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NATIONAL BUREAU OF STANDARDS REPORT

8398

WALL CLADDING MATERIALS:

SMOKE PRODUCTION MEASUREMENTS UNDER SIMULATED FIRE CONDITIONS

First Progress Report

by

D. Gross

J. J. Loftus

and

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NBS

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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Fire Research Section
Building Research Division

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ABSTRACT

Preliminary test results are presented of the smoke production characteristics of several materials within the Rohm and Haas XP2 Smoke Density Test Chamber. A variety of specimen exposure conditions were examined and the results were compared for reproducibility.

The Beer-Bouguer law appears to be applicable to the attenuation of light by smoke, and quantity of smoke is therefore reported in terms of optical density rather than percent light absorption.

Preliminary results are presented which indicate a fair degree of correlation between the optical density of smoke produced by a material in the test chamber and the gravimetric smoke deposit from a standardized flame-spread test (ASTM E162-62T).

1. Introduction

When accidental fires occur, the smoke generated often represents the major life danger to occupants. Although lethal amounts of carbon monoxide are invariably present, the obscuration of vision by dense smoke all too often prevents the direct and logical escape by occupants, or rescue by firemen, during the few minutes available prior to the onset of unrespirable conditions, monoxide unconsciousness, etc.

Smoke hazard is appreciated only in a qualitative way, and uniformity in its description and quantitative measurement are seriously lacking. The "smoke generation" limitations on structural or decorative finish materials imposed by some building codes are almost entirely empirical and very little is known about the actual hazard under the wide variety of real fire situations. Many localities and jurisdictions have no smoke requirements for decorative finish materials; and ordinary furnishings are almost entirely free of restrictions.

The test methods presently used for establishing smoke requirements were devised principally for comparative surface flammability measurements, and the relationship between the results of such tests and the visual obscuring qualities of smoke are not well established. It is the immediate objective of this study to investigate the suitability of a laboratory method for evaluating the appropriate optical properties of smokes which obstruct human vision in building fires.

Some people consider smoke to be the gaseous products of burning organic materials in which small solid and liquid particles are also dispersed. Others limit smoke to the unburned solids, such as carbon and ash, suspended in air. However, under typical conditions of non-flaming thermal decomposition, it has been fairly well established that wood smoke consists for the main part not of carbon particles, but primarily of homogeneous spherical tarry droplets [1], and of liquid droplets of organic substances of fairly high boiling points, approximately 100°C [2]. In addition to its effect upon visibility, smoke is usually extremely irritating both to the eyes and to the mucous membranes of the respiratory tract.

The earliest smoke measuring methods appear to have been developed in attempts to control stack effluents and the terminology used in describing the smoke quantitatively is unfortunately lacking in clarity and uniformity. "Smoke density" and "opacity," terms normally appropriate for generic descriptions have been associated with a variety of unassociated test methods. For example, the "total obscuring power" (T.O.P.) of a smoke is considered to be the product of (1) the volume produced per unit weight of material used, and (2) the "density of concentration" [3].

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 light source or an illuminated sign drops to four feet, a room is smoke-logged to a degree that would seriously impede the escape of occupants [4]. It was inferred that this limit was reached when the light transmitted was reduced to 10 percent of the value in the absence of smoke.

Test methods for measuring smoke are generally of two types: (1) those in which light transmission 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 transmission.

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, etc., in which visual comparisons of the unknown smoke are made relative to reference shades or gray glasses. 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 the smoke. The readings are commonly expressed as percent absorption, or in terms of the Ringelmann scale (0 to 5). Attempts have been made to relate the percent light transmission to an optical density scale and to a quantitative smoke concentration (i.e., mass per unit volume) [1, 4]. Such methods are considered generally valid and will be discussed in more detail later. There does not seem to be any satisfactory justification for integrating the area under a percent light absorption versus time curve [5] or for making allowance for residue deposits on lenses at the end of a test by simple subtraction of light absorption 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 that the Beer-Bouguer law could be applied to smoke shade spots, and that optical density ($= \log_{10} \frac{100}{\%T}$) based on light transmission is an appropriate measure [6]. Others have shown a preference for light reflectance measurements on smoke shade [7].

2. 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 influence of the target, the amount and distribution of light and certain psychophysical properties related to human vision (e.g. contrast level, response time and adaptation to levels of illumination). The problem is a very complex one lying as it does somewhere between 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 and it is necessary at the outset to ignore complications due to eye irritations or respiratory effects, hysteria and associated physiological and psychological factors.

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 in contrast. A "quantity of smoke" can only be defined when the total weight of material in suspension, its physical properties and the state of its dispersion are completely known. Since it is impracticable 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, 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, commonly known as the Beer-Bouguer law (sometimes also as the Lambert-Beer Law, or simple Beer's Law) is given by

$$F = F_0 e^{-Kcl}$$

where F is the transmitted flux

F_0 is the incident flux

K is the attenuation coefficient

c is the concentration, and

l is the path length.

Optical density is defined as

$$D \equiv \log_{10} \frac{F_0}{F} = \frac{Kcl}{2.303} \tag{2}$$

This relation and the Beer-Bouguer law are strictly true 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 extinction coefficient [1].

When two smoke clouds are compared by optical density measurements (reduced to a common path length), a comparison is thus being made of the product Kc. Since the attenuation of light is the very property required to determine visibility through smoke, it may be unnecessary to relate particle size distribution, refractive index, coagulation, etc. to particle concentration. It has been shown, however, that the particle size distribution in a smoke is a major factor in determining its optical density, and that in many cases, an increase in the size range of a given smoke leads to a decrease in optical density [10]. When coagulation of heterogeneous smoke is considered, the variation in optical density with time is expected to be less pronounced.

The contrast between an object of brightness B and the background of brightness B' (e.g. a small luminous object seen against an extensive darker background) is given by

$$C = \frac{B - B'}{B} \tag{3}$$

As C decreases, a point is reached where the object can no longer be distinguished from its background, and the value of C is then known as the "threshold of brightness-contrast" or simply "threshold contrast." An unpleasant aspect of the present problem is the question of the effectiveness of a person's vision when he is aware that failure to use his eyes sufficiently well may result in his sudden death. We will assume that this is the situation which confronts a person trapped in a smoke-filled room or building.

The presence of a particulate cloud between the object and the observer serves to attenuate the light from the object and from the background, and also to scatter external light coming from all directions. The attenuation of light directly transmitted through a particulate cloud is expressed in terms of the exponential extinction relation, so that, for the apparent brightness of the object

$$B_t = B\,e^{-Kcl} = B\,e^{-2.303D} \tag{4}$$

and for the apparent brightness of the background

$$B_t' = B' e^{-Kcl} = B' e^{-2.303D} \qquad (5)$$

External light scattered from the cloud gives rise to glare, G, which is superimposed on the brightness of both object and background.

Hence the new contrast, which is in effect an "obscuration threshold," will be

$$C_t = \frac{(B - B') e^{-Kcl}}{B e^{-Kcl} + G} = \frac{(B - B') e^{-2.303D}}{B e^{-2.303D} + G} \qquad (6)$$

If the value of C_t falls to the threshold value for given conditions, the object will be indistinguishable from its background, i. e., it will be obscured.

Elaborate research on the threshold of brighness-contrast was carried on during World War II and reported by Blackwell [11]. In general, C was found to be a function of the angle subtended by the stimulus, the adaptation brightness, the sharpness of the boundary, and the presence of disturbing stimuli in the field of view.

Using this data, it may be instructive to estimate the optical density of smoke through which a 60 watt incandescent lamp (brightness ~1000 foot-lamberts) may be distinguished against a dark background and in the absence of glare. As an extreme, it is assumed that adaptation from a normal brightness level of 10 foot-lamberts occurs with sufficient rapidity down to a practical lower limit of 10^{-5} foot-lamberts. At a distance of 6 feet, a typical incandescent lamp subtends an arc of 2 degrees, and from the data of Blackwell (for a 6-second viewing exposure and for 50 percent probability), the threshold of brighness contrast is 0.346. This yields an optical density of 7.85, or 1.31 per foot, and suggests that, for a one-foot smoke path, it is probably desirable to make laboratory measurements of transmittances of 1 percent or less.

It should be borne in mind that these results apply to a 50 percent probability of detection by trained observers who were seeking a contrast difference in a known location. To allow for 98 percent probability of an average observer detecting a contrast difference in any (unknown) direction, a "field factor" of 10 or so should probably be applied to the contrast threshold value. Furthermore, adaptation to such levels of brightness may not be sufficiently rapid or even attainable due to interference in sensory adaptation by the smoke. Finally, in atmospheres of dense, heterogeneous smoke, and in the presence of external light, the effect of scattering (glare) would be expected to affect the contrast threshold.

It may be useful to note that the apparent color of light seen through a haze or smoke is a function of the color temperature of the lamp, the thickness of the smoke layer and the number and size of the particles. For example, an ordinary lamp operating at 2850°K may appear to be a fairly saturated orange at a distance of 1/2 mile through a common industrial haze. The apparent color of red signal lights is not appreciably changed by the atmosphere.

3. Method of Test

The basic test apparatus used in the initial phase was developed by the Physics Laboratory of the Rohm and Haas Company [12] and was made available by them for our use. As shown in Fig. 1, the Smoke Density Test Chamber consists of a sheet metal chamber 12 by 12 by 30 inches, instrumented to permit the measurement of the obscuring qualities of the smoke with respect to light and visibility produced during the burning of a small specimen. No account is taken of the irritating or toxic effects of the combustion products.

A 3-watt light source, a barrier-layer photoelectric cell with visual correction filter and a meter are used to measure the transmission of light across the chamber. The 12-in. light beam path is located approximately 11 inches from the top of the chamber. A white-on-red "Exit" sign, back-lighted by two 6-watt fluorescent lamps, is mounted on the back panel and may be viewed through a transparent glass door. However, no visual observations with respect to obscuration of this sign have been made.

The chamber is closed and unventilated during test except for 1-inch-high ventilation openings around the bottom. Although with high smoke-producing materials there is some spillover of smoke through these openings this may be considered negligible. As indicated in the Introduction, all light transmission values were converted to the logarithmic optical density scale, the instantaneous values of which are a direct measure of the total or integrated quantity of smoke produced up to that time. After the chamber is cleared of smoke at the end of a test, a final optical density value is obtained which may be subtracted from the test values to allow for residue deposits on the lenses.

The standard exposure, according to Rohm and Haas Physics Laboratory Method P-148B, consists of a flame from a propane burner operated at a pressure of 40 psi. The test specimen is 1 by 1 by 1/4 inches, and is preconditioned prior to being placed on a prescribed supporting screen for test, the duration of which is 4 minutes. However, because of large variations in test results caused by random variations in ignition behavior during test, modifications from "standard conditions" were freely made and are discussed under "Results." One of the principal advantages of this test method is that procedural changes and the exploration of variables can be made quickly and economically.

In order to provide a continuous record of light transmission values during each test, the meter output was fed into a 100 millivolt full-scale recorder. Since the Test Chamber was provided with a high sensitivity switch (X10), and since the recorder sensitivity could be readily switched to 10 mv full scale, a total of three ranges of light transmission were available, 0 to 100 percent, 0 to 10 percent, and 0 to 1 percent.

4. Results

A. Dilution Tests

A series of tests were performed to demonstrate the applicability of the exponential extinction law for a range of smoke types and levels produced with a propane burner exposure. For this purpose, a large cylindrical carton was placed close to the Smoke Density Test Chamber and connected to it at top and bottom with 3 in. dia. tubes (See Fig. 2). By attaching the upper tube to the Chamber's blower exhaust and closing the ventilation openings (except for the lower tube), a closed system of greater volume resulted through which a given quantity of smoke could be circulated. Using a variety of test conditions (propane pressure, screen type, specimen size, etc.) and materials (cellulose-base, rubber, magnesium), a wide range of light transmission (maximum smoke absorption) readings were obtained. Upon reaching an established value, which was noted, the exhaust blower was turned on and the smoke circulated and diluted into the larger volume. A second light transmission value was then obtained. The ratio of the optical density for the initial condition (test chamber volume only = 2.58 cu ft) to the optical density for the final condition (total volume of test chamber, carton and interconnecting tubes, 8.49 cu ft) is plotted in Fig. 3 as a function of the optical density of the smoke prior to dilution. Exact conformance to the Beer-Bouguer law, for which optical density is directly proportional to concentration or inversely proportional to volume, would yield a value of $\frac{8.49}{2.58} = 3.29$ for this ratio. It might be noted that deposition, condensation or other loss of suspended smoke particles upon circulation would result in high values for the optical density ratio. Considering the wide range in the level of smoke investigated, the general validity of the exponential law appears fairly well established. The applicability of the Beer-Bouguer law to the attenuation of light by wood smoke over a mass concentration range of 0 to 2 mg/l was also verified by Foster [1] on the basis of optical and gravimetric density measurements.

B. Gas Flame Exposure Tests

Using the "standard" exposure, Rohm and Haas Method P-148B, considerable variation in test results were obtained from duplicate tests on a standard hardboard. These differences were mainly associated with whether ignition occurred slowly or rapidly, whether one corner was exposed to a greater extent than another, and whether flame extinction occurred during a five-minute exposure. More reproducible results were obtained at 20 psi than at 40 psi and this pressure was used for subsequent tests. When the optical density reading for one test is plotted against the optical density reading for a repeat test, the results for a variety of wall finish materials plot as shown in Fig. 4A. Good reproducibility of results would yield points close to the 45° line.

Several alternate exposure conditions were investigated in an attempt to improve reproducibility of data. One involved placing the 1 by 1 in. specimen over a metal shield containing a 7/8 by 7/8 in. opening (to reduce edge smoking effects) and employing a horizontal multi-holed burner of larger area (1.5 in. dia.) in order to provide a more uniform flame exposure. However, due mainly to the metal shield, increased smoking and generally higher values of optical density were obtained. Results for duplicate tests under these conditions are shown in in Fig. 4B.

Another alternate exposure condition involved mounting the 1 by 1 in. specimen vertically in a holder, so that the standard burner flame impinged at a 45 degree angle on the surface and with all other surfaces (except the top edge) covered. This permitted a greater access of air to the flame-exposed surface and resulted in generally lower optical density readings, the results for duplicate tests being shown in Fig. 4C.

C. Electric Furnace Exposure Tests

In an effort to obtain more reproducible results, a small electrically-heated furnace was constructed, and placed on the floor of the Test Chamber. The 1 by 1 in. specimen was placed in a shallow porcelain combustion boat and inserted into the pre-heated furnace at zero time. When operated at 80 volts, the air temperature at the specimen location was approximately 750°C and active flaming resulted in every case. The use of a small pilot burner was explored but was not considered necessary at this time. Results of duplicate tests under these conditions are shown in Fig. 4D.

A series of tests were also performed on a standard hardboard material using a range of voltage settings (and corresponding temperatures). The results of this series is shown in Fig. 5. It may be noted that at a voltage setting of 40 volts, corresponding to an air temperature of about 360°C, a slow non-flaming pyrolysis was obtained with considerable smoke production. This smoke appeared to consist of small particles of light grey or blue color, the smoke produced during flaming under 750°C exposure consisted of large black particles. These exposure conditions are considered representative of those encountered in the early and advanced stages of building fires, respectively, and may represent two possible test conditions for the evaluation of the smoke generation characteristics of a material.

For these test conditions, replicate tests were performed on the following materials: hardboard, red oak, and acrylic and polystyrene plastics. Typical results are shown in Figures 6A and 6B. Whereas the higher temperature exposure produced rapid flaming and peak optical density values in 1 or 2 minutes (Fig. 6A), the lower temperature exposure under nonflaming conditions resulted in much slower smoke production rates (Fig. 6B). It may be noted that the peak optical density values for hardboard and red oak were higher for the lower temperature exposure whereas those for the two plastics were lower.

As shown in Fig. 4 and Table 1, the electric furnace exposure provided fairly consistent results, and generally low coefficients of variation compared to the other test conditions explored. However, it is possible that some variability may be introduced due to the existence of temperature gradients along the furnace axis. A second electric furnace is being planned in which the electric resistance winding will be arranged to provide a more nearly uniform temperature in the central portion of the furnace.

D. Smoke Data Correlation

A comparison was made between the optical density values from the Smoke Density Test Chamber (electric furnace exposure, 80V) and the smoke deposit values from a standard radiant panel flame spread test (ASTM E 162-62T) on a wide variety of materials. These results are shown in Fig. 7. Although there is considerable scatter for several heavy smoke producing materials, a definite and reasonable correlation is seen to exist.

5. Conclusions

A small-scale laboratory test chamber appears to be useful for the evaluation of the smoke generation characteristics of materials under simulated building fire conditions. The use of a controlled exposure within an electrically-heated furnace appears to be capable of yielding more reproducible results in the Rohm and Haas XP2 Smoke Density Test Chamber than any of several exposures using an open propane burner flame.

On the basis of the dilution experiments described in this report and the results of Foster [1], the Beer-Bouguer law for the attenuation of light by smoke over a wide range in concentration appears to be valid. The entire theoretical background of the subject leads naturally and logically to a logarithmic rather than a linear scale, and it is appropriate, therefore, to use optical density rather than a linear light absorption scale to characterize "smoke density".

Preliminary results indicate that a fair correlation exists between the optical density of smoke produced by a material in the electrically-heated Test Chamber and the gravimetric smoke deposit from a standardized flame-spread test (ASTM E 162-62T).

6. Future Work

Work will continue in an effort to establish suitable and reproducible test conditions and procedures with the Rohm and Haas Smoke Density Test Chamber. Tests will be performed on a wide variety of typical wall cladding materials. Tests results on typical materials will be analyzed and compared with similar results obtained by other smoke test methods. In addition, the applicability of the test results to conditions in full-size rooms will be considered.

7. References

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Table 1.

Reproducibility of Test Results for Several Exposure Conditions

Method	No. Materials Tested	Avg. Optical-Density	Avg. Coefficient of Variation percent
A. Rohm & Haas Method P-148B	18	.52	35
B. Horizontal Multi-Holed Burner with Metal Shield	25	.91	11
C. Vertical Mount Gas Burner	40	.11	74
D. Electric Furnace (750°C Exposure)	26	.39	15

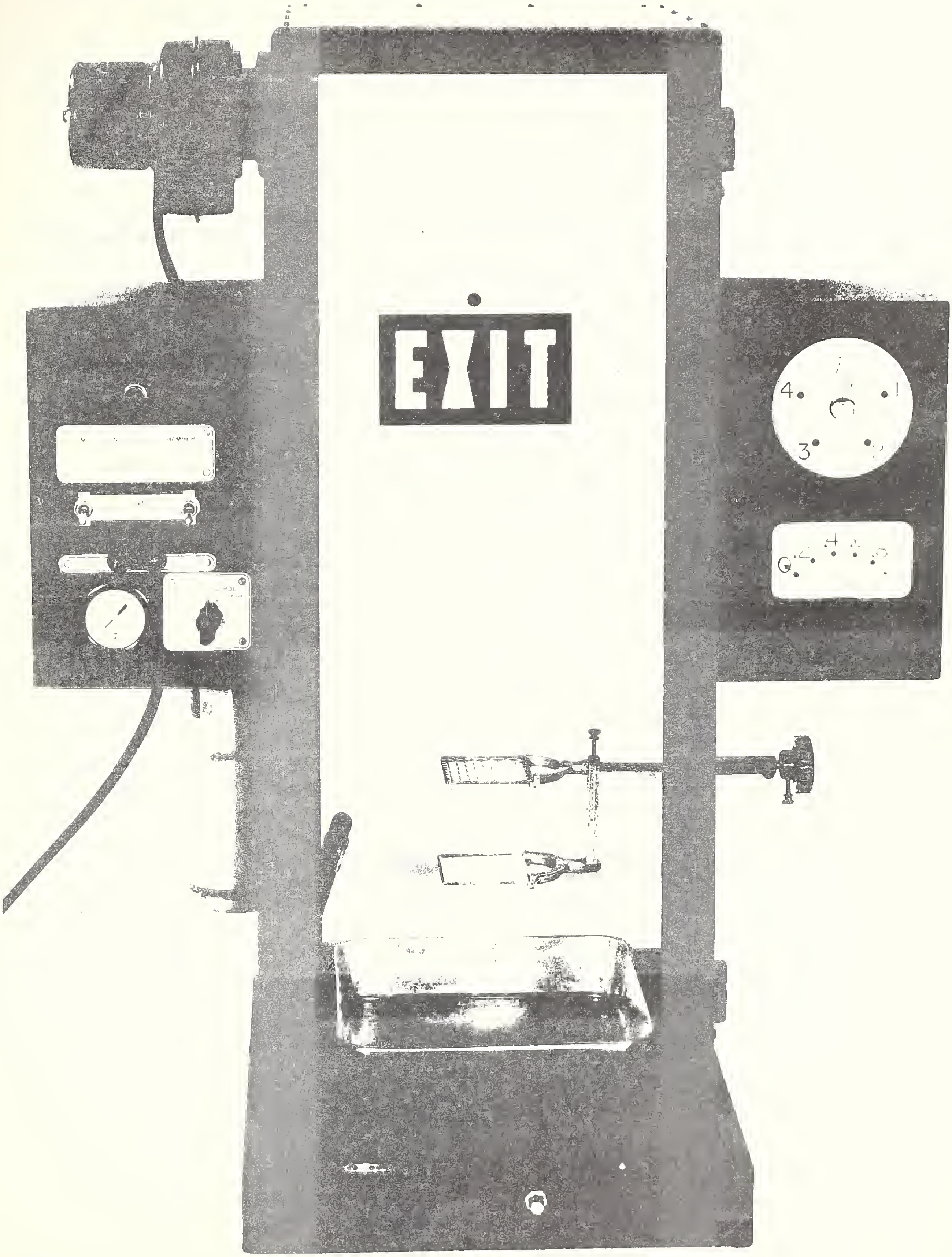

Fig. 1 Smoke Density Test Chamber
(Courtesy Rohm & Hass Co.)

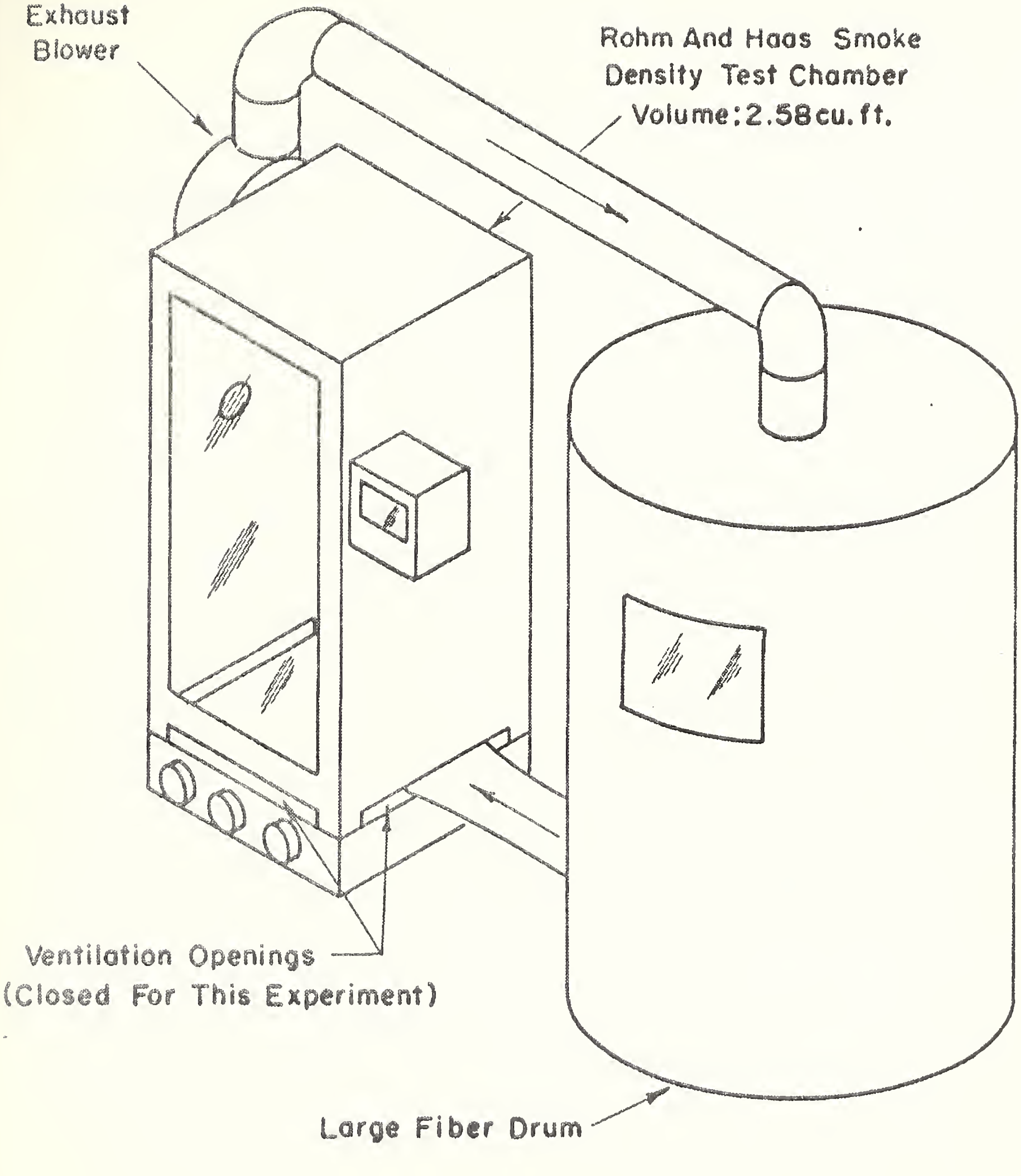

FIG. 2 – SKETCH OF SMOKE DILUTION EXPERIMENT

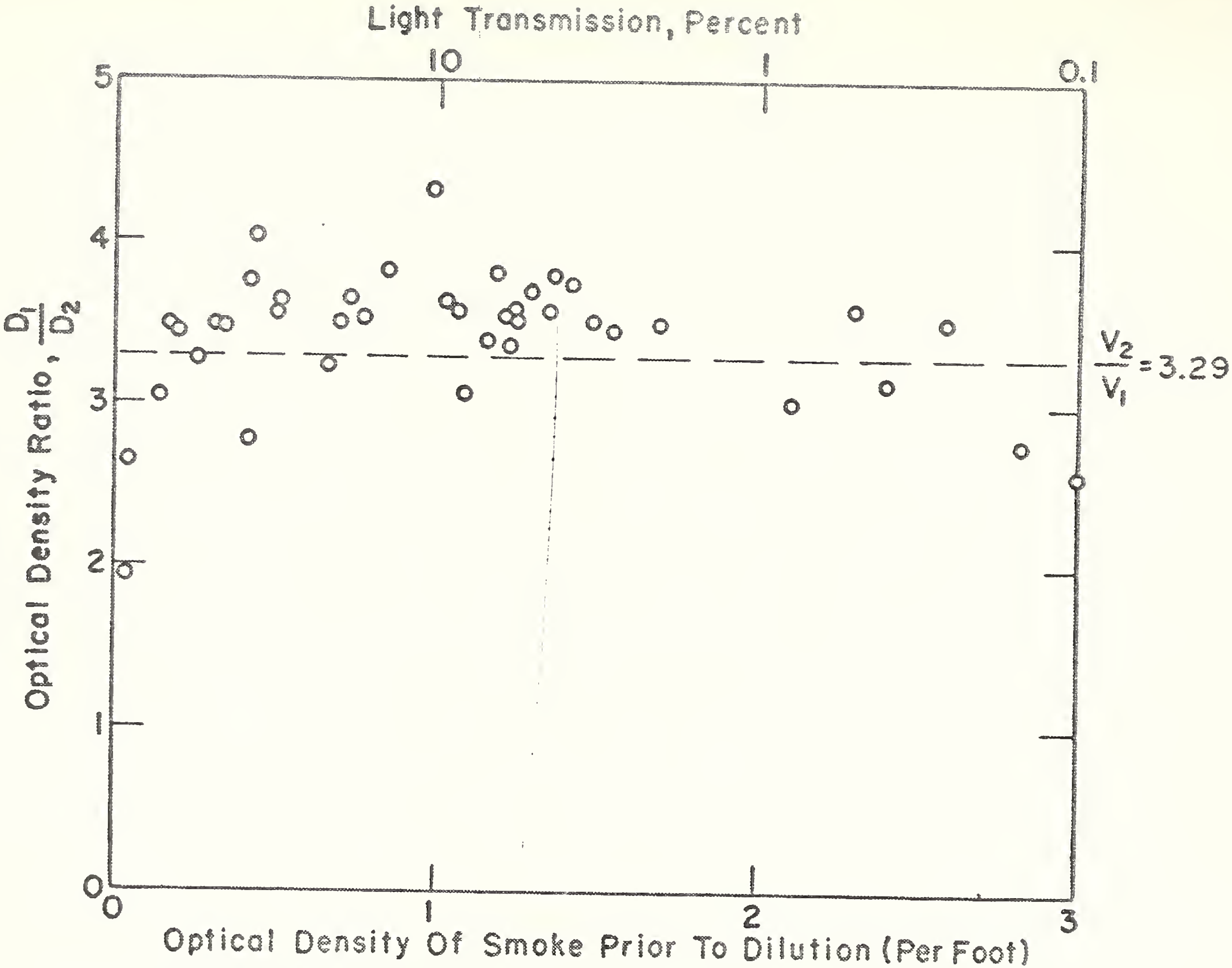

FIG. 3 — OPTICAL DENSITY RATIO vs INITIAL OPTICAL DENSITY, SMOKE DILUTION TESTS

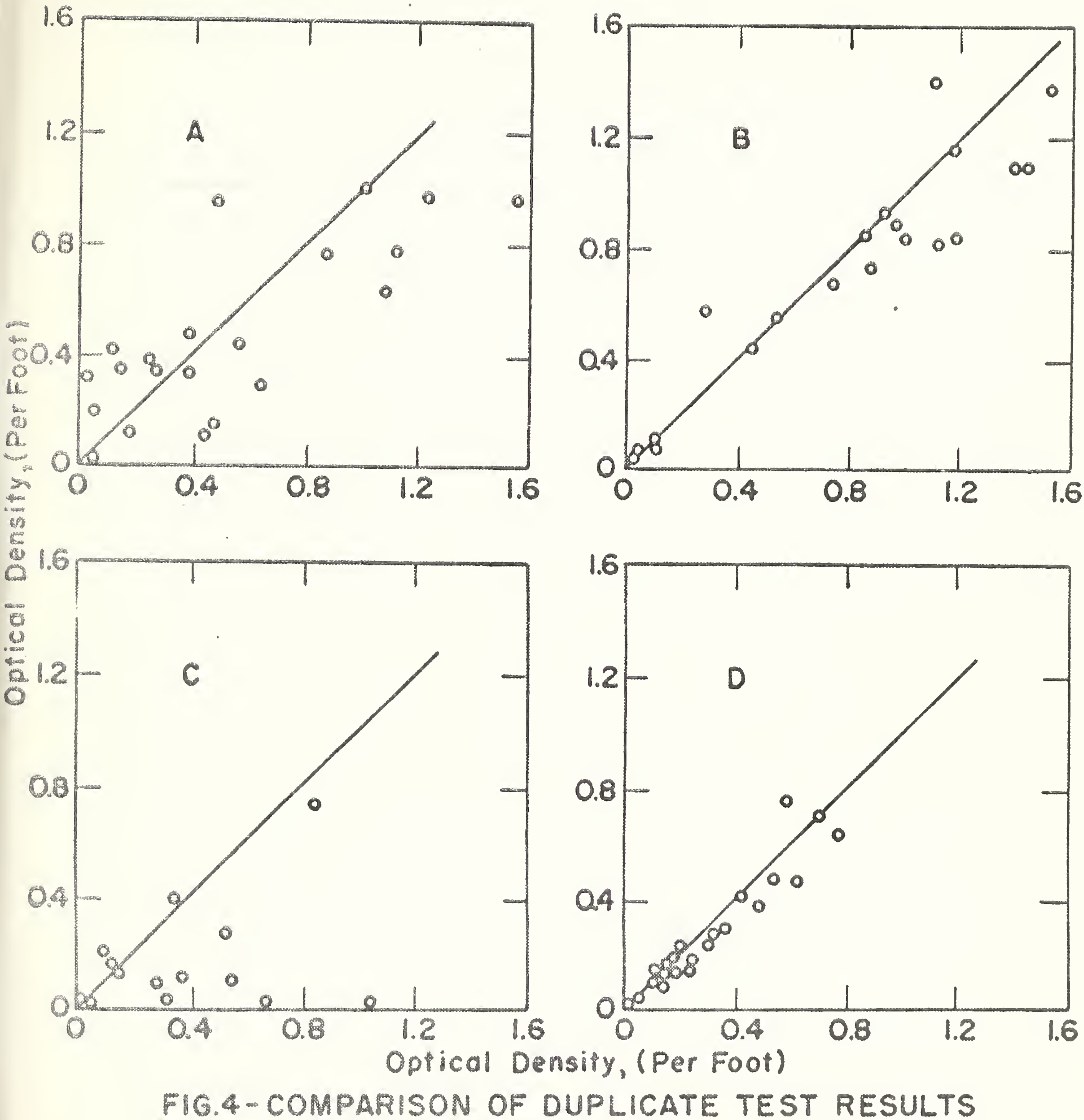

FIG. 4 - COMPARISON OF DUPLICATE TEST RESULTS

A Standard Burner Exposure, 20 psi, Rohm And Haas Method P148B
B Multi-Holed Burner Exposure With Metal Mask
C Standard Burner Exposure, Specimen Vertical
D Electric Furnace Exposure, 80 Volts (750 °C)

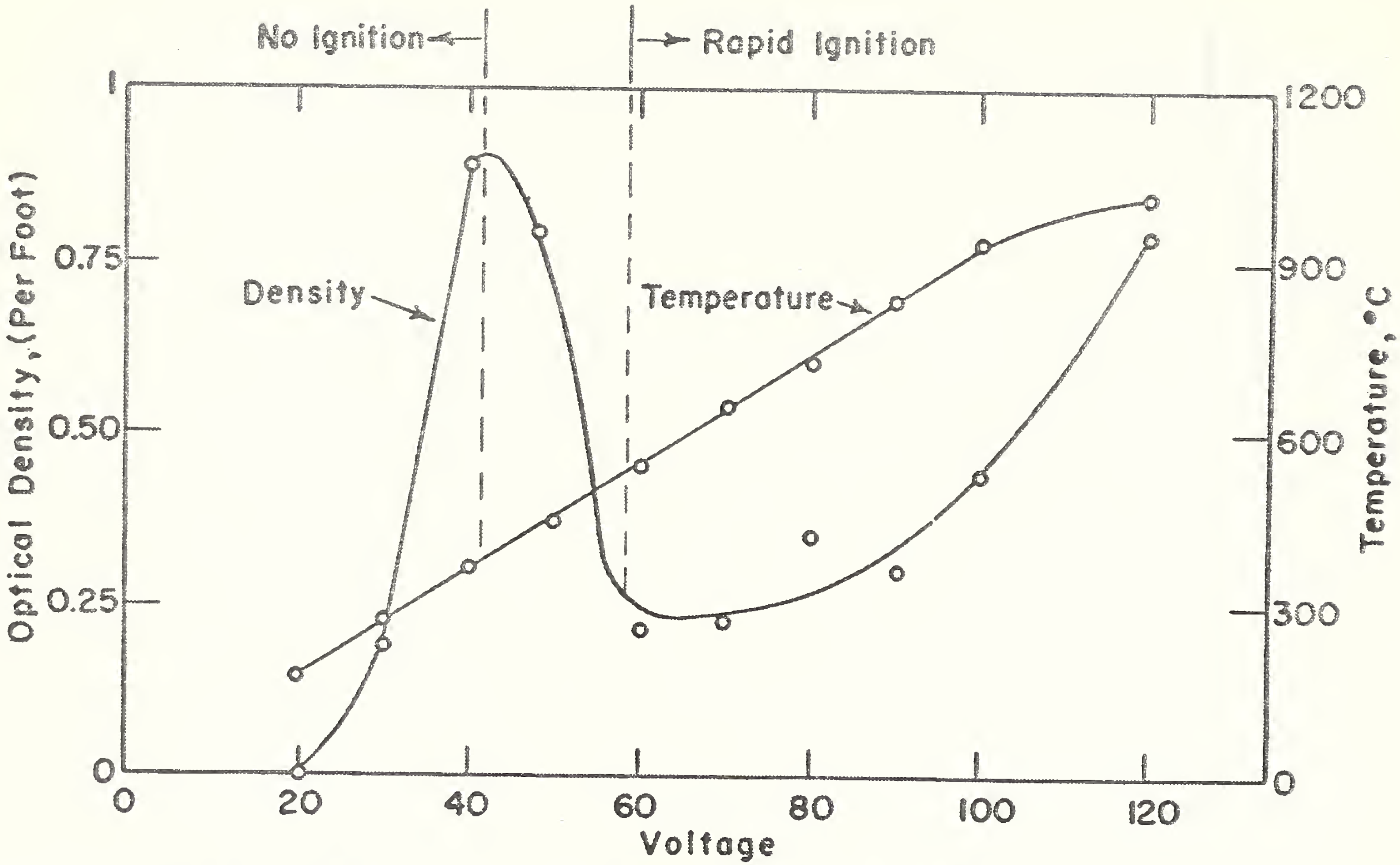

FIG. 5–EFFECT OF VOLTAGE SETTING ON MAXIMUM SMOKE PRODUCTION, ELECTRIC FURNACE EXPOSURE

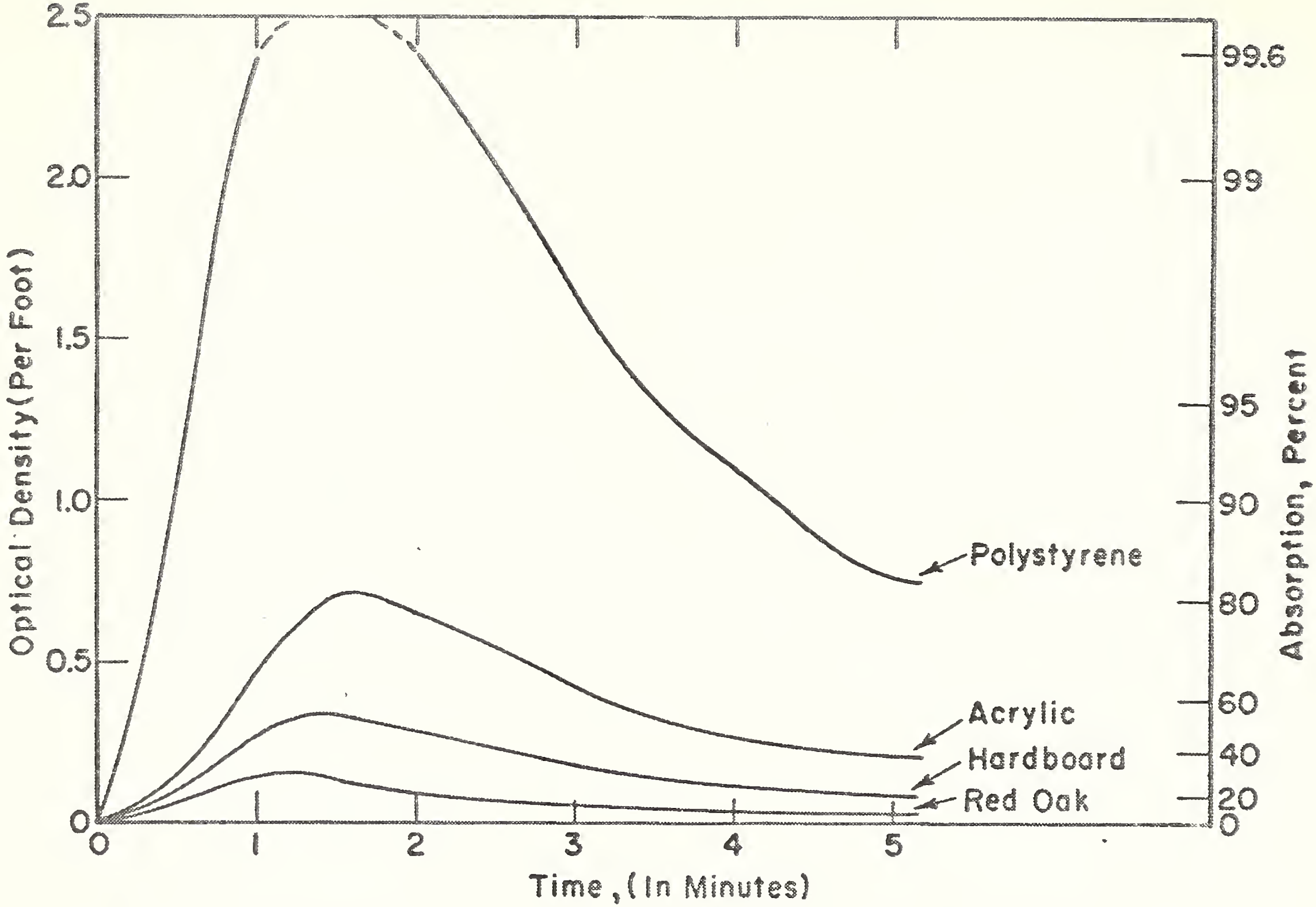

FIG. 6A – TYPICAL TEST RESULTS, ELECTRIC FURNACE EXPOSURE, 80 VOLTS (750°C)

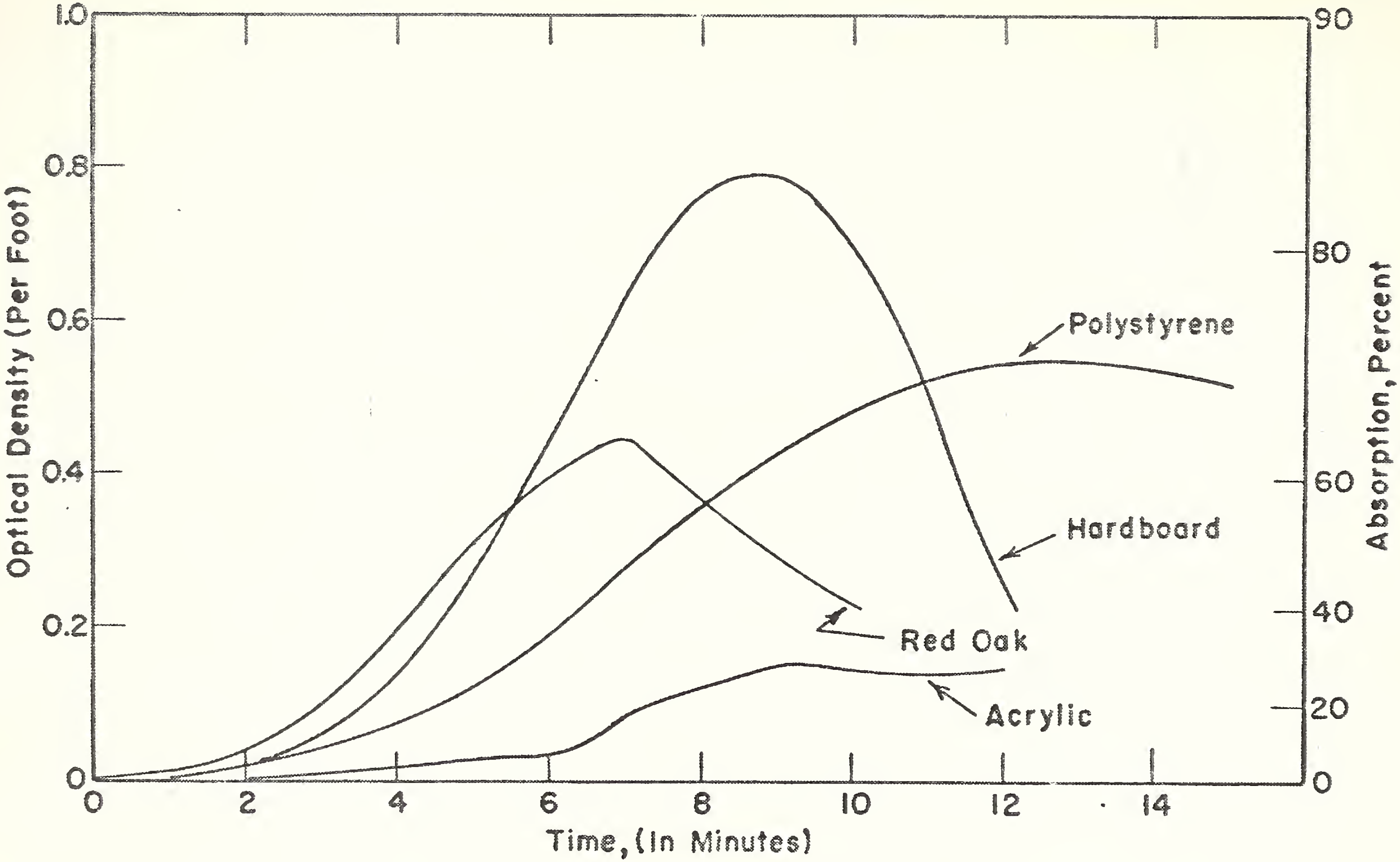

FIG. 6B — TYPICAL TEST RESULTS, ELECTRIC FURNACE EXPOSURE, 40 VOLTS (360°C)

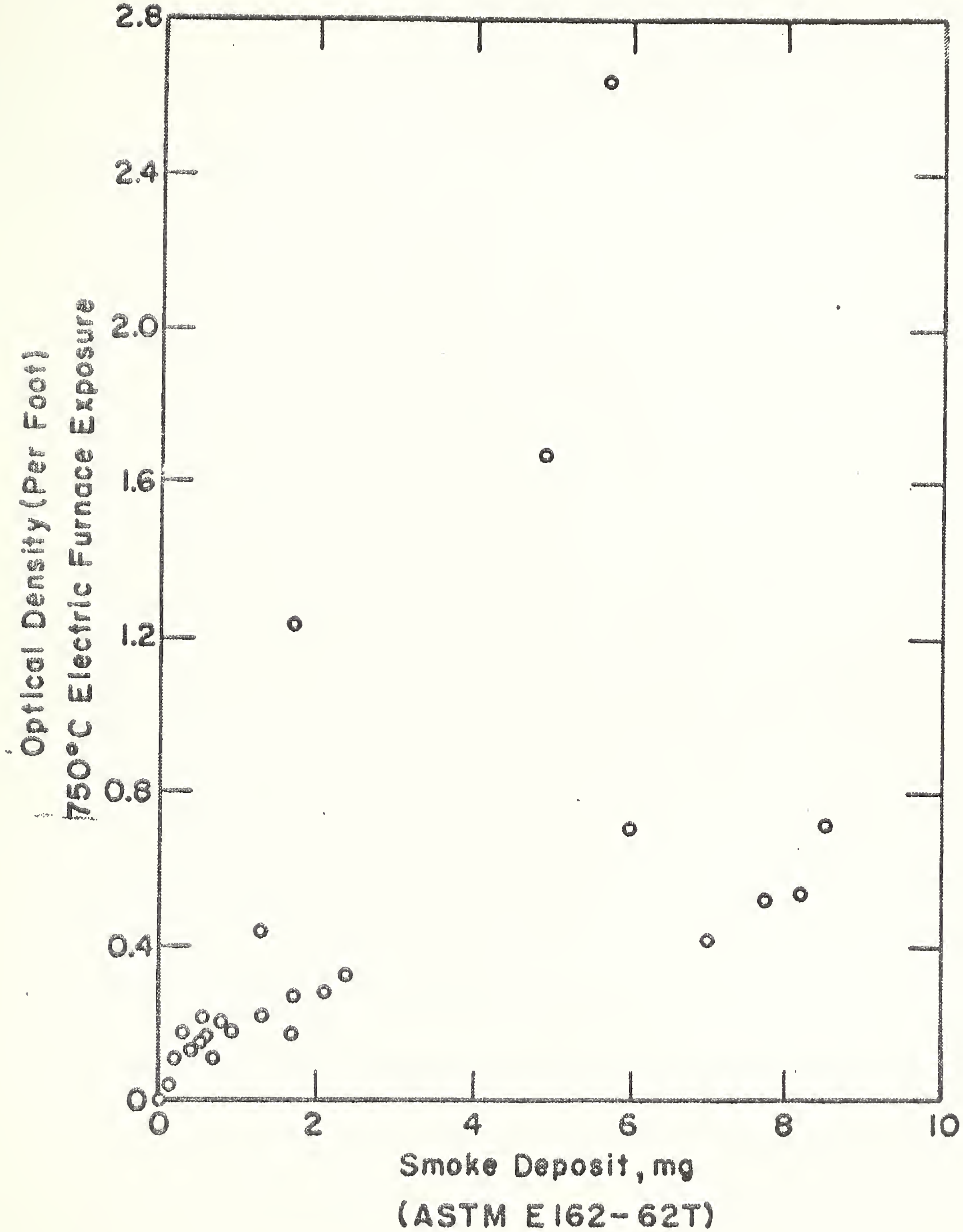

FIG. 7—CORRELATION BETWEEN OPTICAL DENSITY IN SMOKE CHAMBER AND SMOKE DEPOSIT, ASTM TEST E162

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