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Method for Measuring Smoke from Burning Materials*

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ABSTRACT: Based on a study of possible smoke-measuring methods, a laboratory test has been developed for the photometric measurement of smoke from burning materials. The method assumed the applicability of Bouguer's law to the attenuation of light by smoke, and smoke quantity is therefore reported in terms of optical density rather than light absorptance or transmittance. Optical density is the single measurement most characteristic of a "quantity of smoke" with regard to visual obscuration. Experiments have been performed on a variety of building finish materials under both flaming and nonflaming (smoldering) conditions, and the results are reported in terms of (a) maximum smoke accumulation, (b) maximum rate of smoke accumulation, and (c) the time period to reach an arbitrary "critical" smoke level.

KEY WORDS: smoke, combustion, pyrolysis, aerosols, fire tests, optical density

Nomenclature

<i>A</i>	Surface area of specimen
<i>D</i>	Optical density $\equiv \log_{10}(F_o/F)$
<i>D_m</i>	Maximum value of specific optical density
<i>D_s</i>	Specific optical density = $D(V)/(AL)$
<i>F</i>	Transmitted light flux
<i>F_o</i>	Incident light flux
<i>K</i>	Proportionality constant
<i>L</i>	Length of light path
<i>n</i>	Particle number concentration
<i>r</i>	Radius of particle

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<i>R</i>	Average smoke accumulation rate (see Appendix 2)
<i>R_m</i>	Maximum rate of increase in specific optical density, per minute, measured over a 2-min period
S.O.I.	Smoke obscuration hazard index (see Appendix 2)
<i>t_c</i>	Time to reach a "critical" specific optical density (see Appendix 2)
<i>T</i>	Light transmittance, per cent
<i>V</i>	Volume of smoke chamber
σ	Attenuation coefficient in Bouguer's law
μ	Micron

When accidental fires occur, the smoke generated is often considered to represent the major life danger to the building occupants. Although large concentrations of carbon monoxide and perhaps other toxic products may be present, the obscuration of vision by dense smoke often prevents the direct and logical escape of occupants, or rescue by firemen, during the few minutes available prior to spread of the fire, and the onset of lethal conditions.

The smoke-limiting requirements in current building codes have been established in an attempt to regulate and to reduce the potential light-obscuration hazard from smoke generated by the interior building finish materials applied to walls, ceilings, and floors. These requirements are commonly based on the results from tests devised principally for measuring comparative surface flammability. Unfortunately the relationship between the results of such tests and the visual-obscuring qualities of smoke are not well established. In a recent study, an attempt was made to relate the "tunnel" smoke density ratings for a variety of building materials with visual and photoelectric observations in a room in which the smoke from the tunnel was collected [1].⁴

The immediate objectives of the present study are to investigate the suitability of a laboratory method to measure smoke quantity under prescribed and standardized exposure conditions and to evaluate the appropriate optical properties of smokes which obstruct human vision in building fires, without regard to the chemical nature of the smoke or the fundamental processes of its generation.

Measurement of Smoke

Aerosols are collections of small particles suspended in a gaseous medium, and include smoke, dust, fog, and haze. Smoke is generally considered to be the gaseous products of burning organic materials in which small solid and liquid particles are also dispersed. Another definition limits smoke to solid particles, such as carbon and ash, suspended in air. Under

⁴ The italic numbers in brackets refer to the list of references appended to this paper.

typical conditions of nonflaming thermal decomposition, however, it has been fairly well established that the nongaseous portion of wood smoke consists, not of carbon particles, but primarily of homogeneous spherical tarry droplets [2], and of liquid droplets of organic substances of fairly high boiling points, above 100 C [3]. On the other hand, some materials produce smoke containing a large fraction of carbon particles.

Test methods for measuring smoke are generally of two types: (1) those in which light transmittance measurements are made on the smoke aerosol directly, and (2) those in which the smoke particles are collected on a suitable filter paper which can be either weighed or measured for light transmittance.

Of the first group, those employing unaided visual methods, such as the use of the Ringelmann chart, are generally not considered adequate for laboratory measurements. Instrumental visual methods include the smokescope, umbrascope, and others, in which visual comparisons of the unknown smoke are made relative to reference shades or gray glasses.

Light scattering is a useful technique for detecting the presence of small quantities of smoke, particularly for particles which are not readily accessible or where particle size determination is desired [4]. Scattering measurements are generally limited to particles whose size is of the order of the wavelength of visible light. However, where the object is the measurement of smoke as it relates to visibility, the light attenuation method appears to be the most direct and practical approach.

The most common method for smoke suspension measurements today employs a light source and a photoelectric cell, arranged so that the electrical output of the cell may be used as a measure of the attenuation of light by smoke. The readings are commonly expressed as per cent absorptance, or in terms of the Ringelmann scale (0 to 5). Attempts have been made to relate the per cent light transmittance to an optical density scale and to a quantitative smoke concentration, that is, mass per unit volume [2,5,6]. Such methods are considered generally valid and will be discussed in more detail later. There does not seem to be technical justification for integrating the area under a per cent light absorptance versus time curve [1], [ASTM Test for Surface Burning Characteristics of Building Material (E 84 - 67)] or for making allowance for residue deposits on lenses at the end of a test by simple subtraction of light absorptance readings.

In the second type of smoke measurement, a known volume of gas is filtered through a known area of filter paper, and the resultant spot is classified according to its degree of blackness, and commonly referred to as "smoke shade." It has been assumed by some that Bouguer's law could be applied to smoke shade spots, and that optical density, $\log_{10}(100/T)$, based on per cent light transmittance is an appropriate measure [7]. Others have shown a preference for light reflectance measurements of

smoke shade (ASTM Test for Smoke Density in the Flue Gases from Distillate Fuels (D 2156 - 65)). However, considering all types and colors of smoke, a direct relationship between such measurements and light attenuation measurements through disperse smoke aerosols is not obvious.

Physical Optics of Light Transmission

In formulating the requirements for a suitable laboratory smoke meter, primary consideration should be given to the optical properties of the smoke, but it is necessary also to understand the nature of the visible target, the amount and distribution of light, and certain psychophysical properties related to human vision (for example, contrast level, response time, and adaptation to levels of illumination). The problem is a very complex one, involving elements of both physics and psychology. Considerable aids to understanding various aspects of the problem are the very complete study of particulate clouds in a book by Green and Lane [8], and the comprehensive survey of available knowledge on vision through the atmosphere given in a book by Middleton [9]. To reduce the problem to a level of possible solution, certain simplifications and assumptions must be made, since it is not possible at present to evaluate quantitatively complications due to eye irritations or respiratory effects, hysteria, and associated physiological and psychological factors.

Considering only the limited problem of visibility through smoke, a criterion sometimes used is based on the assumption that when the "visibility" (preferably "visual range") of a hand-lamp illuminated sign drops to 4 ft, a room is smoke-logged to a degree that would seriously impede the escape of occupants [5]. It was inferred that this limit was reached when the light transmitted over a 4-ft. path was reduced to 0.25 per cent of the value in the absence of smoke. This density of smoke was later found to correspond to the perception of a 10-w lamp at a distance of 11 ft, under idealized conditions involving dark-adapted observers stationed outside a smoke-filled room.⁵ On the other hand, it has been reported that observers within a smoke-filled room became "apprehensive about personal safety" when smoke concentration reached levels corresponding to approximately 40 per cent and 80 per cent light transmittance at a distance of 10 ft, depending on whether or not self-contained breathing apparatus was used.⁶ These two different findings represent a very wide range in smoke concentration.

To relate the visibility of an object to the obscuration caused by the presence of a "quantity of smoke" (or other particulate cloud), it is necessary to apply the appropriate laws of extinction and of reduction

⁵ G. Williams-Leir, private communication.

⁶ See page 93.

in contrast. A "quantity of smoke" can be completely defined only when the total weight of material in suspension, its physical properties, and the state of its dispersion are completely known. Since it is usually impractical to determine all this information, even in the laboratory, it becomes necessary to substitute for it a single measurement which is as characteristic of the smoke as possible. The property most frequently selected for this purpose is its optical density; this defines the attenuation of a beam of light passed through the smoke [10].

If we consider a volume of smoke through which a parallel beam of light is passed, then the law of extinction, properly known as Bouguer's law (sometimes also as Lambert's law or Beer's law) is given by:

$$F = F_0 e^{-\sigma L} \dots \dots \dots (1)$$

where:

- F = transmitted flux,
- F_0 = incident flux,
- σ = attenuation coefficient, and
- L = path length.

For a monodisperse aerosol, the attenuation coefficient is usually expressed as $\sigma = K\pi r^2 n$, where K is a proportionality constant, r is the radius of each particle and n is a particle number concentration, that is, the number of particles per unit volume.

Optical density is defined as:

$$D = \log_{10} \left(\frac{F_0}{F} \right) = \frac{\sigma L}{2.303} = \frac{K\pi r^2 n L}{2.303} \dots \dots \dots (2)$$

This relation and Bouguer's law are strictly applicable only for monochromatic light for which the optical density is independent of the light intensity and the receiver sensitivity. However, it has been shown that the relation can be applied to light from a tungsten lamp passing through wood smoke by the use of an effective attenuation coefficient [2].

When two smoke clouds are compared by optical density measurements (reduced to a common path length), a comparison is thus being made of the attenuation coefficient, σ , and is the very property required to determine visibility through smoke. Where visibility is of prime concern, it may be unnecessary to relate particle size distribution, refractive index, coagulation, or other particle properties to particle number concentration, even though they have a large effect on optical density.

Throughout this paper, the terms "smoke accumulation," "smoke quantity," and "smoke density" refer to optical density levels, and not to mass or number concentration.

If the smoke is produced from a surface of area A and collected in a closed chamber of volume V , the optical density of the generated smoke should be directly proportional to A and inversely proportional to V .

Optical density is also proportional to the optical path length L , so that it is appropriate to write

$$D = D_s \frac{AL}{V} \dots \dots \dots (3)$$

D_s may be termed the "specific optical density," and represents the optical density measured over unit path length within a chamber of unit volume produced from a specimen of unit surface area. Thus

$$D_s = D \frac{V}{AL} = \frac{V}{AL} \log_{10} \left(\frac{F_0}{F} \right) \dots \dots \dots (4)$$

Smoke measurements expressed in terms of D_s , which is dimensionless, have the advantage of representing a smoke density independent of box volume, specimen size or photometer path length, provided a consistent dimensional system is used. During the smoke accumulation process, therefore, the change of D_s with time will ideally depend only upon the thickness of the specimen, its chemical and physical properties, and the exposure conditions. Since the ratio V/AL may be a fairly large number, the magnitudes of D_s can be much greater than the optical density (D) values. In a closed chamber under prescribed exposure conditions, D_m is used to designate the maximum value attained by D_s .

However, there are definite limitations to the use of specific optical density for extrapolation and comparison with other box volumes, specimen areas and photometric systems, and for extension to human visibility. The degree to which such extensions are valid depend upon a number of major assumptions:

1. The distribution of smoke is uniform.
2. The smoke generated is independent of the amount of (excess) air available, and of any "edge effects" due to thermal conduction, convection currents, or radiation.
3. For any given smoke, the optical density is a linear function of concentration.
4. Coagulation (agglomeration), deposition, and other changes in the smoke after its generation are similar regardless of the specimen size, or the size and shape of the chamber.
5. Human and photometric vision through light-scattering smoke aerosols, expressed in terms of optical density, are similar.

Experimental Methods

Rohm and Haas Test Chamber

The test apparatus used in the initial phase was developed by the Physics Laboratory of the Rohm and Haas Co. [11], and was made available by them for our use. The 12 by 12 by 30-in. XP2 test chamber

was instrumented with a 3-w light source, a barrier-layer photoelectric cell with visual correction filter, and a meter to measure light transmittance horizontally across the 12-in. light beam path. In the prescribed test, a propane burner operating at a pressure of 40 psi and using air supplied from outside the chamber, provided a flaming exposure to a 1 by 1 by 1/4-in. specimen placed on a supporting metal screen. The chamber was closed and unventilated during the 4-min test period except for 1-in. high ventilation openings around the bottom. A principal feature of this test method is that procedural changes and the exploration of variables can be made quickly and economically.

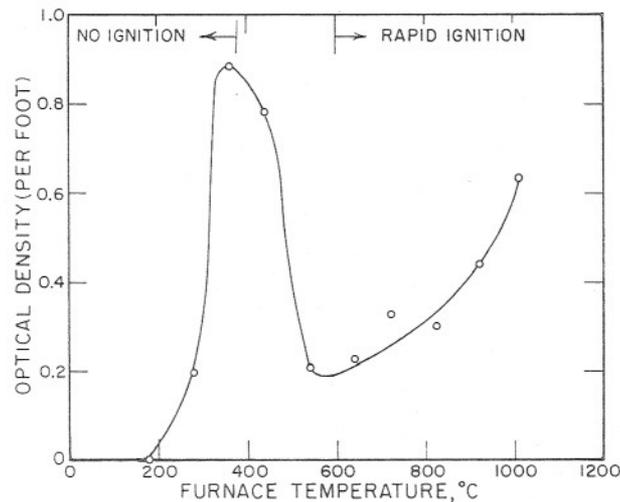


FIG. 1—Smoke production of hardboard within a heated furnace.

It became apparent, after considerable experimentation, that several changes in the equipment were desirable in order to permit (1) measurement of the maximum quantity of smoke accumulated, (2) surface exposure of the specimen rather than complete immersion, (3) pyrolytic as well as flaming exposure, and (4) a higher degree of reproducibility for all types of materials.

The critical importance of the type of exposure used was demonstrated by employing an electrically heated furnace in place of the propane burner and performing a series of tests on unfinished hardboard specimens over a wide range of temperatures. It is evident from Fig. 1 that smoke accumulation from pyrolytic decomposition was low at temperatures below 300 C, but that peak smoking occurred when the temperature was approximately 380 C. At higher temperatures, self-ignition with flaming combustion occurred, reducing the smoke accumulation. At very



FIG. 2—Smoke test chamber.

high temperatures, the smoke accumulation again increased. Although not explored, a relation of similar form would be expected as a function of irradiance level on a single exposed surface of cellulosic materials.

These considerations led to the construction of a new chamber which was completely closed to prevent smoke loss, was of greater capacity to permit burning of larger size specimens, used a vertical rather than horizontal photometer beam to minimize measurement differences due to smoke stratification, and employed an electrically heated furnace and a small auxiliary pilot flame for close control of irradiance on the exposed specimen surface.

NBS Smoke Test Chamber

A completely closed cabinet, comprising a box 3 ft wide, 3 ft high, by 2 ft in depth was developed (see Fig. 2). The 3 by 3-in. specimen was arranged for support in a frame limiting thermal exposure to the surface of $2\frac{9}{16}$ by $2\frac{9}{16}$ in. size. Provision was made for two types of thermal exposure. One involved simple irradiance of the specimen with a flux of 2.5 w/cm^2 yielding nonflaming pyrolysis (smoldering) conditions. The second involved a similar exposure but with the addition of a small pilot flame impinging on the lower portion of the specimen to initiate flaming combustion.

A vertical photometer path over the full 3-ft box height was used. The photometer system incorporated a collimating lens at the source and a small aperture diaphragm at the focal plane of the receiving lens. This effectively limited the field of view of the phototube to the photometer beam itself and reduced interference from outside illumination. A 1P39 vacuum phototube, with an S-4 spectral response, was connected in series with a 67.5-v battery and a suitable resistor including a shunt for the potentiometer input to provide a signal of at least 1 v with full illumination. A potentiometric type recorder with four decades of sensitivity increase was used for continuous measurement of light transmission, ranging to below 0.01 per cent transmission, corresponding to an optical density of about 4. In the most sensitive range it was necessary to make corrections for the dark current of the phototube. The 30-w light source used was operated from a constant voltage transformer at a color temperature of about 2400 K. Further details on the construction of the equipment and test procedure used are included in the Appendix.

In some of the work reported, specimens were burned in a box of approximately 250 ft³ volume. This box was used primarily for the purpose of confirming the validity of optical density as a quantitative means for measuring smoke. In this case, the photometer made use of a 5-ft path length.

Experimental Results

Prior to performance of extensive tests with the smoke chamber, it was necessary to explore the effects of many procedural variables on the results obtained. These experiments will not be discussed in detail, but those considered most important will be mentioned briefly.

Standardization of Specimen Exposure

Significant variations in experimental results were found to occur depending on the way in which the specimen was backed. This was caused by the flow of smoke through the specimen and its escape from the rear surface. Since the method was expected to be used principally for in-

terior finishes within buildings, it was considered desirable to reduce, so far as possible, the release of smoke from the rear of the specimen. This was accomplished by the use of an aluminum foil wrapper and an asbestos board backing as described in the Appendix.

Maintaining a constant specimen irradiance level, the rate of smoke production was found to depend upon the spacing between the front face of the furnace and the specimen. The reason for this has not been clearly identified, but appears to be associated with adequate space for free convection of air past the specimen during pyrolysis. The spacing selected for standardizing the test procedure was $1\frac{1}{2}$ in.

The volume of the smoke cabinet was chosen to provide adequate air for complete combustion of the specimen. The volume selected provides

TABLE 1—Results of replicate tests on hardboard, nonflaming exposure.

Test	Maximum Smoke, D_m	Maximum Rate, ^a $R_m, \text{ min}^{-1}$	Time to $D_s = 16, \text{ min}$
1.....	556	68	5.10
2.....	618	52	5.50
3.....	678	50	5.29
4.....	645	46	5.34
5.....	595	49	5.54
6.....	532	42	6.65
7.....	506	46	5.94
8.....	579	54	6.14
9.....	618	65	5.70
10.....	507	51	6.51
Mean.....	583	52	5.77
Standard deviation.....	58	8.3	0.53
Coefficient of variation.....	10%	16%	9.2%

^a R_m is the maximum optical density increase per min, based on a 2-min time period.

an air-fuel ratio, on a weight basis, of over 20:1 based on the combustion of a $\frac{1}{4}$ -in. thick hardboard specimen of unity specific gravity. This is about four times the air requirement for complete oxidation of the fuel. Measurements were made of CO, CO₂, and O₂ following both flaming and smoldering combustion of specimens in the cabinet. Typical results for smoldering and open-flaming combustion, respectively, of hardboard showed: O₂ content 19 and 17 per cent, CO content 0.4 and 0.5 per cent, and CO₂ content 0.45 and 2.5 per cent. Although in no case was the specimen completely consumed, it appeared that extinguishment of open flaming during such tests resulted primarily from fuel depletion at the burning layer and thermal shielding by char formation rather than lack of available oxygen. Further studies to definitely establish this point appear desirable before the results are applied to situations involving considerably higher ratios of volume to exposed surface area.

A few measurements confirmed the fact that significant variations in smoke production were caused by changes in moisture content of the specimen. For the sake of standardizing experimental conditions, it was decided to condition dried specimens to equilibrium with air at 73 F and 50 per cent relative humidity.

Initial experiments with ignited specimens were performed with short duration exposure ($\frac{1}{4}$ to 2 min) to the pilot flame. Considerable variability in the time of cessation of flaming of the specimens was noted, resulting in large differences in smoke production. It was decided, therefore, that the pilot flame should be applied continuously during the exposure period for specimens tested in the flaming combustion condition.

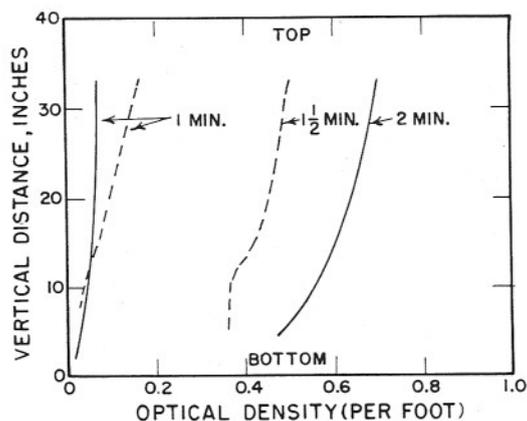


FIG. 3—Vertical distribution of smoke, fiberboard, nonflaming—polystyrene, flaming.

Test reproducibility was investigated by performing replicate non-flaming tests on a selected hardboard material over a period of four months. The test results are summarized in Table 1 and indicate that even very high optical density values can be reproduced with reasonable precision.

Spectral Response of Photometer

Experiments were performed to determine the degree to which smoke measurements would be changed by variations in the spectral range of the photometer. These were performed using the same type of incandescent tungsten light source and with phototubes of three spectral sensitivity ranges: vacuum phototubes with S-1 and S-4 spectral response, and a barrier-layer photocell corrected to approximate the average human eye. For an incandescent lamp operating at a color temperature of 2870 K, the wavelengths corresponding to the peak responses were at approximately 8300, 5100, and 5800 Å, respectively. Within this range of

variation, only very slight changes in smoke measurements were observed. However, for purposes of standardization, the 1P39 vacuum phototube having an S-4 surface and low-loss base was used. Care was taken to select a tube with a very low dark current.

Smoke Stratification

A few measurements were made to evaluate the magnitude of smoke stratification. This was accomplished by arranging a horizontal smoke photometer assembly so that it could be slowly raised or lowered inside

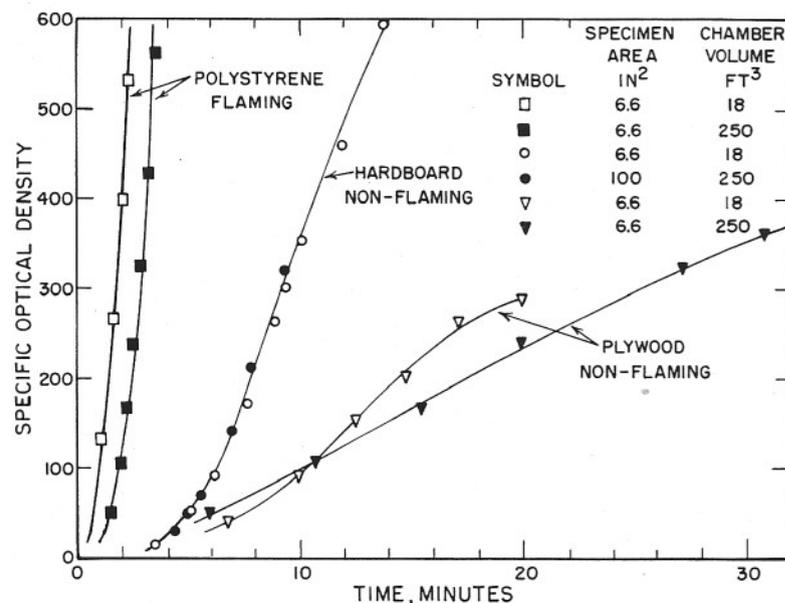


FIG. 4—Effect of specimen area and chamber volume on smoke buildup.

the smoke chamber and light transmittance readings were taken during two tests. As shown in Fig. 3, stratification was quite significant during the first few minutes of test. Although not shown, greater mixing and a close approach to uniform smoke distribution was noted as the smoke quantity increased.

Scattering Effects

Although the photometer optics used were selected to provide freedom from off-axis illumination, it was considered possible that errors in smoke measurement might still be present due to scattering from smoke surrounding the direct beam path. This was examined in two ways: (a) by employing a beam-limiting aperture which permitted only the direct

photometer beam to pass to the detection unit, and (b) by employing a shutter of such size as to interrupt only the direct photometer beam. These tests were performed with the box filled with smoke produced from smoldering cellulosic material. In both cases, the decrease in optical density, attributable to scattered light, was less than 1 per cent.

Size and Volume Effects

Early work had verified the general validity of reporting smoke accumulation in terms of optical density. It now appeared likely that the specific optical density of smoke produced from specimens of different sizes, and in boxes of differing volumes, should show good agreement as a function of time until smoke accumulation stops or photometer dark current limits measurement. As shown in Fig. 4, there is fair agreement in the specific optical density curves even for a volume ratio of almost 14 and, in one case, a surface area ratio of 15. These results, although limited in number, tend to confirm the validity of the measurement

TABLE 2—Smoke measurements on clear spruce of various thickness.

Thickness, in.	Flaming Exposure			Nonflaming Exposure		
	Maximum Smoke, D_m	Maximum Rate, R_m , min^{-1}	Time to $D_s = 16$, min	Maximum Smoke, D_m	Maximum Rate, R_m , min^{-1}	Time to $D_s = 16$, min
1/8.....	45	6	5.5	147	21	5.1
1/4.....	115	18	4.2	275	49	4.3
1/2.....	145	19	4.3	378	39	4.6
3/4.....	310	14	4.8	421	36	4.8

method used and the usefulness of the concept of specific optical density as a means for quantitative measurement of smoke under specific burning conditions.

When specimens of 1/4-in.-thick hardboard of various widths (1/4, 1/2, 1, and 2 1/16 in.) were tested under nonflaming exposure, a fairly good agreement was obtained in the specific optical density curves for the 1 in. and full-size specimens. However, the D_s curves for specimens of smaller width, 1/4 in. and 1/2 in., were noticeably different, due to thermal edge effects.

Smoke is produced by thermal degradation or burning and is generally considered to result from reactions at the specimen surface. As heat penetrates into the specimen, products of combustion, including condensable vapors, also originate from various depths, the quantity depending mainly upon diffusion, ablation, and char formation effects. To explore this effect, measurements were made of the smoke produced by various thicknesses of matched clear spruce specimens, and the results are shown in Table 2. For this range of thickness, smoke accumulated at a fairly constant rate (slightly faster for the thinner sections). The

maximum smoke produced increased with thickness, but not in proportion to thickness above 1/4 in.

In some tests, the maximum quantity of smoke may yield optical densities within the chamber which may exceed the measurement capability of the photometric system. The existence of such limitation may be verified by noting the extent to which an approach has been made to the phototube "dark current," which is the reading obtained when the light source is totally shielded or turned off. By mixing the smoke into an ad-

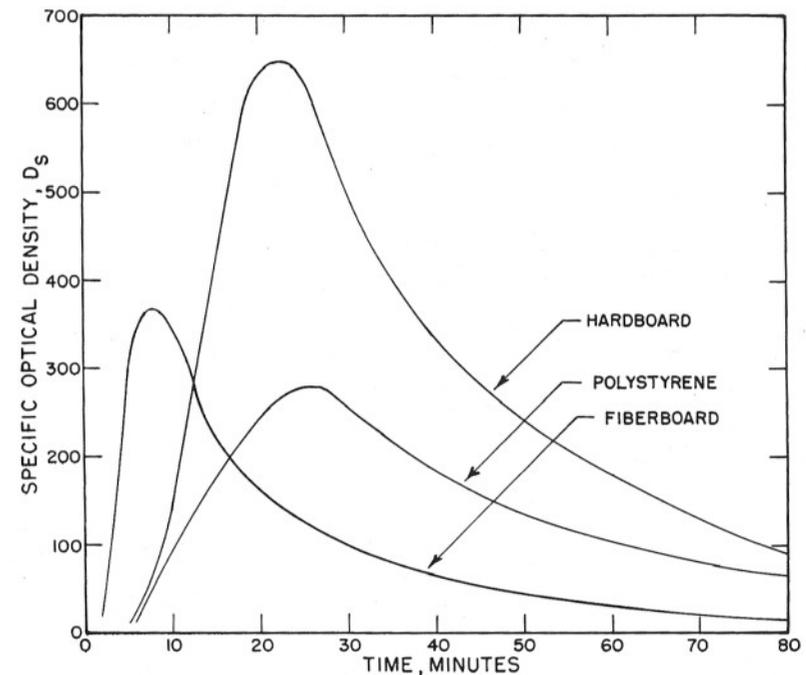


FIG. 5—Buildup and disappearance of smoke, nonflaming exposure.

joining chamber of sufficiently large volume, the change in optical density resulting from the dilution (which is inversely proportional to the volume increase) will be measurable by the photometer in the smoke chamber. The procedure for accomplishing this measurement is described in the Appendix, and permits determination of the peak specific optical density (maximum smoke accumulated) on a large majority of heavy smoke-producing materials.

A smoke aerosol within a confined space gradually disappears due to coagulation, to settling, and to condensation on the chamber walls. The rate of disappearance depends upon the relative motion of the particles

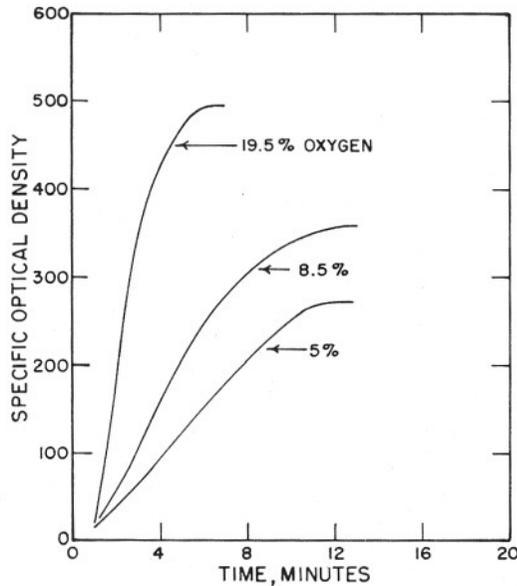


FIG. 6—Smoke buildup in reduced oxygen atmosphere, fiberboard, nonflaming exposure.

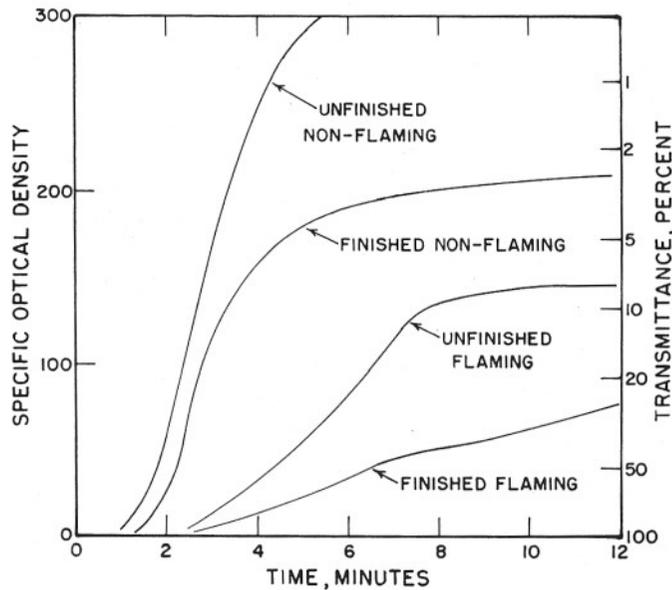


FIG. 7—Smoke buildup for a typical cellulose fiberboard. Effects of (a) exposure and (b) paint coating.

as well as upon concentration and particle size. Typical curves for smoke buildup and disappearance are given in Fig. 5, from which it may be noted that the rate of disappearance is greater for higher concentrations.

Influence of Ambient Atmosphere

It appeared likely that changes in the oxygen concentration of the ambient atmosphere of the specimen would influence smoke production significantly. Accordingly, tests were performed with fiberboard specimens pyrolyzed in atmospheres diluted with nitrogen and the results are

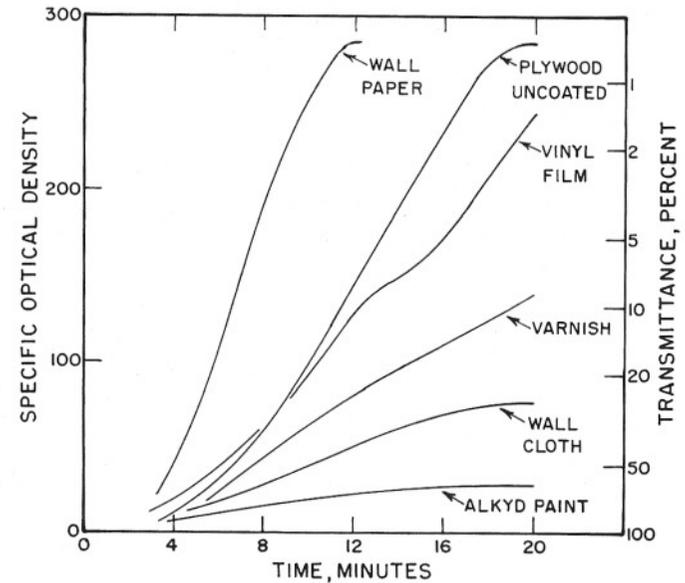


FIG. 8—Effect of surface coatings on smoke buildup for plywood, nonflaming exposure.

shown in Fig. 6. It is evident that when smoke is produced from fiberboard by nonflaming pyrolysis, the quantity generated as measured by photometric means is an increasing function of the oxygen concentration of the ambient atmosphere. Similar studies for flaming combustion were not made.

Smoke Production from Typical Materials

In Fig. 7 are shown smoke production curves for the finished (front) and unfinished (rear) surfaces of a typical cellulose fiberboard. These tests were performed under both flaming and nonflaming exposure conditions, and illustrate the wide range of smoke levels possible from a

TABLE 3—Summary of test results.^a

Material	Thickness, Nominal or Actual, in.	Density		Smoke Chamber								Smoke Deposit		Smoke Density Rating ASTM Method E 84
				Flaming Exposure				Nonflaming Exposure				ASTM Method E 162		
		lb/ft ³	lb/ft ²	Max. Smoke, D _m	Max. Rate R _m , min ⁻¹	Time to D _s = 16, min	Optical ^b Density Ratio	Max. Smoke, D _m	Max. Rate, R _m , min ⁻¹	Time to D _s = 16, min	Optical ^b Density Ratio	Weight, mg	OD	
<i>Wall Coverings:</i>														
Asbestos-Cement board	0.18	125	...	0	0	NR ^c	...	0	0	NR ^c	...	0.0	...	0
Hardboard	.25	56	...	67	15	9.4	4.3	595	49	5.5	3.7	0.7	...	...
Gypsum board	.375	51	...	13	2	NR ^c	1.4	37	4	8.7	3.7	0.1	...	0 to 45
Mineral-base acoustic tile	.75	23	...	20	2	9.7	2.3	21	2	5.4	2.6	0.0	...	0 to 10
Fiberboard, finished	.50	16	...	80	9	4.2	...	208	63	1.8	2.7	0.2	1.2	...
Fiberboard, unfinished	.50	16	...	146	27	3.2	...	376	92	1.7	3.3	0.2	1.2	...
Spruce	.75	21	...	310	14	4.8	...	421	36	4.8	...	...	...	...
Plywood, exterior, Douglas fir	.25	33	...	112	15	4.7	4.6	287	23	4.6	4.1	0.8	...	...
Plywood + latex paint	0.25 + 0.004	34	...	108	10	5.6	4.9	258	15	3.8	4.8	1.3	...	...
+ alkyd paint	+ 0.003	33	...	84	6	4.8	2.7	236	40	4.6	...	0.4	...	...
+ varnish	+ 0.004	33	...	71	11	4.3	4.0	262	44	5.0	4.6	0.6	...	...
+ wallpaper, 5 coats	+ 0.035	34	...	132	15	4.4	5.0	285	37	3.3	4.6	0.6	...	...
+ wall cloth	+ 0.011	34	...	56	6	4.7	3.4	79	5	5.1	4.3	1.9	...	...
+ enameled wall covering	+ 0.055	40	...	79	6	4.3	4.0	184	17	4.1	4.8	6.0	...	...
+ vinyl film	+ 0.004	39	...	75	4	1.7	4.5	268	15	3.7	4.3	2.4	...	...
+ vinyl counter top	+ 0.070	46	...	355	89	0.7	3.8	355	24	2.7	3.0	7.7	...	...
Plywood, prefinished A	0.25	35	...	27	3	9.3	...	336	24	2.6	3.2	0.0	0.80	87
Plywood, prefinished B	0.25	34	...	138	25	3.9	...	345	26	1.8	3.4	0.1	0.79	107
Plywood, regular base	0.25	38	...	64	9	6.5	...	295	22	3.1	3.4	0.3	>5	95
Plywood, vinyl-base	0.25	34	...	141	18	4.2	...	328	21	3.9	3.4	0.7	>5	72
Plywood, walnut veneer, uncoated	0.75	35	...	89	9	3.7	...	160	9	3.3	5.1	0.1	0.33	11
Plywood, walnut veneer, coated	0.75	33	...	209	62	0.8	...	210	50	1.4	5.0	0.2	0.45	21
Hardboard, cherry A	0.25	56	...	73	16	10.3	...	465	60	6.7	3.7	0.8	>5	184
Hardboard, cherry B	0.25	56	...	36	2	9.6	...	415	50	4.5	5.0	0.6	>5	152
Hardboard, cherry C	0.25	63	...	81	12	7.0	...	480	61	7.7	3.4	1.3	>5	223
Hardboard, oak	0.25	56	...	155	18	3.9	...	350	34	4.8	4.1	1.4	>5	160

<i>Floor Coverings:</i>														
Red oak	0.78	41	...	117	17	7.8	...	660	19	7.1	4.5	0.3	...	100
Floor tile	0.094	93	...	218	54	0.8	...	304	17	2.4	4.0	0.2	1.49	82
Wool rug	0.3	...	0.42	178	47	2.0	4.7	215	29	1.1	...	...	...	...
Acrilan rug	0.3	...	0.50	159	29	0.6	4.1	319	49	1.5	2.5	...	...	...
Nylon rug	0.3	...	0.35	269	105	1.8	4.4	320	45	2.8	3.6	...	...	...
Polypropylene rug	0.18	...	0.25	110	50	1.7	4.8	456	60	2.3	4.4	0.1	...	...
<i>Polymers:</i>														
Acrylic	0.219	75	...	107	23	2.6	4.8	156	60	9.2	5.8	...	...	...
Glass-reinforced polyester	0.156	80	...	395	170	1.2	...	350	35	4.9	...	...	...	...
Glass-reinforced polyester, flame-retardant	0.156	87	...	618	90	0.9	4.3	361	84	2.7	...	...	...	...
Cellulose acetate butyrate	0.25	75	...	49	12	5.0	3.7	434	45	2.7	...	...	...	...
Polystyrene	0.25	66	...	>660	243	1.3	...	372	24	7.3	3.7	...	...	...
Polycarbonate	0.125	75	...	174	43	2.1	4.7	12	1	NR ^c	...	...	...	...
Polyvinyl chloride	0.25	88	...	>660	134	0.8	4.2	300	12	3.9	4.6	...	...	...
Chlorinated polyethylene foam	1.0	2	...	32	8	0.8	3.8	22	2	5.3	3.1	...	...	...
Acrylonitrile-butadiene-styrene	0.046	65	...	>660	400	0.6	...	71	4	4.8	...	...	...	...
Polyurethane foam	0.5	2	...	20	3	0.5	2.9	156	16	0.5	4.9	...	...	...
Natural rubber foam	0.75	6	...	>660	400	0.1	...	236	42	0.9	...	...	...	...
<i>Fabrics:</i>														
Wool	0.024	...	0.076	16	1	7.3	1.6	60	20	1.2	3.8	...	...	...
Modified acrylic	0.024	...	0.064	79	21	0.5	4.0	54	18	0.5	4.0	...	...	...
Vinyl	0.026	...	0.16	198	76	0.3	4.9	261	33	1.4	...	...	...	...

^a Results apply to listed thickness.

^b Ratio of optical densities before and after dilution (volume ratio = 1:4). Values corrected for smoke deposit on window and zero drift, where appropriate.

^c Not reached.

single interior wallboard, the front surface of which is prefinished with a factory-applied paint coat.

Figure 8 further illustrates the effect of surface coatings in modifying the smoke production of an exterior grade plywood base material, 1/4-in. thick. It is evident that thin surface coatings (in the thickness range 0.003 to 0.035 in.) can have a very large effect on the maximum smoke generated and on its rate of release.

Table 3 summarizes flaming and smoldering test results for a wide variety of typical interior finish materials in terms of the maximum smoke accumulation, D_m , the maximum rate of smoke accumulation (averaged

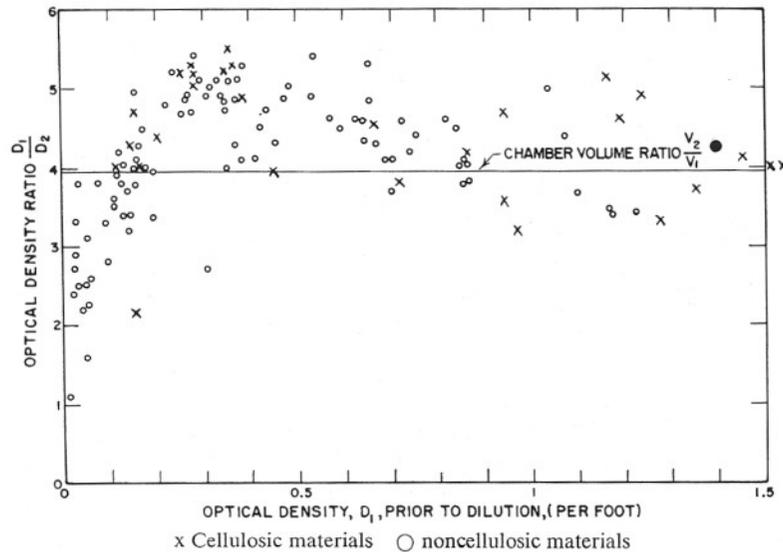


FIG. 9—Optical density ratio in smoke dilution tests.

over a 2-min time period), R_m , and the time period to reach a specific optical density of 16. For tests in which the maximum smoke accumulation in the test chamber approached the "dark current" limitation of the phototube, the smoke was diluted by mixing into an adjoining chamber of 54-ft³ volume. Care was taken to ensure that the peak smoke level had been achieved prior to making a reading. In other tests, the dilution process was also accomplished, and this permitted application of the inverse relation between concentration and volume, and, in fact, provided a general verification of it as shown in Fig. 9. Here, the ratio of the optical density for the initial condition (test chamber volume only = 18 ft³) to the optical density for the final condition (total volume of both chambers = 72 ft³) is plotted as a function of the optical density of the smoke prior to dilution. The condensation and settling of smoke

during dilution was partially accounted for as suggested in the Appendix. It might be noted that deposition, condensation, or other loss of suspended smoke particles upon circulation into the large cooler chamber, would result in high values for the optical density ratio. Values of the optical density ratio considerably below 4 were noted for smokes of very low optical density, 0.15 (per foot) and less. Thus, the general validity of the logarithmic extinction relation, Eq 2, appears reasonably well established for a wide range of smoke types and levels.

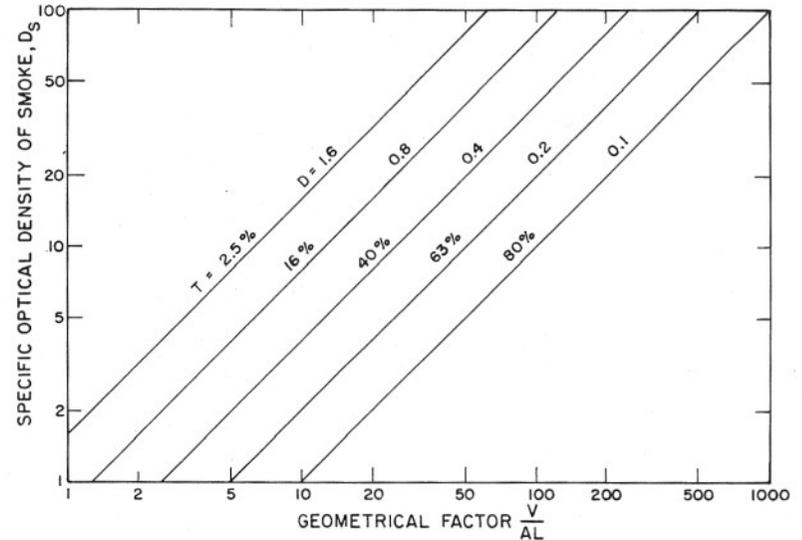


FIG. 10—Specific optical density versus geometrical factor for five selected light transmittance values.

Discussion

For many of the materials tested, a very uniform rate of smoke buildup was obtained. This is evidenced by the almost linear slopes of specific optical density versus time curves as seen in Figs. 4 to 8. The smoke-generating process often terminated fairly abruptly, with a rapid approach to the final reading, representing maximum accumulated smoke. During and after a typical test, smoke disappeared (due to settling and coagulation), the rate being greater at higher concentrations, see Fig. 5. No adjustments were made to the measurements for these losses, since it may be presumed that a similar, though generally not identical, process of smoke buildup (generation less disappearance) will occur in a room or chamber of other size.

Where visibility through smoke is of interest, it is not necessary to convert optical measurements into concentration units, either by weight

or number of particles. On the contrary, the decrease in light intensity in terms of optical density is the precise type of attenuation coefficient desired. As previously mentioned, the terms maximum smoke quantity, and smoke density should be understood to refer to optical density levels, and not to mass or number concentration.

With respect to defining the hazard when a person is trapped in a room where smoke is being generated or accumulated, three aspects were considered important:

1. *Maximum Smoke Accumulation* represents the maximum accumulated quantity from a given area of material under the prescribed exposure (maximum specific optical density).

2. *Maximum Smoke Accumulation Rate* represents how quickly the smoke level increased as averaged over a 2-min period.

3. *Time to Reach a Prescribed Smoke Density* represents the time period prior to attaining a critical smoke level.

The critical optical density through which an exit sign may still be visible can vary over a wide range depending on characteristics of the light source, the general illumination level, and the degree of irritation to, and dark adaptation of the observer's eyes. Assuming a uniformly distributed smoke, the relation between D_s and the geometrical factor V/AL is shown in Fig. 10 for five values of light transmittance ranging from 80 to 2.5 per cent, corresponding to optical densities of 0.1 and 1.6, respectively. For a selected critical transmittance (or optical density), the limiting value of specific optical density D_s can be determined for the viewing distance L , the exposed surface area of the specimen A and the volume of the chamber V . For comparative purposes, it was assumed that a light transmittance of 16 per cent over the viewing distance would be critical. The limiting value of D_s for a 12.5 by 20 by 8-ft room, a viewing distance of 10 ft, and a surface area of 10 ft² would be 16. The times to reach this arbitrary level of smoke for the materials tested have been included in Table 3 together with maximum smoke accumulation and maximum smoke accumulation rate. It may be noted that the observed times to reach this level ranged from as little as 0.1 min to over 10 min.

For a given exposure on a building finish material, measurement of the maximum smoke accumulation, the maximum smoke accumulation rate, and the time to reach a prescribed smoke density, may be obtained from a single test, and it is tempting to devise a formula for combining these properties into a single classification index. However, further study seems desirable in order to estimate the relative weighting of these factors in terms of the smoke accumulations and movements resulting from natural or forced ventilation, and typical openings in rooms and buildings.

For selected cellulosic, plastic and composite materials, the total

smoke produced under both flaming and nonflaming exposure was compared with the gravimetric smoke deposit measurements from a standardized flame-spread test (ASTM Method E 162 - 67) and with the smoke density rating from the standard "tunnel" test (ASTM Method E 84 - 67). The data for matched specimens are listed in Table 3.

For a particular smoke, it is reasonable to expect a correlation between the optical density of the smoke aerosol and gravimetric smoke concentration (mass per unit volume); such a relation has been demonstrated, for example, for smoke generated by burning oakwood sawdust at ele-

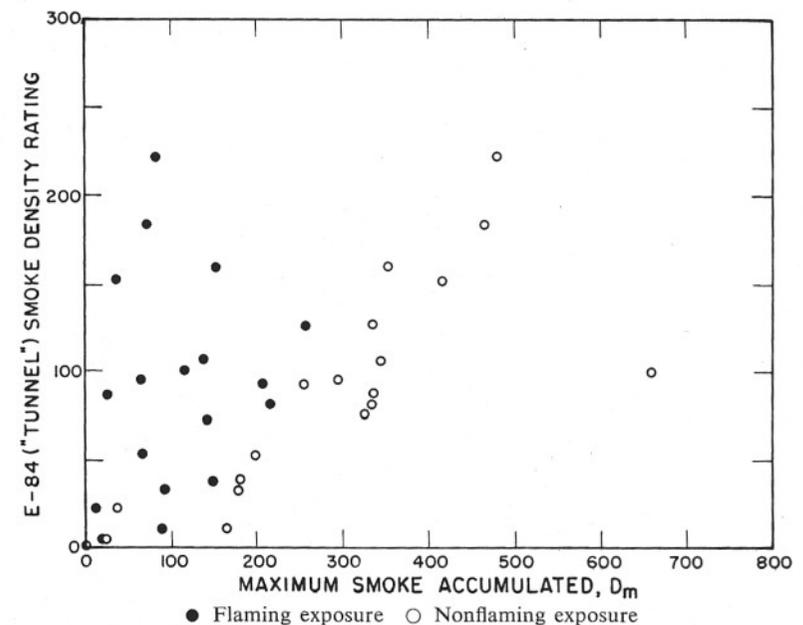


FIG. 11—Comparison of smoke data by two test methods

vated temperatures [2] and for smoke generated in the burning of coal [6]. However, using materials of widely varying chemical composition and physical structure, and under both flaming and pyrolytic exposure, the type of smoke generated would be expected to range from organic liquid droplets of small size ($\sim 0.2 \mu$) to solid carbon particles of large size ($> 1 \mu$) and irregular shape. For this range of smoke types and densities, it is not reasonable to expect any simple or general correlation between optical density of the smoke aerosol and weight of the deposited smoke layer.

Where light transmission measurements are made directly on the smoke aerosol, as in Method E 84, a better correlation could be expected. Such a comparison is shown in Fig. 11, using both flaming and

nonflaming smoke chamber test results. While a fair correlation was obtained for the smoldering tests, no satisfactory correlation was noted for the flaming tests. For these materials, the maximum smoke accumulation values for the flaming tests were always less than those for the smoldering tests, although the differences were considerably less for the noncellulosic materials.

However, since the "smoke density rating" from the "tunnel" test is based on the integrated light absorptance versus time relation (rather than optical density versus time), the results, especially at high smoke levels, are not strictly comparable. In any event, lack of close correlation between the smoke chamber test and either of the preceding flame spread tests, results primarily from the fact that the smoke produced during a flame spread test is invariably generated under a complex combination of strong and weak flaming, and high and low temperature pyrolysis. The controlled smoke chamber test is designed to permit the separation of smoke generated by flaming versus nonflaming exposure, and to evaluate more readily the effects of a wide variety of test conditions for both the specimen (for example, surface coatings, treatments, moisture content) and its surroundings (for example, ventilation, oxygen concentration). That such evaluation is necessary is apparent from the widely different results obtained under flaming versus smoldering exposure of cellulosic and plastic materials.

Ideally, for a selected exposure in the test chamber, a single test permits extrapolation to surface areas and to chamber volumes of other size. However, since the rate of smoke disappearance due to settling and coagulation depends upon mass concentration, the results will not always be identical in chambers of different size (different values of V/A), and this is a limiting factor particularly in using the measured value of D_m as the true total smoke with confidence. Thermal edge effects must also be considered in any extension to other scale sizes. In addition, further studies may be necessary to establish the extent to which flaming combustion in the smoke chamber can be taken to represent burning under excess air conditions typical of very large volumes.

Finally, it should be clearly noted that conditions in the smoke test chamber are obviously not identical to the situation involving the human eye, seeking a light source in a smoke-filled room. In an actual situation, the light source is not (normally) concentrated in a parallel vertical beam, and the human eye has a much wider viewing angle and a slightly different spectral response from the lens/aperture/phototube combination used. In addition, certain important properties related to human vision—contrast level, response time, and adaptation to levels of illumination—have not been considered in this investigation. Additional studies relating to human vision through smokes are obviously desirable.

Summary

Based on a study of possible smoke-measuring methods, a laboratory test has been developed for the photometric measurement of smoke from burning materials. The test utilizes a closed chamber of 18 ft³ volume containing an electrically heated furnace which provides an irradiance of 2.5 w/cm² (2.2 Btu/sec ft²) on the surface of a nominal 3-in. square specimen. Features of the smoke chamber include the following: (a) each specimen is exposed to the same controlled radiant exposure, and generates smoke primarily from the exposed surface, (b) the results apply to either flaming or smoldering conditions, (c) the photometer light path is vertical to reduce measurement errors resulting from smoke stratification, and (d) the chamber is sufficiently large to reduce effects resulting from premature consumption of air. Details of the test equipment are included to permit duplication by others.

Results are presented which illustrate the wide variation in smoke production to be expected (a) between materials, and (b) for the same material under different thermal exposure and reduced oxygen concentration. The effects of stratification, scattering, and photometer spectral response on the measurement were briefly studied, and typical results were obtained to illustrate the relationship between chamber volume, optical path length, and exposed surface area of specimen.

The method assumes the applicability of Bouguer's law to the attenuation of light by smoke, and smoke quantity is therefore reported in terms of optical density rather than light absorptance. Optical density is the single measurement most characteristic of a "quantity of smoke" with regard to visual obscuration. To take into account the optical path length L , the volume of the chamber V , and the surface area of material producing smoke A , a specific optical density is defined as $D_s = V/LA [\log_{10}(100/T)]$, where T is the per cent light transmittance. Thus, for a selected exposure in the test chamber, and within the limitations discussed, a single test permits rough extrapolation to surface areas and to chamber volumes of other size.

Experiments have been performed on a variety of building finish materials under both flaming and nonflaming (smoldering) conditions, and the results are reported in terms of: (a) total maximum smoke accumulation, (b) maximum rate of smoke accumulation over a 2-min. period, and (c) the time period to reach a "critical" specific optical density of 16 under the test condition.

This study was concerned with the limited problem of measuring the optical density of smoke as it relates to the obscuration of human vision in building fires. No detailed attempt was made to measure and analyze the fire-generated toxic combustion products which are likely to be the major and direct danger to life.

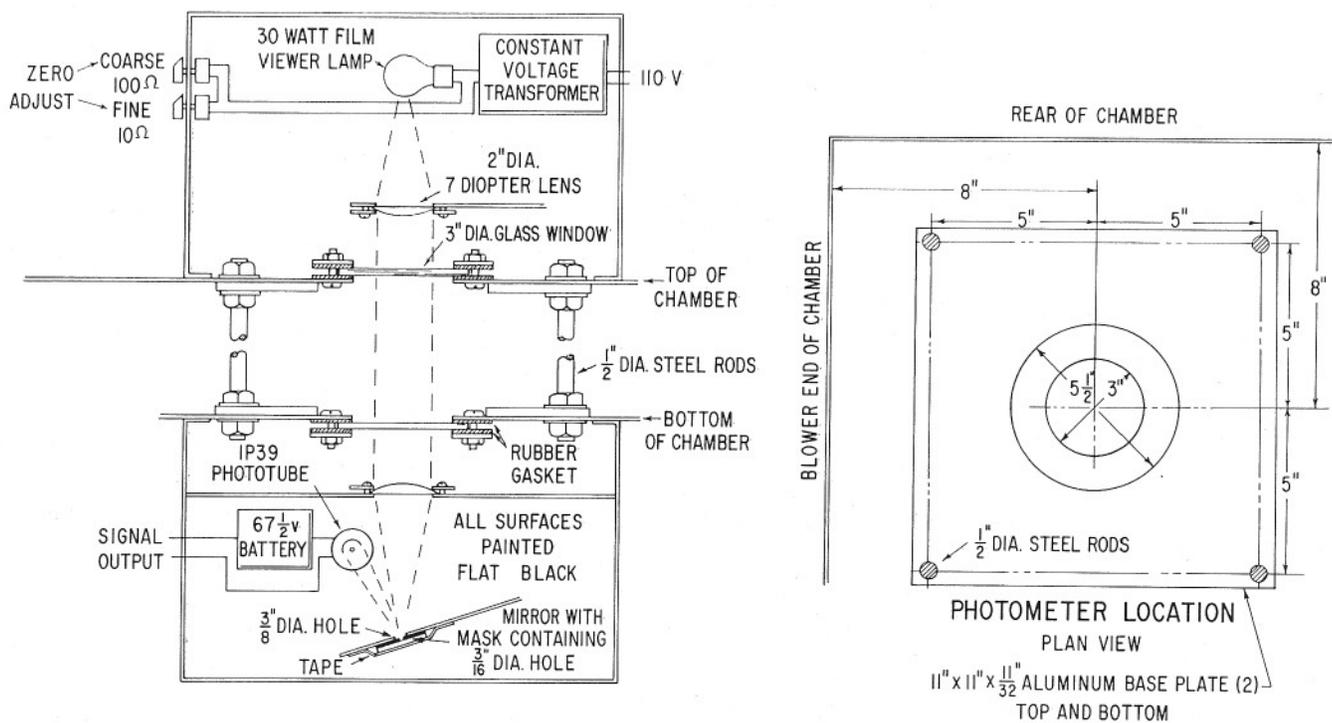


FIG. 15—Photometer details.

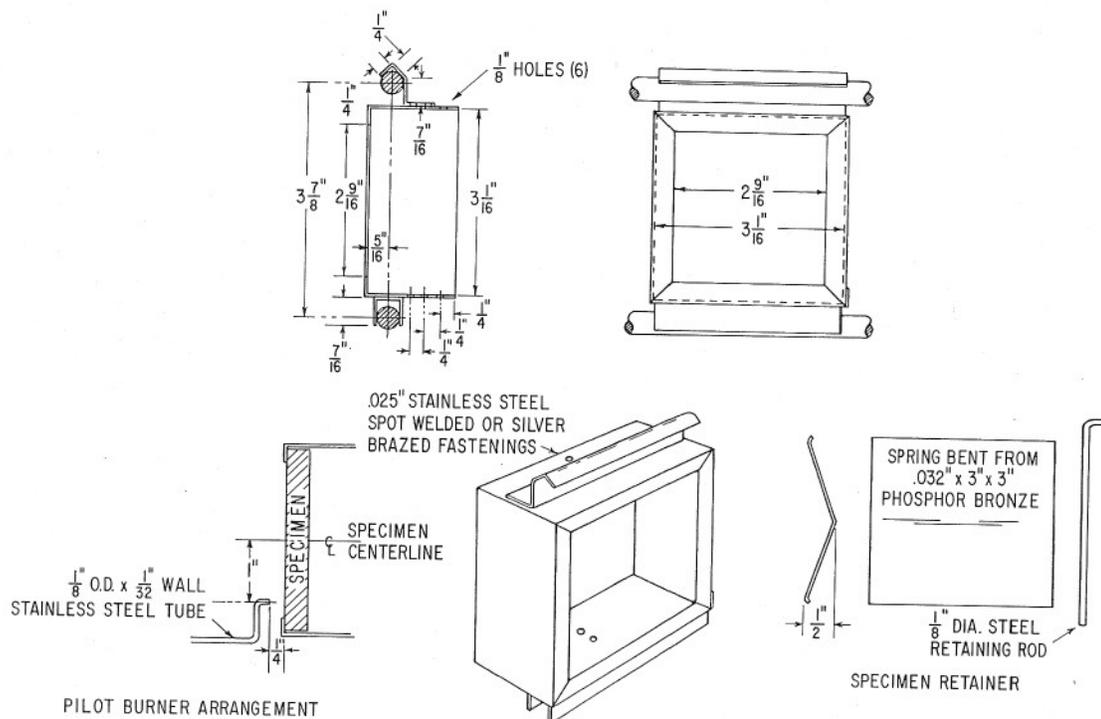


FIG. 16—Details of specimen holder and pilot burner.

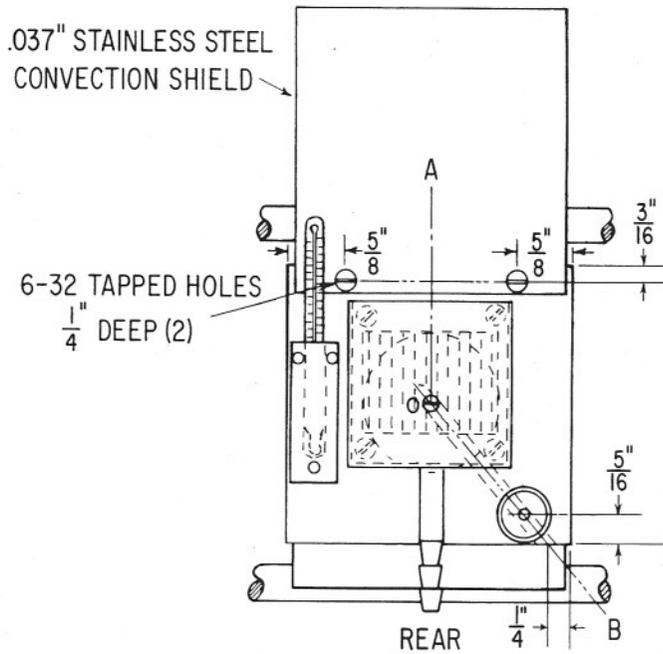
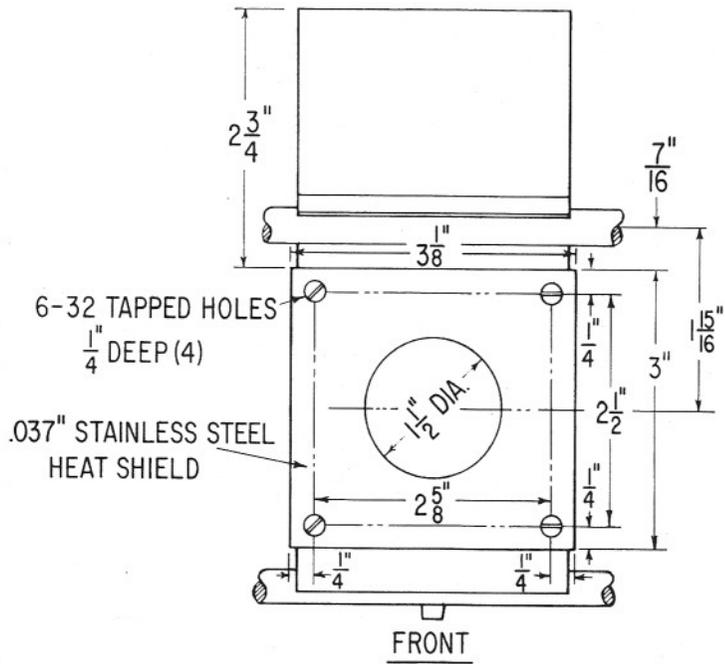


FIG. 17—Radiometer details.

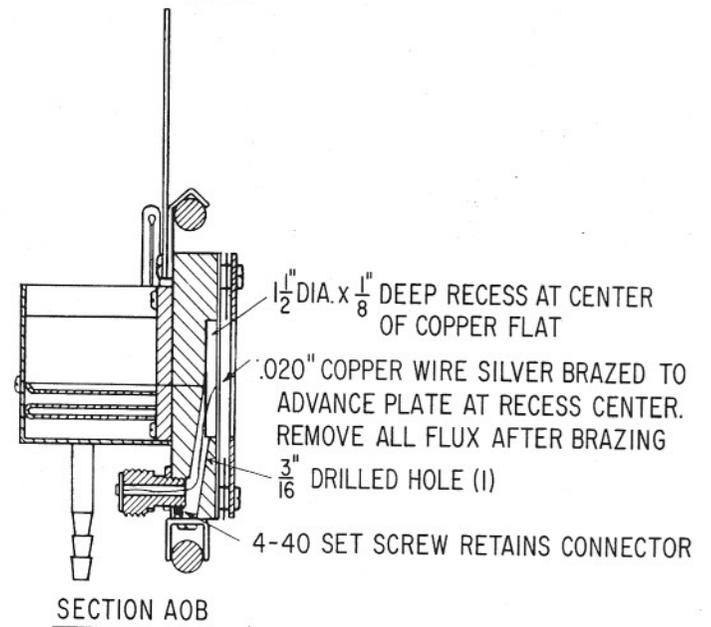
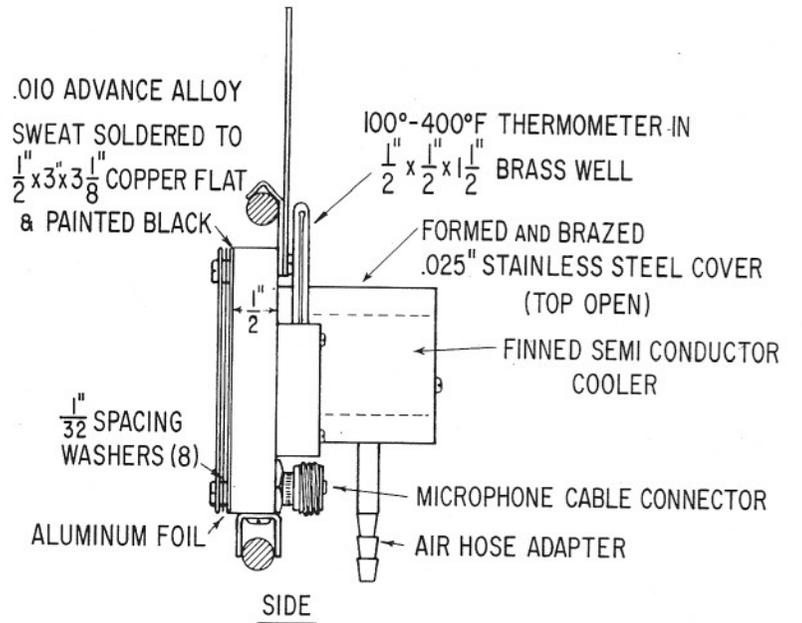


FIG. 17—Continued

to transmittance values of 0.01 per cent of the incident light. At the lowest levels of light transmittance a correction becomes necessary for the dark current of the vacuum phototube, since this represents zero light transmittance.

The photometer system was checked occasionally and any accumulated smoke and dust deposits on the lenses, mirror, and phototube removed. The phototube should be inspected, and replaced if necessary, when there is an indication of a shift in dark current between tests or of excessive zero shift during test. A check of photometer linearity was readily made using either wire screens of known open area, or calibrated neutral density gelatin filters.

Specimen Holder

The 3 by 3-in. specimen was placed in a holder (see Fig. 16), designed for rapid positioning and for maintaining, by means of the furnace support, the specimen surface $1\frac{1}{2}$ in. in front of and parallel to the furnace opening. The furnace support also served as a positioning mount for a radiometer, Fig. 17, which established the prescribed irradiance level at the specimen surface just prior to its exposure.

The stainless steel specimen holder was fabricated by bending and brazing (or spot welding) to give a $2\frac{1}{16}$ by $2\frac{1}{16}$ in. exposed area. The back, edges, and front nonexposed surfaces of the specimen were covered with a single sheet of aluminum foil (thickness 0.001 in. or greater) to prevent smoke passage at any but the exposed specimen surface. Behind the specimen was placed a 3 by 3 by $\frac{1}{2}$ -in.-thick sheet of asbestos millboard (conforming to Federal Specification HH-M-351). A phosphor bronze spring and a steel pin were used to maintain a snug assembly.

When the proper spacing ($9\frac{3}{8}$ -in.) was maintained between the spacing stops of the furnace mount (Fig. 14), the loaded specimen could be quickly and accurately positioned by placing it on the support bars and sliding the radiometer or another holder to the limit of its travel.

Radiometer

The desired irradiance level (2.5 w/cm^2) at the specimen surface was measured by means of a circular foil radiometer of the type described by Gardon [12]. It is of simple construction, has a sufficiently rapid time-constant, and produces a millivolt output which is nearly proportional to the irradiance level. The use of a reflective heat shield, with aperture, on the front of the radiometer and a finned convector supplied with compressed air on the rear, help to maintain the radiometer body at a more constant temperature and to minimize effects due to variable convective and radiative losses. The body temperature was monitored by means of a thermometer placed in a well. (After brazing the copper wire to the center of the receiving plate, it is necessary to remove all flux.) The receiving surface was spray-coated with an infrared-absorbing black paint containing a silicone vehicle.* The absorptivity of the paint to infrared energy is approximately 0.93 for a film thickness of 1 mil.

Details of the radiometer construction are shown in Fig. 17. The air-cooled radiometer was calibrated by placing it at suitable distances from a radiant energy source and measuring its electrical output as a function of the irradiance level. The latter was determined calorimetrically by measuring the

* Type 8X906 Flat Black Paint, Midland Industrial Finishes Co., Inc., Waukegan, Ill.

rate of temperature rise of a copper disk of known weight, area, specific heat, and absorptivity.

Test Procedure

All specimens, prepared in the 3 by 3-in. size, were predried for 24 hr at 140 F and then conditioned to equilibrium with an ambient of 73 ± 5 F and 50 ± 5 per cent relative humidity. The specimen was representative of the material or composite as intended for use and was prepared by the intended application procedures. Where the intended application of a finish material was not specified, or could be any of several, the following procedures were established for preparing specimens for test:

(a) Surface finish materials, in either liquid or sheet form, including those intended to control and reduce the smoke produced by supporting base materials, are tested in the assembly or assemblies proposed for use. In the absence of specific information, the finish material is applied to the smooth surface of $\frac{1}{4}$ -in.-thick tempered hardboard sheet using recommended (or practical) application techniques and spreading rates.

(b) Liquid films, such as sealers and adhesives, and other materials intended for application to noncombustible base materials intended for application to noncombustible base materials or being tested for their inherent smoke contribution are applied to the smooth surface of $\frac{1}{4}$ -in. thick asbestos cement board of 120 lb/ft^2 density, using recommended spreading rates.

(c) Materials intended for air-backed applications, such as suspended ceilings or hanging drapes, are mounted in a specimen holder providing a $\frac{1}{8}$ -in. air space behind the specimen. This is accomplished by use of an asbestos board back fitted with $\frac{1}{8}$ -in.-thick, $\frac{1}{4}$ -in.-wide asbestos strips at the borders.

To perform a test, the electrically powered furnace and associated controls were turned on. The radiometer was placed in a specimen holder and positioned in front of the furnace. The compressed air supply to the radiometer convector was turned on and the flow rate (or pressure) was adjusted to correspond to the value used for calibration. The controller temperature setting was adjusted to produce a millivolt output of the radiometer corresponding to an irradiance of 2.5 w/cm^2 . The two autotransformers were adjusted to suitable voltage levels (generally between 80 and 100 v) to minimize cyclic variations in irradiance.

The photometer light source and the recording meter were turned on. Using the lamp and load resistor adjustments, the output reading was set to full scale on a convenient range (1 v or higher). The zero reading on the most sensitive range was verified by shorting the meter input.

A preconditioned specimen in a cool specimen holder was mounted, using a single sheet of aluminum foil (0.001 in. or thicker) along the back edges and unexposed periphery of the front surface of the specimen, care being taken not to puncture the foil. The specimen was backed with a sheet of $\frac{1}{2}$ -in. asbestos millboard and assembled into the holder snugly, using the spring and pin.

For nonflaming (smoldering) tests, the air supply to the radiometer was turned off and the loaded specimen holder was placed on the bar supports and moved into position at time zero by displacing the radiometer. The door was closed. Values of light transmittance versus time were recorded, making full-scale range changes (in decade steps for maximum convenience) as appropriate. Observations were made of characteristic smoking or burning patterns, the color and nature of the smoke, and so forth. At very low light

levels, the window was covered to avoid stray light effects. The test proceeded until a minimum light transmittance value was reached. The "dark current" light transmittance was recorded by switching off power to the photometer light source and setting the recorder at a suitable high sensitivity. The zero reading was verified again by shorting the meter input. The door was opened a small amount and the exhaust fan turned on to clear the chamber of smoke. The specimen was discarded and the chamber completely cleared of smoke. With the photometer light on, the final light transmittance value under clear air conditions in the chamber was recorded, making the appropriate meter range changes. The glass window was cleaned (ethyl alcohol generally satisfactory), and the meter reading was again adjusted to 100 per cent transmittance in preparation for the succeeding test.

For tests employing pilot ignition, gas was supplied to the pilot burner (see Fig. 16) at a rate of 350 Btu/hr (0.35 SCFH of 1000 Btu/ft³ natural gas, or equivalent). The horizontally oriented gas jet was ignited using an electrically powered platinum "hot wire." The lighted pilot burner was positioned to impinge on the specimen surface when the loaded specimen holder displaced the radiometer in front of the furnace. If the pilot burner was blown out during a test, it was reignited using the platinum hot wire. The test proceeded as before.

For tests in which the phototube dark current was reached, the smoke was mixed after 20 min into an adjoining large chamber (54 ft³) by means of a blower and short connecting ducts, and the transmittance of the diluted mixture was measured. When necessary, corrections were applied for smoke deposition and settling, by extrapolating the transmittance increase back to the time at which the dilution was initiated.

Test Results

The result of a smoke measurement test of a material is a curve of specific optical density versus time. For each test, the following information was noted:

- (a) Identification of the material, including data such as density, thickness, and type of base material (if used).
- (b) Test conditions, including irradiance level (2.5 w/cm²), flaming (pilot) or nonflaming (no pilot) exposure, and so forth.
- (c) Important visual observations of specimen, color, and nature of smoke, and test chamber conditions both during and after test.

The reduction in the light transmittance caused by smoke was converted to specific optical density using the relation:

$$D_s = \frac{V}{LA} \left[\log_{10} \left(\frac{100}{T} \right) \right] = 132 \log_{10} \left(\frac{100}{T} \right)$$

where T is the per cent transmittance and $L = 3$ ft, $A = 0.0456$ ft², and $V = 18$ ft³ for the standard chamber.

For each test, a record was retained of: (a) the phototube dark current (with photometer light source off and recorder set at a suitably high sensitivity), and (b) the final transmittance value (after removing specimen and clearing chamber of smoke).

To correct for light transmittance readings approaching the dark current value, the ratio between them was used as the corrected light transmittance, and the optical density then computed. No correction for smoke deposits on

windows was made except in instances where the smoke dilution measurements were made.

The important test results summarized were: (1) the peak specific optical density, (2) the maximum 2-min rate of optical density, and (3) the time to reach a specific optical density of 16.

APPENDIX 2

In preparing this paper it has seemed premature to include suggestions on the most useful way in which an overall smoke obscuration hazard index

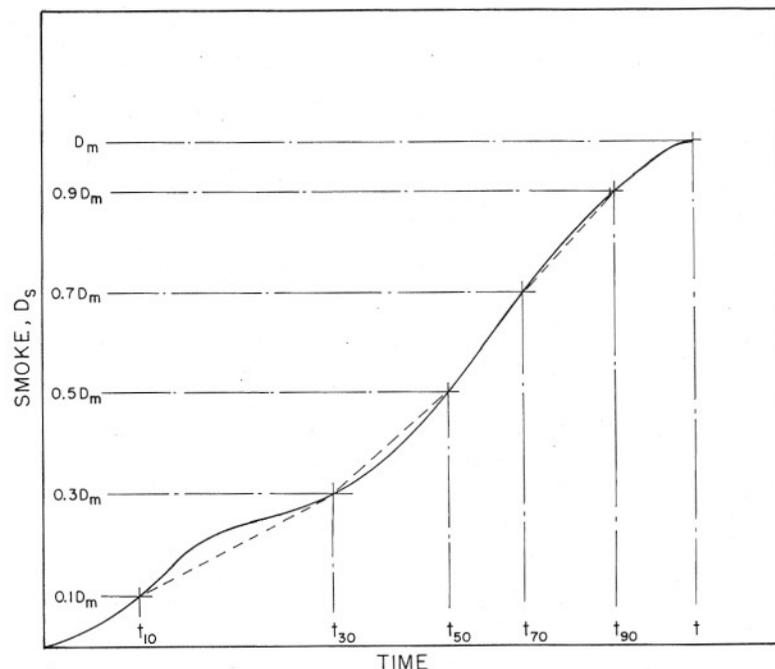


FIG. 18—Points on typical smoke accumulation curve used in developing the Smoke Obscuration Index (S.O.I.).

might be developed on the basis of the measurements reported. There are, obviously, numerous ways in which this could be done, but probably no way is uniquely appropriate for all fire situations. It might be useful, nevertheless, to indicate one such possibility.

It will be assumed that the hazard to visibility is directly related to the product of the maximum observed smoke accumulation and the observed average rate of accumulation, and, inversely, to the time to reach a critical

smoke accumulation level, corresponding to D_s of 16. These are identified by the symbols D_m , R , and t_c , respectively.

If the average accumulation rate is defined as the average of the linear rates for each of the four 20 per cent smoke intervals between the 10 and 90 per cent levels, Fig. 18, then the average accumulation rate, R , may be written as:

$$R = \frac{D_m}{20} \left(\frac{1}{t_{30} - t_{10}} + \frac{1}{t_{50} - t_{30}} + \frac{1}{t_{70} - t_{50}} + \frac{1}{t_{90} - t_{70}} \right)$$

where t_{10} , t_{30} , etc., indicate the time in minutes at which the smoke accumulation reaches 10, 30, etc., per cent of the maximum indicated accumulation D_m .

TABLE 4—Computed smoke obscuration index for various specimens.

Material	Specimen Measured Thickness, in.	Density, lb/ft ³	Smoke			
			Flaming		Smoldering	
			D_m	S.O.I.	D_m	S.O.I.
Hardboard	0.25	56	67	0.6	595	56.0
Fiberboard (prefinished insulating board)	0.50	16	80	1.6	208	72.0
Plywood (exterior grade)	0.25	33	112	2.4	287	13.0
Red oak	0.78	41	117	2.1	660	21.0
Wool rug	0.30	0.42 ^a	178	33.0	215	27.0
Acrylic	0.22	75	107	11.0	156	1.6
Cellulose acetate butyrate	0.25	75	49	1.3	434	64.0
Polystyrene	0.25	66	>660	>1270.0	372	9.5
Polyvinyl chloride	0.25	88	>660	>970.0	300	11.0

^a Lb/ft².

The smoke obscuration hazard index is then defined as:

$$S.O.I. = \frac{D_m R}{100 t_c} = \frac{D_m^2}{2000 t_c} \left(\frac{1}{t_{30} - t_{10}} + \frac{1}{t_{50} - t_{30}} + \frac{1}{t_{70} - t_{50}} + \frac{1}{t_{90} - t_{70}} \right)$$

where the factor of 1/100 is used to yield index numbers usually greater than one. This index assumes the dimensions of reciprocal minutes squared.

Table 4 shows the result of applying this method of deriving an overall index to selected materials included in Table 3. A comparison of the S.O.I. values with the smoke accumulation curves for these specimens in Figs. 19 and 20 suggests that the ranking achieved is intuitively correct although it is evident that significant emphasis has been placed on the time at which the smoke has been released and for some materials early rapid smoke accumulation can overshadow the total quantity and rate of accumulation.

It must again be emphasized that these indexes are specimen rather than material properties, since specimen thickness and surface finish may be important uncontrolled variables.

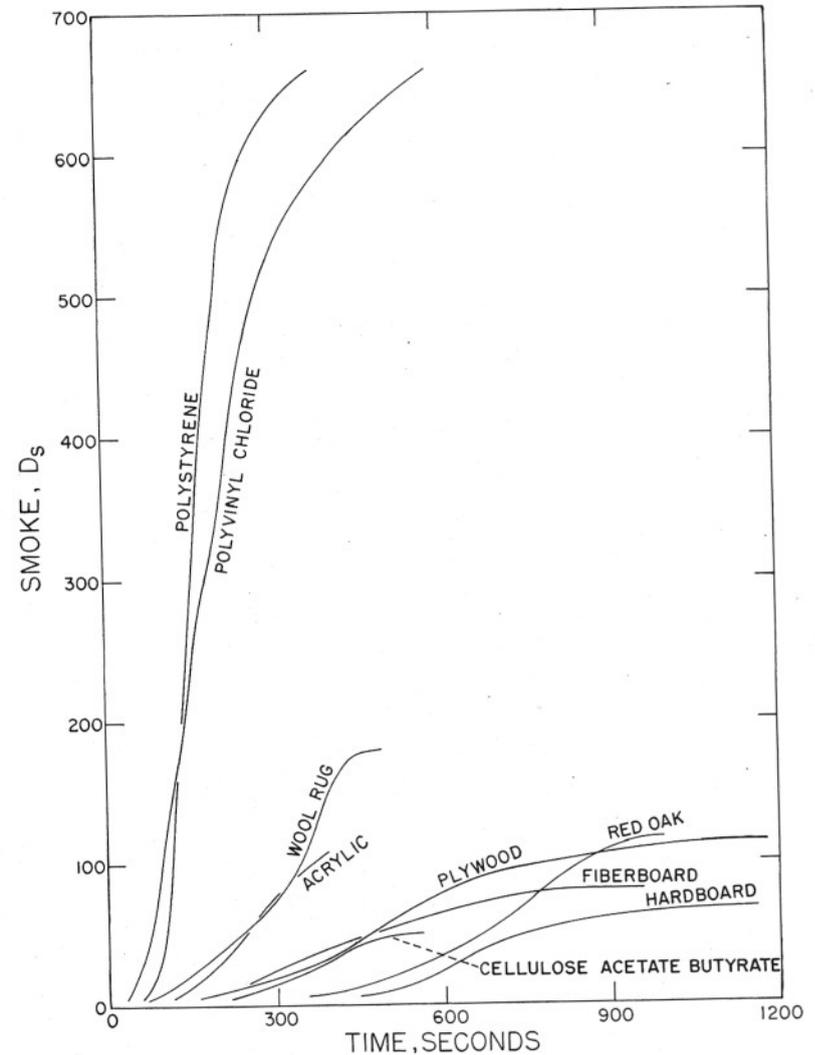


FIG. 19—Smoke accumulation curves for active flaming conditions for specimens of various materials.

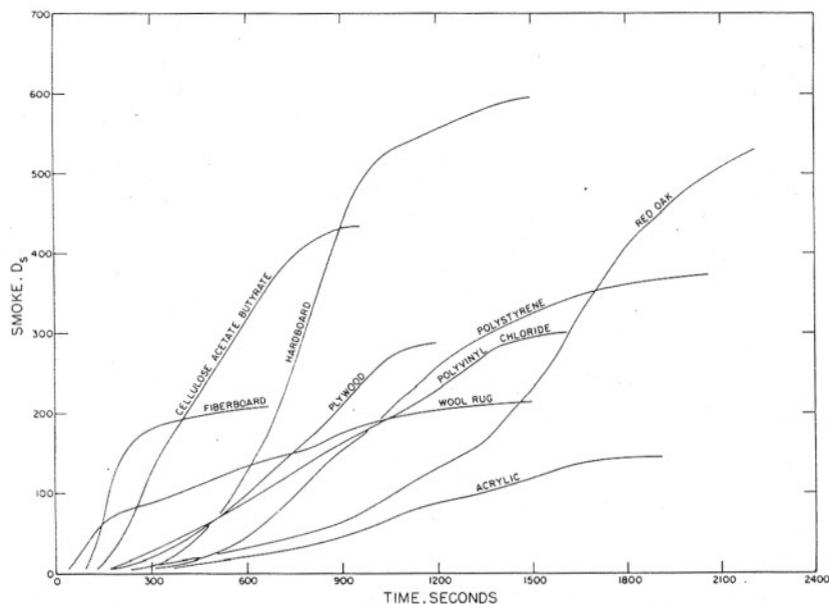


FIG. 20—Smoke accumulation curves for smoldering exposure of specimens of various materials.

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