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OPACITY OF SMOKES FROM CERTAIN WOODS AND PLASTICS
UNDER SMOLDERING AND BURNING CONDITIONS

James R. Gaskill

Charles R. Veith

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OPACITY OF SMOKES FROM CERTAIN WOODS AND PLASTICS UNDER SMOLDERING AND BURNING CONDITIONS

by

James R. Gaskill and Charles R. Veith

Hazards Control Department
Lawrence Radiation Laboratory, University of California
Livermore, California

Introduction. As a part of its responsibility to Lawrence Radiation Laboratory, the Hazards Control Department is examining the opacity of products generated when materials used in construction or fabrications are exposed to radiant heat with or without the presence of an igniting flame. Subsequently, we shall examine the toxicity of such products by physico-chemical means.

One object of our efforts is to work out, cooperatively with others, an acceptable test system to determine the opacity -- and toxicity -- development of the products evolved from smoldering or burning materials of interest. For simplicity, we refer to these products as smoke.

Examination of the literature and discussions with fire safety personnel have led to the general agreement that smokes from heated or burning materials are hazardous in three respects: (1) rapidly formed opaque smokes make difficult the escape of occupants from a fire area; (2) these smokes make fire fighting difficult and may cause accidents among fire-fighters; and (3) smokes are known to be toxic.¹ Hence, we should like to choose materials of construction which will preferentially exhibit minimum flame-spread and smoke-generating characteristics. If we can do this, we may be able to build some degree of fire safety into a facility or piece of equipment.

A literature search plus discussions with workers on fire test methods indicate that no satisfactory or generally acceptable smoke measurement test is available. However, Rohm and Haas Company has developed a smoke chamber² 12 X 12 X 30 in. high, in which a 1-in.² sample is burned by a propane torch. The rising smoke column interrupts a horizontal light beam directed onto a photocell. The results are reported in percent light absorbed (100 minus percent transmission) plotted over a 4-min period.

The Fire Research Section of the Bureau of Standards has modified the Rohm and Haas design³ and has built a larger chamber which uses a radiant heat source. In consultation with the Bureau, we have built such a chamber and made further modifications to make our investigations more flexible. We have also begun a program to determine the opacity of smokes -- and later the toxicity of such smokes -- produced from materials of interest under selected conditions of ventilation, radiant heat flux, and the presence or absence of an igniting flame (flaming vs smoldering condition).

Apparatus. Our smoke chamber is essentially a copy of the unit built at the U. S. Bureau of Standards. It consists of an 18-cubic-foot metal box with a glass front door, and containing a radiant source furnace and sample holder, a vertical path light-source and phototube system, and an exhaust fan located in the upper left side toward the rear. Associated with the chamber are furnace and light-source controls, a radiometer, an air-cooling system for the radiometer, and a small pilot gas flame system, together with its regulated gas and premixed air supply. The gas flame is used to induce ignition in cases when flaming exposures are desired.

Our modifications consist of the following: (1) replacable Pyrex lens covers; (2) a more sophisticated photometer amplifier; (3) a small manifold jet burner, which in some cases is more efficient than the NBS-single jet burner; (4) an illuminated exit sign in the back of the chamber, in the hope of correlating visibility with optical density; (5) a manometer to measure changes in chamber pressure; (6) a remote handling sample positioner; and (7) a regulatable ventilation system. With the latter, we can obtain up to 20 air changes per hour.

Similar to NBS, our test samples are 3-in. squares usually 1/4 in. thick. They are mounted in a stainless steel frame and held in place with an asbestos-board backing plate and a spring clip. The frames have top and bottom channels that fit the rods in the furnace assembly, enabling the samples to slide in front of the heat source or away from it. Samples are usually wrapped in aluminum foil, with the face cut away, to prevent smoke from leaking out through the back of the holder. The exposed sample face measures 2.56 X 2.56 in. (6.57 in.²).

Chamber Operation. In operation, the furnace is switched on and adjusted to the appropriate heat level as measured by the radiometer and recorder, the desired ventilation adjustment is made, and the system is allowed to come to equilibrium. With the photometer range switch set at X 1, the light source iris and controlling voltage are adjusted to yield a rating of 100% transmission on both the photometer and the recorder. A previously conditioned and prepared sample is mounted in the holder and placed on the rods next to the radiometer, which at this time is directly in front of the radiant source. At a given signal, the sample is pushed along the rods in front of the furnace (thus displacing the radiometer to one side), a timer is started, and the recorder drive is started. The optical transmission of the light source to the phototube is read at 1-min intervals until a minimum transmission is attained and the resultant curve shows a definite and final reversal. Notes are made of observed phenomena; ignition, auto-ignition, splitting, puffing, flaring, flame extinction and re-ignition, etc.

The optical transmission data are used to calculate the specific optical densities of the smoke from the test sample, according to the considerations shown in Fig. 1. Note that the specific optical density D_s is an intrinsic property of the smoke obtained from the material under the particular conditions. The optical density is independent of the sample and chamber sizes and the length of the light path. Of course, D_s will depend upon the mass and thickness of the sample and upon any surface coatings associated with it.

For convenience, we have prepared a film strip that shows the conversion from percent transmission to specific optical density units for values of T varying from 100 to 0.001%. In practice, we plot D_s vs time in 1-min increments in each test.

The experimental values in which we are interested are shown on the top half of Fig. 2. These are D_m , the maximum optical density attained in a test; T_m , the time at which this occurs; R_m , the maximum rate increase of D_s averaged over a 2-min period; T_{Rm} , the time at which this occurs; and D_s-16 , the time at which $D_s = 16$. Our reason for this interest is as follows: A very dense smoke which occurs early in the smoldering or burning period is more hazardous than a lighter smoke, or one that occurs later; considerations by Gross³ indicate that an observer would find it difficult to see an exit sign through 10 ft of smoke with $D_s = 16$. The time at which this occurs is our obscuration value.

Shown in Fig. 3 is the definition and derivation of a Smoke Obscuration Index proposed by the Bureau of Standards. This index is simply the product of the maximum smoke density and the rate of density accumulation divided by the time to reach a critical density level, i.e. $D_s - 16$. We have applied this calculation to our results.

Work Done. To date our experiments have been limited to determining the opacity of smokes from a number of woods and plastics, with the following parameters: heat flux of 2.5 W/cm²; smoldering and flaming exposures; closed chamber with normal air content; and ventilation rates of 3, 6, 12, and 20 air changes per hour.

Initially, we made a number of tests using oil-tempered hardboard as a standard; we also exchanged samples of this material with the Bureau of Standards and made comparative studies.

Results. Figure 4 shows the D_s vs time curves for our hardboard both with and without an igniting flame. Note that the smoldering yields a denser smoke with obscuration ($D_s - 16$) occurring in about half the time, as

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compared with flaming ignition. The agreement among replicate tests seems to be good.

Figure 5 shows the effects of ventilation on maximum smoke density (D_m) for hardboard under smoldering and flaming conditions. As would be expected, ventilation tends to clear away the smoke; in this case a low rate, (i.e., three to six changes an hour) has the most effect.

Comparative smoke test data were obtained by NBS and LRL on exchange samples of hardboard. Generally the agreement is very good for non-flaming exposures, but less satisfactory for the flaming conditions. Both we and personnel at the Bureau are studying the question of complete ignition of the smoke by either of the two burner systems.

A summary of the pertinent data obtained for various woods without ventilation and under smoldering and flaming conditions is shown in Table 1. It is obvious from the results that smoldering woods yield denser smokes than burning woods; the opacity increases at a greater rate in the former case. With some exceptions, obscuration occurs in about half the time as when the woods are burning.

The effects of ventilation on the maximum smoke densities attained by these woods are shown in Table 2. Again, the contrast between smoldering and burning conditions is apparent. However, under smoldering conditions some woods — red oak, white oak, and black walnut — require about twice as much ventilation as the others to reduce the density to a value of 100-150.

The results of the tests on eleven plastics are shown in Table 3. With two exceptions, smoldering plastics yielded quite dense smokes; obscuration occurred in about two to four minutes. With the same two exceptions, flaming exposure yielded faster obscuration times. The smoke densities attained in this latter condition varied: the flame-resistant materials yielded generally denser smokes; the others, lighter smokes — all compared to the smoldering densities. Three materials, two acrylics and a polystyrene, tend to auto-ignite.

When these plastics are ventilated under smoldering conditions, the maximum smoke densities show the same trends as the woods (see Table 4). However, under flaming exposure, five of the seven materials tested showed little or no decrease in smoke intensity, regardless of the ventilation rate. In fact, in two cases ventilating the material increased the smoke density.

The smoke obscuration indices for the various materials tested are shown in Table 5. The values are shown for both kinds of exposure and with selected ventilation rates. Without ventilation, the smoldering woods show indices in the range of 25 to 80; burning woods show values of less than 10. Ventilation of course reduces these values significantly. Unventilated smoldering plastics show generally the same range of values as the woods. However, the flaming plastics show an extraordinary range, i.e., from 10 to 2400. The ventilation effects on flaming plastics discussed before are also evident in the indices shown.

The interesting contrasts in the behaviors of the three acrylics are shown in three sets of typical curves in Fig. 6. Also shown are the auto-ignition effects.

Finally, the effect of mass and/or thickness on smoke density is shown for one material, a clear, rigid, polyvinyl chloride, on Fig. 7. Under smoldering conditions, the mass/thickness effect does not become evident for about 7 min, at which time smoke is fairly dense. Subsequently, the greater thickness/mass of material yields a higher, more persistent density. Under flaming conditions, there is for practical purposes no difference, except possibly for the persistence of the very dense smoke in the case of the greater mass and thickness.

Discussion. Based on our work to date, we believe that the modified, NBS-developed chamber is a very useful tool in examining smoke opacity development of materials under various fire conditions. Data accumulated offer suggestive evidence of choices of materials of construction and fabri-

cations to minimize the smoke opacity hazard. Much work remains to be done. We have an additional 20 materials awaiting test; also, we plan to look into lower and higher oxygen atmospheres and also the effects of a higher radiant heat insult. If one may assume the existence of results not yet obtained, then it is possible to suggest that the smoke index of a material might be defined as follows:

S.I. = $S_{nfv} + S_{fnv} + S_{vnf} + S_{vfv} + S_{hnf} + S_{hnf}$ where the S's are all smoke obscuration indices obtained under the following conditions:

nfv = no ventilation or flame, heat = 2.5 W/cm^2 ;

fnv = flame, no ventilation, heat = 2.5 W/cm^2 ;

vnf = no flame, heat = 2.5 W/cm^2 , ventilation = an agreed upon value;

vfv = flame, heat = 2.5 W/cm^2 , ventilation = the same agreed upon value;

hnf = no flame or ventilation, but with a heat insult of say, 25 W/cm^2 .

The intent of this index is to describe the smoke opacity characteristics of a material under fire parameters which might be expected to occur in most cases. Conceivably, a toxicity index might be arrived at in a similar manner once the studies have been made and the values have been agreed upon.

We gratefully acknowledge the support of our Department management, and the assistance of colleagues and shop support personnel. This work was performed under the auspices of the U. S. Atomic Energy Commission.

References

¹Survey of Available Information on the Toxicity of the Combustion and Thermal Decomposition Products of Certain Building Materials under Fire Conditions, Bulletin of Research, No. 53, Underwriters' Laboratories (July 1963).

²"A Method of Measuring Smoke Density," Anon. National Fire Protection Association Quarterly, Q 57-9 (January 1964).

³D. Gross, J. J. Loftus, and A. F. Robertson, "A Method of Measuring Smoke from Burning Materials," American Society for Testing and Materials, Publication STP-422 (1967).

Fig. 1

OPACITY OF SMOKES

$$F_t = F_0 e^{-\sigma L}$$

$$D = \log_{10} \frac{F_0}{F_t} = \frac{\sigma L}{2.303}$$

$$D = D_s \frac{AL}{V}$$

$$D_s = \frac{V}{AL} \log_{10} \frac{F_0}{F_t}$$

For our chamber

$$D_s = 132 \log_{10} \frac{F_0}{F_t} = 132 D$$

Fig. 2

PERTINENT EXPERIMENTAL VALUES FOR SMOKE EVOLUTION FROM SMOLDERING OR BURNING MATERIALS

D_M = Maximum D_s = Maximum specific optical density attained

T_M = Experiment time = time (min) to attain D_M

D_{s-16} = Obscuration time = time (min) to reach a value of $D_s=16$

This is equivalent to a 16% transmission over a viewing distance of 10 ft in a $12.5 \times 20 \times 8$ ft room assuming that a 16% transmission is critical.

R_M = Max rate = $\text{Max} \frac{dD_s}{dt}$ averaged over a 2-minute period

T_{RM} = Maximum rate time = time at which R_M occurs

Average accumulation rate, R , is defined as average of linear rates for each of the four 20% smoke intervals between 10 and 90% of D_M - thus

$$R = \frac{1}{4} \left[\frac{0.9D_M - 0.7D_M}{t_{0.9} - t_{0.7}} + \frac{0.7D_M - 0.5D_M}{t_{0.7} - t_{0.5}} + \frac{0.5D_M - 0.3D_M}{t_{0.5} - t_{0.3}} + \frac{0.3D_M - 0.1D_M}{t_{0.3} - t_{0.1}} \right]$$

$$= \frac{D_M}{20} \left[\frac{1}{t_{90} - t_{70}} + \dots \right]$$

Hence $SOI = \frac{D_M \times R}{D_{s-16}} = \frac{D_M^2 \times [1/t_{90} - t_{70} \dots]}{20 \times D_{s-16} \times 100}$

where 1/100 is an artificial factor.

Fig. 3. Smoke obscuration index (SOI) defined as maximum smoke accumulation \times average rate of accumulation/time to reach a critical accumulation level

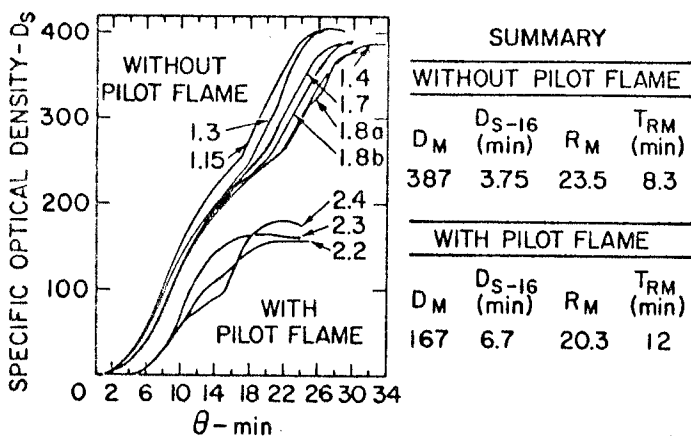


Fig. 4. Smoke density from oil-tempered hardboard.

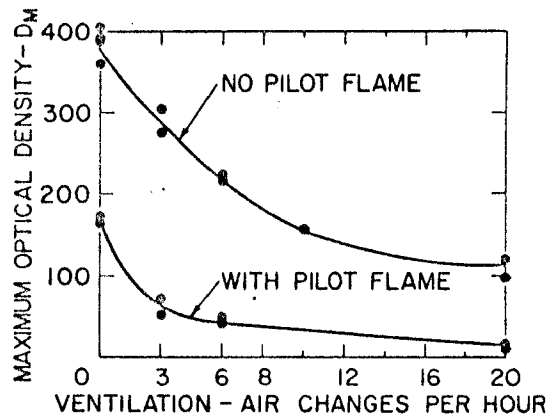


Fig. 5. Effect of ventilation rate on maximum smoke density for oil-tempered hardboard.

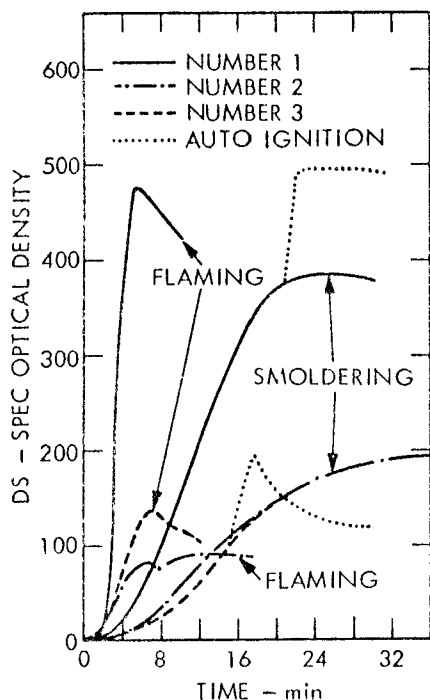


Fig. 6. Smoking behavior of three clear acrylics

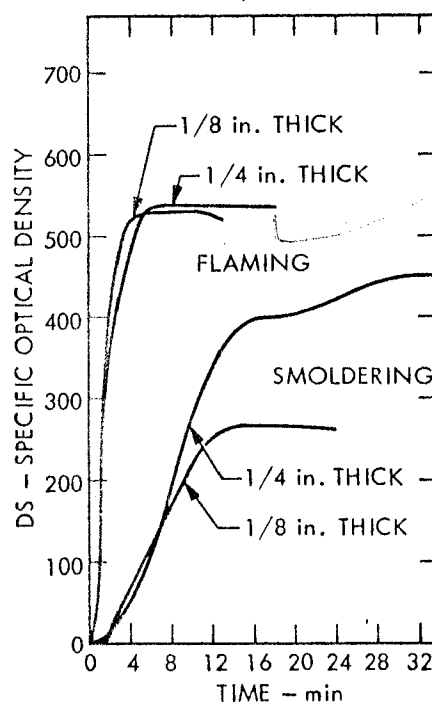


Fig. 7. Smoke opacity development of a clear, rigid polyvinyl chloride without ventilation

Table 1. Smoke densities of various woods.

Material	Smoldering - No Ventilation				
	Time to Max. Density (min)	Max. Density	Obscur. Time (min)	Max. Rate (min ⁻¹)	Time for Max. Rate (min)
Marine plywood	16	285	2.7	40	10.5
Red oak	20	395	4.1	54	14.5
Redwood	14+	260	2.7	43	8
DF Int. plywood	18	350	3.4	45	12
Douglas fir	20	380	2.1	35	11
White pine	15	325	2.3	50	8
Black walnut	16+	460	3.4	84	10.5
White oak	14+	420	3.5	85	9
Range	14-20	260-460	2.1-4.1	38-85	8-15
Flaming - No Ventilation					
Marine plywood	15	62	5.4	10	7
Red oak	17	76	8.0	15	10
Redwood	13	133	2.5	16	4
DF Int. plywood	14	96	5.3	16	7
Douglas fir	19	156	4.6	20	8
White pine	16	155	2.7	20	5
Black walnut	15	91	7.5	20	10
White oak	14	107	6.6	26	8
Range	13-19	62-156	2.5-8.0	10-26	4-10

Table 2. Effects of ventilation on maximum smoke densities from smoldering or burning woods.

Vent - Air Changes/Hr	Smoldering Conditions				
	0	3	6	10/12	20
Marine plywood	285	240	180	-	75
Red oak	395	325	285	205	125
Redwood	260	190	155	105	80
DF Int. plywood	350	285	210	95	95
Solid douglas fir	380	300	225	150	90
White pine	325	270	185	120	100
Black walnut	460	405	375	265	160
White oak	420	395	300	205	155
Flaming Condition					
Marine plywood	60	51	20	-	10
Red oak	75	55	50	20	5
Redwood	135	90	75	60	20
DF Int. plywood	95	55	45	25	15
Solid douglas fir	155	65	70	60	25
White pine	155	110	55	65	30
Black walnut	90	70	45	25	10
White oak	105	100	60	40	15

Table 3. Some density values of some plastics.

Smoldering - No Ventilation					
	Time to Max. Density (min)	Max. Density	Obscur. Time (min)	Max. Rate (min)	Time for Max. Rate (min)
Acrylic FR UV-Abs	29	380	3.8	44	9
Acrylic FR UV-Abs ¹	26	480	3.7	56	23
Acrylic HR UV-Abs	34	195	6.3	12	10
Acrylic HR UV-Trans ²	33	190	6.5	14	14
Acrylic HR UV-Trans ²	18	200	6.5	50	16
Polyethylene	17	470	5.5	93	9
Polystyrene	26	345	4.0	32	9
Polystyrene ³	6	460	4.0	222	5
Polytetrafluoro- ethylene	36	0	NR ⁴	-	-
Polystyrene Foam FR	23	10	NR	2	1
Phenolic Canvas Lam.	28	450	2.5	41	7
Phenolic Canvas Lam. FR	35	460	2.4	44	11
Rigid Polyvinyl Chloride-filled	30	490	1.6	33	5
Rigid Polyvinyl Chloride-unf. ⁵	14	272	2.1	28	6
Rigid Polyvinyl Chloride-unf. ⁶	33	470	2.1	46	8
Range	6-35	0-490	11.6-00	2-220	1-23
Flaming - No Ventilation					
Acrylic FR UV Abs	7	480	1.8	151	4
Acrylic HR UV Abs	13	90	2.2	21	3
Acrylic HR UV Trans	6	140	2.3	39	4
Polyethylene	9	150±	4±	59±	4
Polystyrene	4	470	1.2	199	2
Polytetrafluoro- ethylene	30	55	11	4	9
Polystyrene Foam FR	11	260	0.9	50	8
Phenolic Canvas Lam.	20	460	1.7	89	4
Phenolic Canvas Lam. FR	24	210	3.7	34	14
Rigid Polyvinyl Chl-filled	11	530	0.5	250	1
Rigid Polyvinyl Chl-unf. ⁵	5	525	0.5	195	2
Rigid Polyvinyl Chl-unf. ⁶	10	535	0.6	170	2
Range	4-30	90-530	0.5-11	4-250	1-24

¹Auto ignition at 20-24 min.²Auto ignition at 14 min.³Auto ignition at 4 min.⁴NR = not reached.⁵1/8-in. thick.⁶1/4-in. thick.

Table 4. Effect of ventilation on maximum smoke densities from some smoldering or burning plastics.

Vent. Rate - Air Changes/Hr	0	3	6	12	20
Smoldering Condition					
Acrylic FR UV Abs	380/480	275	225	130	85
Acrylic HR UV Abs	195	100	65	35	30
Acrylic HR UV Trans	190/200	110	65	40	30
Polystyrene	345/460	250	160	80	45
Phenolic Canvas Lam.	450	370	290	160	80
Phenolic Canvas Lam. FR	460	350	270	205	95
Rigid Polyvinyl Chloride Filled	490	335	235	160	120
Flaming Condition					
Acrylic FR UV Abs	480	490	490	445	425
Acrylic HR UV Abs	90	115	160	165	125
Acrylic HR UV Trans	140	180	205	190	145
Polystyrene	470	465	465	465	465
Phenolic Canvas Lam.	460	445	410	275	180
Phenolic Canvas Lam. FR	210	215	135	80	90
Rigid Polyvinyl Chloride Filled	530	535	535	475	375

Table 5. Smoke obscuration indices for various materials.

Material	No Ventilation		6 Air Changes/Hr		20 Air Changes/Hr	
	Smold.	Flaming	Smold.	Flaming	Smold.	Flaming
Hardboard	25	5	7	1	2	0
Marine plywood	25	1	10	0	2	0
Red oak	35	1	15	1	3	0
Redwood	30	8	10	3	3	0
Black walnut	80	1	60	2	8	0
White oak	80	4	30	1	7	0
Acrylic FR UVA	25	360	10	350	1	240
Acrylic HR UVA	3	10	1	20	0	15
Acrylic HR UVT	3	35	1	40	0	20
Polyethylene	65	20	-	-	-	-
Phen. Lam. NFR	60	190	20	90	2	35
Phen. Lam. FR	45	10	25	9	1	3
PVC-Rigid-Filled	70	2400	15	525	5	165
Polystyrene	21	900	5	1175	1	1165

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