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of ASTM Committee E-5 on Fire Tests of
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The Control of Smoke In Building Fires — A State-of-the-Art Review

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ABSTRACT: ASTM Committee E-5 on Fire Tests of Materials and Construction has been increasingly concerned with the life hazard of smoke and noxious gases generated during fires in buildings. A task group within Subcommittee IV on Fire Tests of Acoustical and Similar Finishes has reviewed the situation with respect to smoke and has found that the exact nature of the hazard has not been well defined. As a result, efforts to control the use of materials alleged to produce objectionable amounts of smoke when exposed to fire situations lack a desirable degree of uniformity. The nature of smoke, its development in building fires, efforts toward control through regulation and building design, existing and proposed test methods for smoke measurement, and test criteria are discussed in this paper.

KEY WORDS: buildings, construction, construction materials, building codes, fire protection, fire safety, fire control, fire losses, fire resistance, fire tests, smoke, smoke abatement, smoking

Two lives were lost in a million dollar fire starting on the 33rd floor of a new 50-story Manhattan skyscraper. All of the employees had to be evacuated. Smoke damaged computer rooms on the 11th and 43rd floors, with "very heavy" smoke and soot deposits in the latter case [*1*].[1]

Four children died in a fire confined to a pile of rags in a second floor closet of a modest dwelling in Memphis. Two suffered second and third degree burns; two had no external burns. Smoke inhalation was given as the cause of death—the burns, it was thought, came after death [*2*].

Thirty-two elderly persons lost their lives in an Ohio nursing home fire. "Smoke caused most of the deaths . . . Smoke damage was also responsible for the estimated $125,000 loss" [*3*].

A common denominator in these recent fires and many others is the generation of heavy smoke. The damaging effects of smoke on life and property are widely recognized but poorly defined. It has been well established that a large percentage, probably more than one half, of the fatalities that result from accidental fires can be traced to causes other than burns [*4*], namely, smoke, heat, noxious gases, and hypoxia (oxygen deficiency). It is known that the large volumes of smoke generated during fires in buildings make it difficult for the occupants to find and use the exits provided. Smoke induces panic both by its presence and by obscuring vision. It effectively impedes the work of firemen in rescue, in locating the source of the fire, and in extinguishment.

An increasing awareness of the part that smoke plays in fires is paralleled by an increasing number of products, coming into use as building materials or in building furnishings, which produce varying quantities of smoke. Many building codes now specify limitations on the acceptability of building materials based on their propensity to develop smoke under burning conditions.

This paper will discuss the development of smoke in fires in buildings and review the means now used or proposed as controls to minimize the hazard that it presents.

The Nature of Smoke

In the public mind "smoke" is an all-inclusive term. The daily press may report on the number of persons overcome by smoke or succumbing to "suffocation" or "asphyxiation." However, to consider smoke in an all-inclusive sense is to pose a problem so large and having so many facets that it would be difficult to approach in a rational manner. As early as 1950 the National Fire Protection Association issued a fire gas research report which stated, in part, "While the danger from flame is obvious and instinctively avoided, the dangers from breathing smoke, gases produced in fires, and oxygen deficient atmospheres are often not apparent" [*5*]. For practical reasons, therefore, smoke problems are considered here separately from the thermal, gas toxicity, and oxygen deficiency hazards presented by fires.

There is some evidence of the physiological effects of smoke particles that may be inhaled or ingested. Little information on this subject has been found, and much of it is of a subjective nature. Thus this aspect of the smoke problem has not been included within the scope of this discussion.

In this paper smoke will be considered as particulate matter and dispersed liquids suspended in air—principally unburned carbon resulting from incomplete combustion [*6*]. The visible particulate matter, unburned carbon and tars, generally is not considered toxic. However, smoke may contain strong irritants or lachrymators that can affect the eyes and nasal passages. These elements alone can result in reduced vision, coughing, extreme discomfort, or pain and may lead to panic.

Smoke particles vary in size, shape,

Members of the Task Group are: C. H. Yuill, chairman, A. J. Bartosic, G. T. Castino, H. W. Eickner, J. R. Gaskill, N. S. Pearce, A. F. Robertson, and Z. Zabawsky (exofficio).

[1] Italic numbers in brackets refer to the list of references at the end of this paper.

weight, and density. The larger particles may be heavier and less susceptible to transport by air movements than the remainder of the particulate matter. Obversely, the particles may be so small that they are invisible individually to the naked eye but may exist in such quantity as to effectively obscure vision. Particles of concern are those which are light enough in weight to be carried by natural air movement or convection currents formed during the fire itself.

The Development of Smoke in Fires

Considering the wide variety of ways in which materials may be burned and smoke accumulated, it is not surprising that conditions under which severe smoke development occurs have not been well defined. Some materials produce heavy smoke when burning under nonflaming conditions while others smoke severely when burned with flaming combustion. Some materials burn, with ample ventilation, with little smoke in direct flame but produce considerable smoke if the ventilation is such that the available oxygen becomes restricted. The latter condition again may produce smoldering combustion. As one author concluded, "Smoke density data on natural and synthetic cellular polymers exhibit a wide range of values, the values of each material varying with exposure conditions and specimen size" [7].

The density of smoke in an area within a building will depend on the material burning or exposed to sufficient heat to cause decomposition, the amount of surface area involved, the volume of the space in which the smoke is dispersed, the diffusion within that space, and the amount of ventilation provided. Obviously, wide variations of these conditions are likely to occur and the prediction of precise smoke levels likely to be expected in any particular fire is practically impossible.

In 1958 the Division of Building Research, National Research Council of Canada, conducted controlled burns on buildings to be destroyed for the St. Lawrence Waterway [8]. Many facets of building fires were examined including measurements of radiation, carbon monoxide, oxygen levels, temperature, and smoke development. A concluding statement of a report on this program again emphasized the importance of smoke from the visibility point of view:

> With reference to the survival of occupants, it was found that all dwellings become smoke-logged within 6 minutes of the ignition of the cribs. In all but one case the criterion for decrease in visibility was exceeded before the other criteria for survival—the carbon monoxide concentration, reduction of oxygen, and temperature. The smoke criterion relates principally to possible unaided escape of occupants in contrast to the lethal effects of carbon monoxide and high temperatures, upon which survival depends more directly and without regard for subsequent rescue.

The Los Angeles Fire Department conducted tests in a room of approximately 6100 ft^3 containing a 25-ft flame spread tunnel furnace [9]. The furnace exhaust was arranged so that it could be emptied into the room. The object was to compare the smoke density values obtained in the 25-ft tunnel furnace with the smoke values measured across the room with the same source of smoke. Observers stationed outside the room at windows and within the room took notes as the tests progressed. The primary conclusion of this program was that density of smoke by itself is not a proper measure of the smoke hazard. Time of burning, area of material actually burning, and volume of space involved also must be considered. The importance of considering the effect of smoke on the eyes and nasal passages of observers was stressed.

The rapidity with which smoke travels in a building fire was demonstrated amply in other tests conducted by the Los Angeles City Fire Department [10]. Most of the 55 test fires were started in the basement at the foot of an open stairway. The conclusion here was that "Smoke was the principal life safety hazard. Untenable smoke conditions preceded untenable temperature conditions in nearly every test." The report states further, "This might be expected with smoldering fires; however, this was true even with free-burning fires." In this study smoke was evaluated in terms of both visibility and irritant effects.

A second series of test fires was conducted involving some 51 fires that were allowed to burn until untenable conditions developed [11]. The same phenomenon with respect to smoke was noted. A pertinent comment from the report on this work is noteworthy:

> It should perhaps be pointed out why untenable smoke conditions constitute the principal hazard. The smoke itself does not contain a high enough concentration of dangerous gases to be lethal in the early stages of a fire. However, the untenable smoke, by its irritant properties and its obscuration of normal visibility, does immobilize the occupants within the area of the building where they happen to be located. They are then "trapped" within the building and, unless rescued promptly, may be killed by the lethal heat and gases which follow shortly.

In trying to define the hazard of smoke, the plastics industry through the Technical Advisory Committee of the Manufacturing Chemists Association sponsored a research program at Underwriters' Laboratories, Inc., to develop a rational classification for smoke emissions [12]. In this program a test structure 32 ft long, 12 ft wide, and 14 ft high was constructed close to the 25-ft tunnel furnace and arranged so that exhaust gases from the furnace could be bypassed into the chamber and diffuse evenly through it. Through observation ports it was possible to record with cameras the time it took to lose sight of a standard exit sign across the 12-ft dimension of the chamber. A variety of interior finish materials was used and it was concluded that

1. Good visibility was obtained with materials having a smoke density factor in the 0 to 16 range.[2]
2. Materials having a smoke density factor of 200 or less did not reduce visibility for periods up to 6 min.
3. Materials having smoke density factors above 325 were in the fair visibility to obscuration range.

A series of three test fires was arranged in Paris, France, in 1963 to study the flow of smoke through the stairways and hallways of a new 22-story apartment house [13]. Fires were started in a room located in a first floor apartment. The apartment door was opened a few minutes after the start of the test fires. A primary conclusion of this study was that, where evacuation of the occupants was of prime concern, "the principal danger is from the elevated temperature of the smoke." Other interesting phenomena were observed in these tests and verified by repeated experiments:

1. Stratification of smoke can change rapidly in a fire situation. Cool smoke tends to diffuse; hot smoke tends to stratify.
2. Optical density of the smoke decreases as its temperature increases. The carbon monoxide hazard becomes significant when the temperature reaches a point where evacuation is difficult.
3. Smoke reached the roof terrace 22 floors above within 9 min after the first fire was started—6 min after the apartment door was opened on the first floor.
4. The smoke emissions in a fire can be controlled to a great extent by natural and forced ventilation in the hallways, stairways, and at the seat of the fire.

In a recent study of fires started on beds and upholstered chairs with cigarettes or matches, it was demonstrated that virtually

[2] The figures used represent a ratio and are derived from the formula presented in ASTM Test for Surface Burning Characteristics of Building Materials (E 84 - 68). Comparative units: asbestos-cement board = 0, red oak flooring = 100. See below, subsection on ASTM E 84 Tunnel Test, p. 00.

complete obscuration by smoke over a 13½-ft light path occurred within as little as 6 min after match ignition and 26 min after cigarette ignition [*14*]. It also was concluded that choking, irritating, and lachrymating elements of combustion products made the test room untenable before dangerous temperatures or toxic gas levels were reached.

Examples of the hazard of smoke in actual fires in buildings are legion. One of the more recent, where heavy smoke was a factor in rescue, fire fighting, and casualties, occurred in the nursing home in Marietta, Ohio [*3*], mentioned at the beginning of this article. There, however, no distinction was made in determining the cause of death between smoke and other combustion products that may accompany smoke, for example, heat, toxic gases, and deficient oxygen.

Building Regulations on Smoke

Situations such as the controlled tests outlined above, in addition to the personal experience of firemen and others in actual fires, have led some authorities to regulate materials on the basis of smoke generated during combustion. The emergence of many new building materials and finishes, some of which are known to produce heavy smoke under some conditions of burning, no doubt led to such action.

In establishing such regulations the difference between smoke and other combustion products has been noted. This is due probably to the fact that no standard exists either for assessing the hazard involved with heat, oxygen levels, or toxic gases or for a standard means of measurement or analysis. For this reason some building codes in regulating interior finishes require that the smoke and products of combustion produced in burning shall be no greater than those obtained from untreated wood when burned under similar conditions. In making such a statement, most building regulations specify the use of the 25-ft tunnel test for smoke density [*15*] but have no test method to offer with respect to other combustion products. Some codes having a similar requirement do not specify a test method for either smoke or toxic gases. Since, as suggested previously, untreated wood can be burned to yield little or much smoke depending upon ventilation, heat source, and volume of the space used, such a statement actually has little meaning.

The amount of smoke released by a given material is proportional to the surface area involved in burning. Therefore, the potential smoke development requirements for buildings, as specified by building codes, should not limit materials solely on the basis of a smoke development characteristic of the material but should relate also to the surface areas of the materials used within the building which are likely to be involved when a fire occurs and the volume of the space concerned.

Table 1—San Francisco Smoke Classification

Class	Smoke Density Range	Application
A	0–25	Unenclosed vertical exits[a]
B	26–200	Enclosed vertical exits[a]
C	201–450	Rooms, private corridors, etc.

[a] Includes related public corridors.

It also must be recognized that combustible contents, which usually are not controlled by building codes, often can contribute smoke products during the early part of a fire in such large volumes that minimum and precise requirements for potential smoke development of wall and ceiling surfaces have little significance. For example, the burning of one seat cushion can develop sufficient smoke to negate close control and limitations for smoke development placed on the entire paneling surface of the room.

In an effort to institute some form of control, the city of San Francisco undertook in 1961 to establish smoke density limits (based on the 25-ft tunnel test) on the same level as flame spread limits [*16*]. Where the code called for a limit of 25, 75, or 225 for flame spread rates,[2] the same limits were applied to smoke emissions even though no relationship between the two factors had been demonstrated.

Following the work at Underwriters' Laboratories, Inc., mentioned earlier [*12*], the Board of Examiners in San Francisco held hearings and adopted revised end points and applications for smoke control. These have since been incorporated into the San Francisco Building Code [*17*]. The revision, in brief, is given in Table 1.

Since the recent nursing home fire in Marietta, where "smoke" was alleged to have been the major factor in causing the deaths of the 32 victims, increased attention has been given to the need for smoke control in building materials. Various levels of end points for smoke emissions ranging from 25 to 250 have been reported,[2] all based on the 25-ft tunnel test. The NFPA standard for air conditioning and heating ducts includes an arbitrary smoke density limit of 50 for duct coverings and linings [*18,19*].

Variations in smoke density limits established by regulatory authorities are indicative of the lack of definitive information on the relationship of smoke and life safety in fires. The extent of these variations is indicated in Table 2. These figures are not comparable in that they apply to particular occupancies, applications, and locations as indicated.

Recognizing a tendency to equate smoke in terms of flame spread and the wide divergence in application of end points on smoke density ratings, ASTM Committee E-5 on Fire Tests of Materials and Construction felt the need for a warning to officials that there is no demonstrable relationship among flame spread rates, fuel contributed factors, and smoke density factors obtained with the ASTM E 84 test method. The standard has been changed editorially, in fact, to emphasize that "Fuel contributed and smoke density as well as flame spread are recorded in this test. However, there is not necessarily a relationship among these three measurements" [*24*].

Those familiar with the operation of the 25-ft flame spread tunnel furnace recognize the need for such a statement. Some materials by their nature burn rapidly and with such high temperature that most of the unburned carbon particles are consumed and, as a result, the smoke is light. Others, as has been indicated, burn rapidly and produce high smoke values. Thus, the flame spread rate may be high and the smoke density factor either low or high depending upon the particular material being investigated.

Evidence exists for the need to exercise a degree of control over the use of materials that produce copious quantities of smoke in fires. More study is needed, first, to determine how best and at what level to set limits and, second, to establish the relative importance of building materials on the one hand and furnishings or other building contents on the other.

Efforts to Control Smoke in Building Fires

Efforts of firemen to reduce smoke accumulation in burning buildings has been subject to public complaint, scorn, and ridicule. Much of the public fails to realize that opening a hole in the roof may be the only means for effecting prompt rescue of trapped occupants or for entering the building to fight the fire at its source. Misunderstanding comes from concern over the damage done and from the fact that as the smoke clears the fire becomes more visible and it appears that the action of the firemen has made the fire burn more vigorously. In some instances this is probably true, as fresh air enters the building and feeds the fire, but it still makes it possible to locate and attack the fire directly.

Similar principles are involved in building design through provision of vents at the top of elevator shafts and other vertical openings. Many such shafts are protected from normal heat loss and from the weather by top closures having heat actuated opening devices. In the event of fire these automatically vent smoke and hot gases. Without such openings the smoke, heat, and toxic gases would tend to spread horizontally at the top of the building and on various other levels. Most codes make provision for this type of protective device.

Another form of relief from the smoke hazard is under the control of the occupant. A person caught in a hotel room during a fire should be sure that his entrance door and any other corridor openings are tightly closed. If there is a double-hung window in the room in which he is trapped, he should, if possible, open it equal amounts at top and bottom, since heat, gases, and smoke tend to go out at the top and fresh air to come in at the bottom.

If the general principles governing the movement of smoke in buildings can be recognized, a great deal often can be done through building design to minimize the smoke hazard. The possibility of confining smoke by various means to the space where it is generated is the subject of other lines of significant investigation. Smoke generated at elevated temperatures reacts in a manner different from cool smoke. In the former case, expansion of air within the involved space will cause pressure increases resulting in the forced flow of smoke through cracks around door or window openings. On the other hand, even with extremely cool smokes, the natural ventilation of a room may be sufficient to cause large losses from the room. This can be especially important in high rise buildings where natural ventilation effects may be greatly magnified.

The temperature differences usually maintained between the interior and exterior atmospheres tend to create forced ventilation of such structures as a result of the buoyancy differences of the air inside and outside the building. Buoyance imposed pressure differentials over the building height may be as large as, if not larger than, those produced by an active fire in a single compartment. Such forced ventilation is greatest when the temperature differential between the interior and exterior of the building is greatest.

Through the planned use of an air conditioning system, corridors can be pressurized at a level that does not interfere with normal usage. If a fire has started in a room off the corridor, the pressurization in the corridor will confine the smoke and gases to the point of origin. These and other approaches to the control of smoke movement in high buildings are under intensive study in Canada [*25*], England [*26*], Japan [*27*], and elsewhere.

Finally, the use of smoke stops and smoke doors in high bay areas and in corridors has assisted in saving many lives in fires. One wing of the Hartford Hospital was not affected in the 1961 fire because of the proper operation of smoke doors in the corridor [*28*]. Another wing did suffer damage because one side of a smoke door, for some unexplained reason, was opened during the fire or was left open when the fire started. The effectiveness of smoke doors sometimes is nullified by the lack of similar protection in the plenum space that may exist above the corridor ceiling.

The role of air conditioning and heating systems in fire situations has not been clarified entirely. A classic fire in 1929 in the Cleveland Clinic resulted in many deaths allegedly due to carbon monoxide and nitrous fumes from burning X-ray film being carried through the hospital by the air conditioning system [*29*]. To prevent such occurrences, smoke detection devices are arranged to cut off air conditioning systems automatically in the event of fire. There are times, however, when it is inexpedient and unwise to cut off air conditioning systems and some type of manual override should be provided in such cases. Automatically actuated dampers in air conditioning and heating ducts also provide a means for confining the fire to the area of origin.

Test Methods for Smoke Measurement

Recognizing the substantial costs involved in conducting full-scale tests, the infrequent occasions when these are possible, and their impracticality for routine control purposes, a review of smaller test methods is in order. Earlier smoke tests developed for other uses are mentioned only to indicate that the smoke question has broad implications that have been of concern for many years.

The Ringelmann chart, perhaps the oldest method used to estimate smoke production, still is in use today and is referenced in many of the new air pollution control ordinances [*30*]. This method, developed in 1861 in France, provides a means for assessment of the density of smoke stack effluents on a scale from 0 to 100 percent. While application of this measurement method may standardize the assessment of how offensive the smoke discharge appears, it is subjective and lacks a capacity for quantitative measurement or for discrimination between colored smokes.

In 1948 a method was described for comparing Ringelmann chart readings with a smoke measurement apparatus used in the Sears Roebuck Co. and Battelle Memorial Institute laboratories [*31*]. These were similar to the system used in present-day apparatus and provide for recording emf output of a photoelectric cell as the light beam from a spotlight is interrupted by the passage of smoke particles. This, basically, is the system used in the 25-ft tunnel furnace, the 8-ft tunnel furnace developed at Forest Products Laboratory, the chamber smoke test developed by Rohm and Haas, and the test chamber developed at the National Bureau of Standards.

The ASTM E 84 Tunnel Test [*15*]/ The first of the test methods mentioned is the 25-ft flame spread tunnel furnace developed originally by Underwriters' Laboratories and eventually adopted as ASTM Standard Method E 84. Other organizations using the same test method have given it their own designation: ANS 2.5, NFPA 255, UBC 42-1, and UL 723.

In this test the 20-in. by 25-ft test specimen rests on top of a long, enclosed, box-like furnace such as is illustrated in Fig. 1. Gas burners at the air intake end provide an exposure flame 4.5 ft long with an induced air flow of 240 ft/min and a heat input of 5000 Btu/min. Flame spread is observed through windows along one side

Table 2—End Points on Smoke Density

Building Code	Classification[2]		
	Class A (or I)	Class B (or II)	Class C (or III)
San Francisco [*17*]	25	200	450
Philadelphia [*20*]	...	...	225
New York City [*21*][a]	25	50	100
Michigan [*22*][b]	50	125	200
Texas [*23*][c]	25	75	200

[a] Applies to interior finishes in exits, corridors, and institutional occupancies.
[b] Applies to interior finishes in school buildings.
[c] Applies to floor coverings in nursing and convalescent homes. In certain conditions intermediate levels are established at 60, 100, 125, 150, and 175.

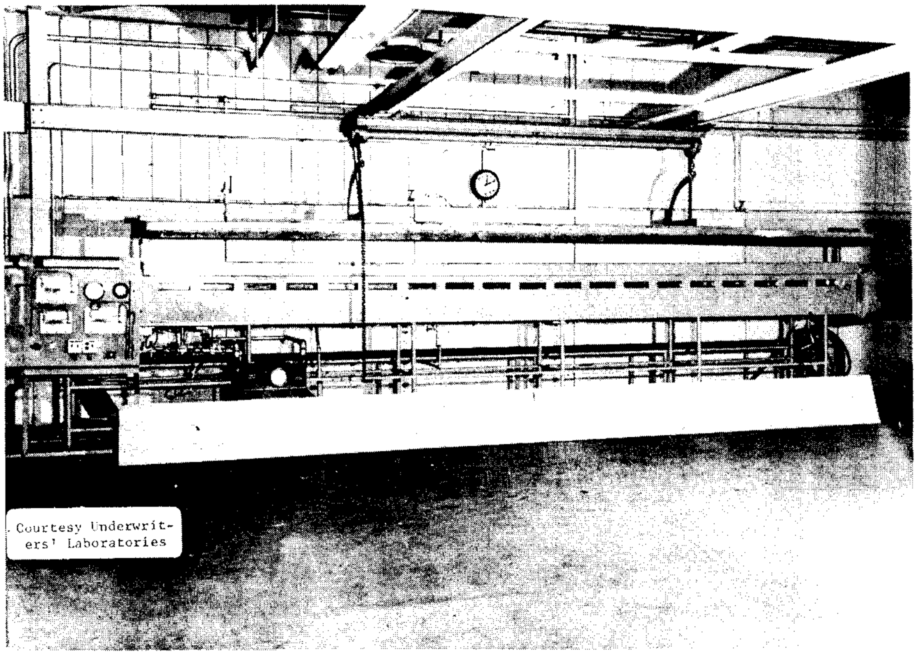

Fig. 1—*ASTM E 84 flame spread tunnel test.*

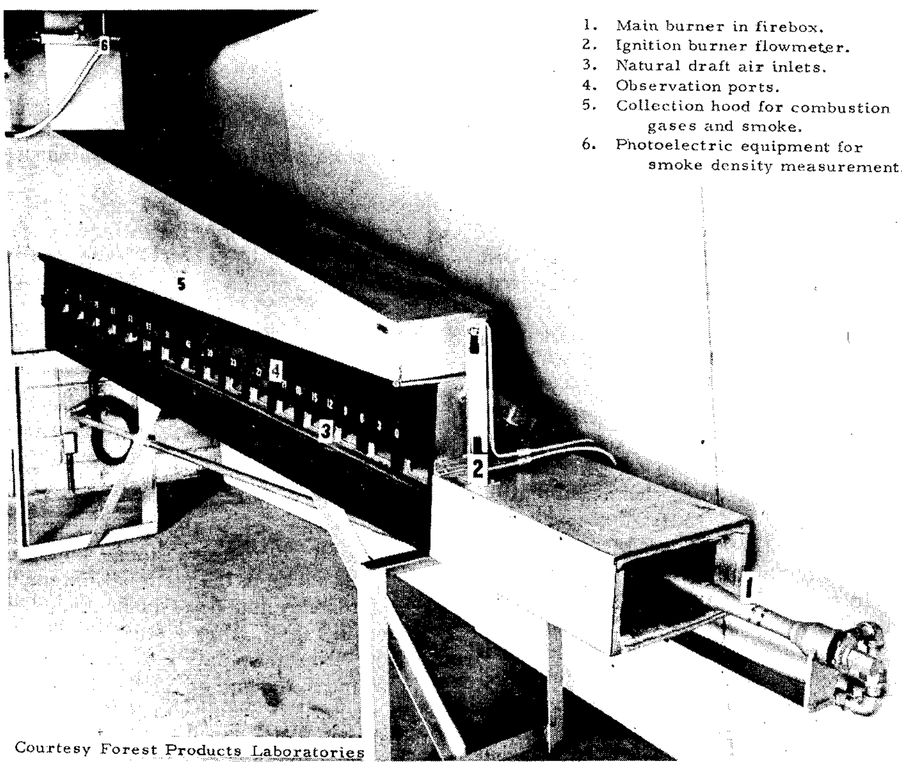

Fig. 2—*ASTM E 286 flame spread test.*

of the furnace, temperatures are measured by thermocouples placed at specified points, and smoke is measured by the output of a photocell and spotlight placed over and underneath openings in the stack. Temperatures and the photocell output are recorded continuously during the 10-min test. The smoke density and fuel contributed ratings are determined by comparing the area under the smoke curve with that obtained with asbestos-cement board and red oak flooring control and calibration materials.

This test was designed to be on a scale large enough to take into account the effects of construction variations such as joints and fastening devices. Its primary purpose was to develop a surface flame spread rating, but it provided also for measurement of the heat developed through a fuel contributed factor and the smoke developed through a smoke density factor. Asbestos-cement board having no combustibles is used as one calibration material and red oak flooring, a fairly uniform building material, as the other. When exposed to standard fire conditions, the asbestos-cement board is given a zero rating for flame spread, fuel contributed, and smoke density; similarly, red oak flooring is given a 100 rating for these three items. Results with all other materials are compared to these ratings. This standard has been adopted widely in building codes throughout the country for the control of flammability of interior finishes, and in many it is used as a control on smoke density as indicated earlier.

The ASTM E 286 8-ft Tunnel Test [32]/ The 8-ft tunnel furnace, see Fig. 2, developed by the Forest Products Laboratory for research and development purposes, also provides data on smoke development as well as flame spread and heat contribution. In this test, the specimen size is $13\frac{3}{4}$ by 96 in. The smoke development, as in the 25-ft tunnel test, is measured in the furnace stack by a light source and a phototube during the progress of the flame spread tests. The light obscuration, as indicated by the phototube system, is then related to the results of tests on red oak and asbestos millboard for calculation of a smoke index value.

The primary heat source for the test specimen is a radiant stainless steel plate and a small pilot ignition flame. Tests of fire retardant materials usually yield high smoke index values, being under nonflaming exposure, in comparison to the standard red oak, which flames under the thermal radiation level present in the furnace. This differs from tests in the 25-ft tunnel furance where a large test flame is continually present for both red oak and fire retardant materials, thus usually resulting in low smoke index values for the retardant products. However, the higher smoke index value for retardant materials in the 8-ft tunnel is an advantage in studying the influence of different retention levels and types of retardant chemicals on smoke production [*33*].

The ASTM D 2843 Smoke Test [*34*]/ A smoke test developed initially by the plastics industry for light transmitting plastics was recently adopted as ASTM D 2843-70. This test originally was developed by the Rohm and Haas Co. and was known as the XP-2 smoke density chamber [*35*]. Its purpose is to determine the extent to which plastic materials are likely to smoke under conditions of active burning and decomposition in the presence of flame.

Courtesy Rohm & Haas Company

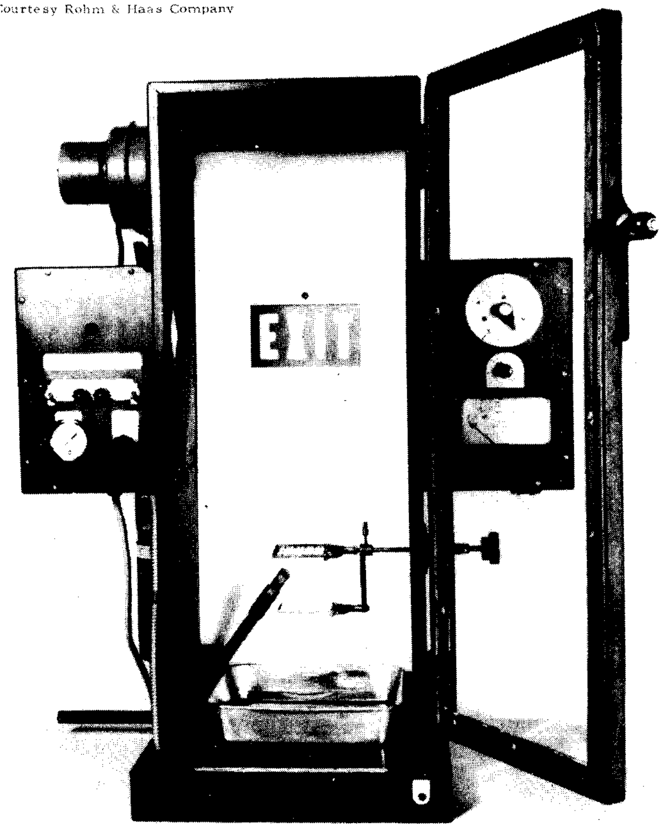

Fig. 3—*ASTM D 2843 smoke chamber.*

Courtesy American Instrument Company

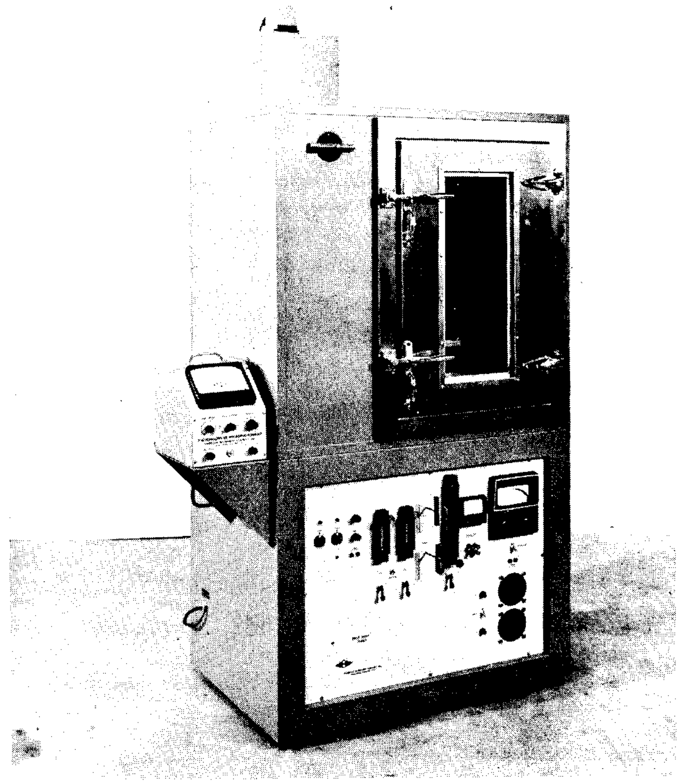

Fig. 4—*Aminco smoke chamber developed by National Bureau of Standards.*

The apparatus, as illustrated in Fig. 3, consists of a box 12 in. square and 31 in. high having a hinged, glass front access door and 1 by 9-in. openings in each side at the base. A 1-in.-square specimen usually $\frac{1}{4}$ in. thick is placed on a supporting metal screen $8\frac{3}{4}$ in. above the base and in the center of the chamber. Materials of a thickness greater than $\frac{1}{4}$ in. also may be tested.

The chamber operates on the premise that under actual fire conditions smoke will be produced if the material is burning or decomposing in the presence of heat or flame; thus, during the 4-min test, the specimen is exposed to the flame of an aspirating-type burner.

Smoke is measured by the output of a photocell mounted on one side of the chamber activated by a light source on the other side. This output is recorded and the total smoke produced determined by measuring the area under a curve of light absorbtion plotted against time. Maximum smoke density during the test also is recorded. An exit sign placed on the inside face of the back of the chamber provides a measure for visually or photographically observing smoke development.

Of the various smoke tests available, this method utilizes the smallest specimen. It is available commercially.

The ASTM E 162 Radiant Panel Test [*36*]/ The National Bureau of Standards has developed a radiant panel test apparatus for evaluating the surface flammability of materials using a test specimen 8 by 16 in. in size. In this test the specimen is held at an angle of 30 deg to the vertical with a pilot flame at the upper edge. A porous refractory panel burning a gas-air mixture constitutes a source of thermal radiation and is positioned to irradiate the test specimen for a period of 15 min at controlled rates. Smoke and other combustion products are drawn into a hood over the apparatus.

This test method provides two methods of smoke measurement both involving collection of particulate material on a glass filter disk. One method makes use of disk weight changes for smoke measurement, and the other involves photometric measurement of the optical density of the smoke particulates collected.

The Monsanto Test Method [*37*]/ A method for smoke measurement was developed at the Monsanto Co. laboratories in 1964. It utilized the ASTM D757 plastics flammability test [*38*] in which a $\frac{1}{8}$ by $\frac{1}{2}$ by 5-in. specimen is ignited on a heated Globar rod. Fumes were drawn through a filter paper which was weighed before and after the test. Smoke emissions were calculated from the formula

$$\frac{\text{Weight of smoke on filter paper}}{\text{Weight of specimen}} \times 100 = \%\ \text{smoke}$$

The test method has been used occasionally but has not received widespread support.

The NBS Smoke Chamber [*39*]/ Continuing its interest in the development of a relatively inexpensive smoke measurement test method, the National Bureau of Standards developed a smoke chamber, shown in Fig. 4. After a study of various existing and proposed test methods for smoke measurement, an enclosed chamber 2 ft deep, 3 ft wide, and 3 ft high was developed, providing for

1. Use of a small 3-in.-square specimen usually $\frac{1}{4}$ in. thick.

2. Exposure of one surface to flame.

3. Exposure of a specimen to a radiant heat source to induce smoldering combustion.

4. Use of a vertical rather than a horizontal light path for photometer smoke measurement.

5. Calculation of results in terms of specific optical density using the formula

$$D_s = \frac{DV}{AL}$$

where

D_s = specific optical density,
D = optical density ($\log_{10}$ (1/transmission)),
V = test cabinet volume,
A = test specimen surface area, and
L = photometer path length.

While this test method may be more elaborate than some (and less expensive than others), it does provide a means for reporting smoke measurement in terms of specimen surface area, volume of collection space, and length of light path in one measurement. The equipment also is available commercially.

Variations of the NBS smoke chamber have been developed by others; notably at the Lawrence Radiation Laboratory [*40*]. Here the chamber was modified primarily to provide controlled ventilation rates up to 20 air changes per hour.

The NBS smoke chamber has been used as a source of samples for analysis of combustion gases. In fact, all test methods discussed in this paper could be used for gas analysis where the auxiliary equipment is available.

Test Criteria

If the objectives of a smoke measuring device can be agreed upon, the problem of developing a test appropriate for use by regulatory officials or industry can be simplified. An examination of test criteria then is in order. The points to be covered include

Type of test
Reproducibility and repeatability
Relation to hazard in building fires
Size and cost of apparatus

The importance of these items depends to an extent on the individual's viewpoint and interests. To the manufacturer, size and cost of the test apparatus, size of the test specimen, and the severity of the test itself are of great importance. Not only is the cost of qualifying his material or system significant but also this factor will dictate whether or not he can install the facility in his own plant and thereby handle development work in his own laboratory.

The regulatory official, on the other hand, is interested in the nature of the test itself. Does it provide an effective tool for controlling the hazard existing in real life situations? Does it provide results in a graduated scale so that materials can be permitted in accordance with the degree of hazard that they represent for specific uses? Are the results consistent among the various laboratories—is the test reproducible?

Type of Test/ A primary objective of Committee E-5 in developing fire test methods has been adherence to the performance concept. Applied to smoke tests, this means that, to the extent possible, one test should be applicable to all materials. The distinction between performance and specification tests is an important one. At the same time, it should be noted that specification or material oriented tests are essential for research, product development, and quality control.

Two types of performance tests should be considered: (1) the "go-no go," or single criterion, type of test and (2) the test that permits classifying a product in a range so that its use may be permitted in some areas or situations but excluded in others according to the degree of hazard. The usefulness of a test method to a regulatory official may be enhanced if a continuous scale of measured performance is available rather than the reporting of results on a go-no go basis. In other words, a test providing numerical results over a wide range will permit the exercise of engineering judgment in code writing.

In regard to smoke, it would not be justified to exclude all materials that smoke while burning. The acceptance of specific materials is and should be based upon the hazard of a particular use and location and on other types of fire protection that may be present. Thus, a type of test that will provide a range of results appears to be desirable.

All of the test methods discussed do provide a range of numerical results. Whether or not in any one test method the scale or range is satisfactory, too narrow, or too wide will be determined by experience. The approach taken in San Francisco in this regard has been cited earlier in this paper.

Reproducibility and Repeatability/ In a technical sense a test method that does not give consistent results within an acceptable tolerance range is of little value. Test results obtained within any one laboratory should be repeatable especially in view of today's fluid personnel situation. Likewise, it is important that comparable results be obtained in whichever laboratory is running the tests. Thus repeatability and reproductibility are basic considerations in any test method.

The 25-ft tunnel furnace (ASTM E 84), the 8-ft tunnel furnace (ASTM E 286), the smoke chamber for plastics (ASTM D 2843), and the NBS smoke chamber have been subjected to interlaboratory and intralaboratory tests. A test series with the 25-ft tunnel furnace showed variations in smoke readings leading to corrective measures. The subsequent construction of other similar furnaces provided opportunities to check performance.

ASTM Committee D-20 sponsored two series of interlaboratory tests of the D 2843 test method which provided a basis for adoption of this standard. The National Bureau of Standards has sponsored a test series on the NBS smoke chamber, with results sufficiently close to encourage the sponsor to submit this test method for adoption by ASTM.

Correlation between different test methods is a more complex problem—fire tests, like materials, have specific performance characteristics. Because of the basic differences in test methods and the effect of scaling, it is difficult to achieve good correlation between test methods. Close correlation can be obtained with one type of material but this may not extend to all materials. Continued effort is needed to improve correlation between tests and to relate realistically the results obtained to performance of a wide variety of materials when they are exposed in building fires.

Relation to Hazard in Building Fires/ The tensile or compressive stresses on a structural member can be calculated within a reasonable degree of accuracy and the ability of a given quality of steel, concrete, or timber to withstand those stresses can be determined using small specimens in the laboratory. The amount of smoke that can be anticipated in any fire and the hazard to life of that smoke have not been determined. The day undoubtedly will come when through the application of modeling techniques we will be able to forecast accurately how a given material or combination of materials will react in an actual fire. Until then full-scale fires should be studied to the point that the smoke hazard can be defined and related to laboratory test results. In such cases, because of the wide variation in the characteristics of fires, there should be assurance that the full-scale fire is one which is representative of more severe exposure conditions. This may require a series of large-scale fires with varying conditions of space, fuel, and ventilation. Otherwise, the validity of the test method would be questioned if and when a serious fire occurred where "approved" materials had been used. While some work of this nature is in progress, the establishment of end points for smoke measurements, under the present state-of-the-art, are generally on an arbitrary basis.

Size and Cost of Apparatus/ From the point of view of public safety, size and cost of the test equipment and of the test itself should be of secondary importance. The larger the test specimen the more likely it is that realistic thermal stresses, joint effects, and other construction details will be considered. On the other hand, smaller test specimens and equipment make it possible to run more tests at several levels of exposure. Regardless of the size of the test, it should either reflect as accurately as possible the hazard being evaluated or provide a qualitative and quantitative measure that can be applied to specific situations.

In addition, industry has need of product development tests providing an indication, at least, of results that might be expected in acceptance tests. It also needs quality control tests to aid in the maintenance of production standards. Since laboratory facilities and funds for supporting research and development activities frequently are limited, the size and cost of test methods are of paramount importance to industry. From the manufacturer's point of view a test that could serve both purposes, product acceptance and product development, would be ideal; however, the two objectives may not be mutually compatible.

A further consideration in relation to cost is that of the size of the test equipment and the space required for storing and conditioning specimens. In the case of the 25-ft tunnel furnace, and to a lesser extent with the 8-ft furnace, this cost is such that few facilities have been built. Even though most building regulations in the United States and Canada reference this test for interior finish, the number of furnaces built for qualifying materials is limited. Thus, industry is forced to ship test specimens long distances, spend considerable time in travel to witness tests, and sometimes wait several weeks for a test date. An equally acceptable test available at lower cost and utilizing less space undoubtedly would be attractive to more laboratories.

Where Do We Stand Today?

The foregoing discussion reflects a variety of approaches to the measurement of smoke as it may develop in building fires. Obviously there are differences in the basic philosophies of the test methods that have yet to be resolved. Experience over a period of years will reveal the advantages and disadvantages of the respective methods, and eventual acceptance by regulatory bodies of any one of the alternative methods may decide the issue. Additional acceptance of alternative test methods would be desirable only if it can be shown that meaningful results can be obtained for the entire range of materials evaluated; otherwise, each manufacturer will seek that test which shows his material to the best advantage.

Experience in fire testing indicates that full correlation between test methods is unlikely. Inherent differences in test methods preclude the achievement of this ideal. Nevertheless, the attempt should be made to compare results from the various tests. To an extent this is being done by at least three laboratories—Forest Products Laboratory, National Research Council of Canada, and Underwriters' Laboratories, Inc.—each of which has at least two of the test methods in operation. Such comparative testing could help to demonstrate the most useful method for use in codes. It also could help to indicate that test which best serves various industries for product development purposes.

It is encouraging to note that some laboratories, notably Lawrence Radiation Laboratory and the National Bureau of Standards, are continuing their efforts to extend the usefulness of the NBS chamber to other areas, particularly gas analysis. Personnel at Underwriters' Laboratories, Inc., are working toward improvement in the smoke measurement associated with the 25-ft tunnel furnace, particularly in the area of changing to an optical density measurement.

Interest in specific test methods should not overshadow consideration of the broad aspects of the problem. A report on work done for the Society of the Plastics Industry at the Illinois Institute of Technology Research Institute concludes [41]

> The data on smoke production indicate that no single smoke rating number can adequately define the relative smoke hazards of interior finish materials. Both environment—exposing fire and location—and other material properties are completely overshadowing whatever inherent smoke-producing quality, if there is such a simple definition, each material exhibits. The causes of the behavior observed here may well be the same causes that produce significant disagreements between various existing test procedures and which even tend to produce scatter in the results of any given procedure. Although as yet not found, it seems reasonable to suspect that a combination of the results of several tests, or of operations of an existing test procedure under two or more widely differing environments, can provide the data needed in order to devise a rating system that adequately accounts for material location and expected fire exposure severity. Certainly, it does not appear justified to judge the smoke producing ability of a material in all locations and occupancies on the basis of any single rating number.

The Research Subcommittee of Committee E-5 in a prepared statement recently concluded [42]

> As far as feasible, the complexity of both fire and building construction materials and methods should not be permitted to require the use of qualitative rather than quantitative test procedures. Real efforts must be made to correlate laboratory test procedures with material and construction behavior during actual large-scale fires. There must be an attempt to identify the material properties of interest and provide adequate test methods for each property. We believe the tendency to use one test method for measurement of several material properties tends to encourage use of qualitative rather than quantitative measurement techniques and should be avoided unless it can clearly be demonstrated to provide the most expeditious and technically useful means of measuring the properties in question.

Perhaps the greatest need at the moment is for large-scale tests through which the true hazard of smoke and meaningful end points can be defined. Work in this direction is in progress at various laboratories in this and other countries. Such work may disclose the significance of smoke as a life safety factor in the initially developing fire as against the fully developed fire. From this point of view, the situation may be quite different in buildings of varying size and height.

Finally, every encouragement should be given to the study of building design as related to smoke development in building fires. As has been indicated, this concept is under intensive study in several countries.

The basic premise of this paper was consideration of smoke as divorced from noxious gases, heat, and other accompanying effects. This probably is necessary, since the techniques for smoke measurement are quite different from those of gas analysis and temperature measurement. Nevertheless, if a toxic gas such as carbon monoxide should develop faster than smoke, smoke measurement loses much of its importance. In other words, attention should be given eventually to the hazard of combustion products as a system. Perhaps the ultimate objective should be the development of a formula by which smoke, toxic gases, oxygen depletion, heat, and the rate at which these conditions develop can be integrated and applied to given situations.

In the same context, the wisdom of seeking life safety in building fires through control of building materials has been questioned, since fires usually have their inception in furnishings and other building contents. Rather, concentration on automatic detection, warning, and suppression systems is suggested. Undoubtedly both approaches should be explored thoroughly and a proper balance established.

With fire losses at such a high level in the United States and Canada, it is our opinion that every avenue of approach must be developed. Smoke certainly is an important problem that must be resolved.

(References continued on page 42)

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