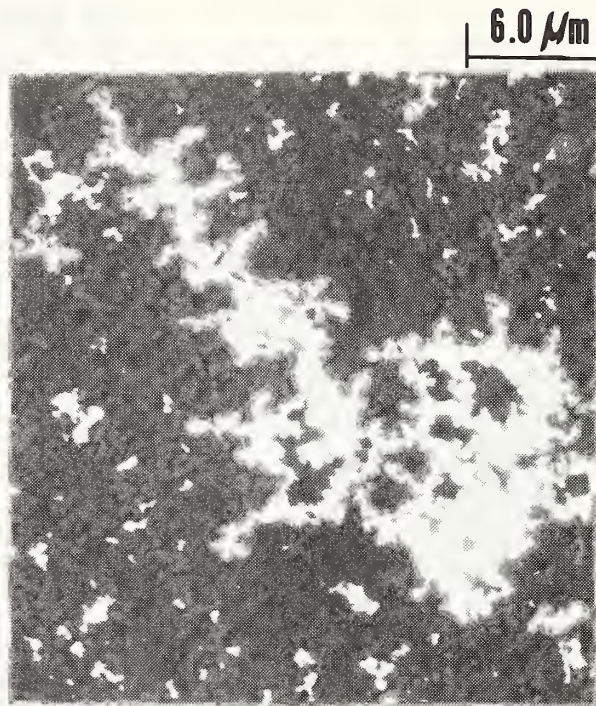




FIG. 20 RED OAK 'FLAMING EXPOSURE' SMOKE PARTICULATE,  
SCANNING ELECTRON MICROPHOTOGRAPHS

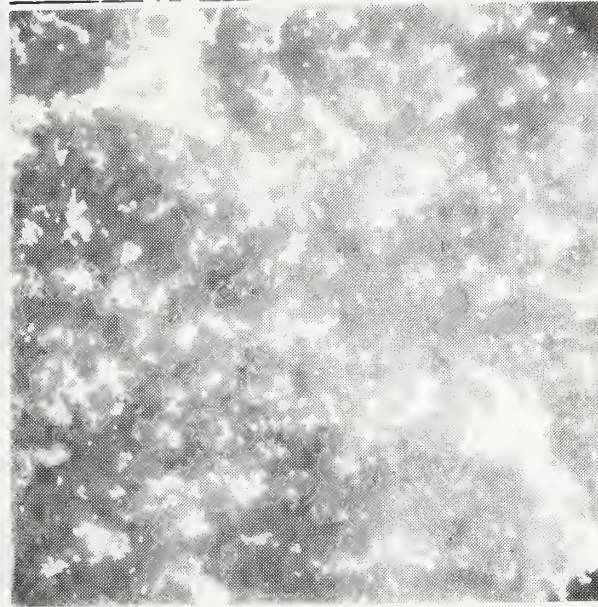


**FIG. 21 ABS 'FLAMING EXPOSURE' SMOKE PARTICULATE,  
SCANNING ELECTRON MICROPHOTOGRAPHS**

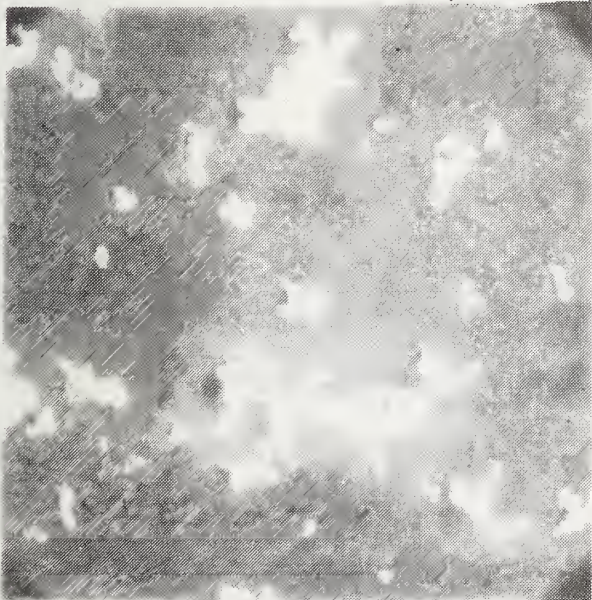


**FIG. 22 POLYSTYRENE 'FLAMING EXPOSURE' SMOKE PARTICULATE,  
SCANNING ELECTRON MICROPHOTOGRAPHS**

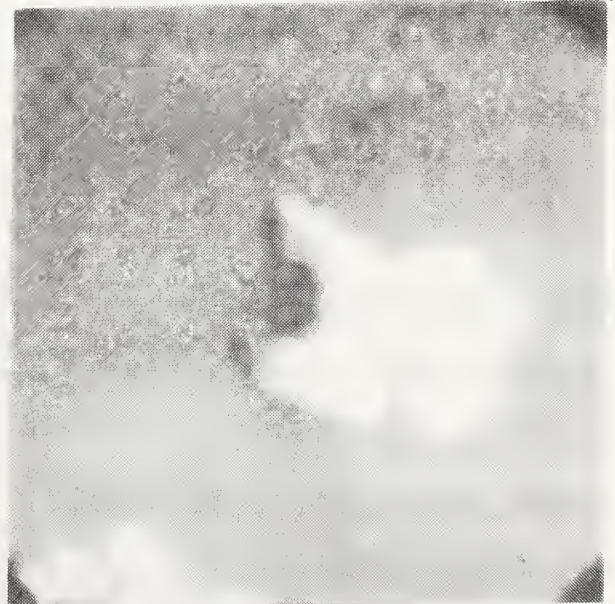
13.4  $\mu\text{m}$



3.4  $\mu\text{m}$



0.6  $\mu\text{m}$



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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)  The effects of physical and chemical factors on the smoke and carbon monoxide generated by burning polymers and red oak in the NBS Smoke Density Chamber are reported.  Smoke and carbon monoxide formation was found to depend on irradiance level and oxygen concentration in the chamber. Smoke optical density correlations with particulate mass density showed that the ratio of these two varied with material composition and burning conditions.				
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