HOW NINE INORGANIC SALTS AFFECTED SMOKE YIELD FROM DOUGLAS-FIR PLYWOOD

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SUMMARY

Surface flammability and fire resistance of assemblies have been the principal fire performance characteristics considered when evaluating building materials for potential use. Now emphasis is being placed on the development of smoke. The effect of nine inorganic chemical salts on smoke produced from plywood is reported here. Smoke was measured in a smoke chamber apparatus similar to a chamber developed at the National Bureau of Standards. Results show that sodium dichromate was the most effective of the salts in reducing smoke yield from wood under both flaming and nonflaming exposures. The other eight chemicals were partially effective in reducing smoke development under the nonflaming exposures. Evidence also indicates borax, boric acid, and ammonium sulfate may reduce smoke development under flaming exposure. A means of decreasing smoke development for wood can result in designing safer housing, in protecting wood in use, and in conserving our timber resource. in addition, the information might also be helpful in developing better fire codes and standards.

Caution: The inorganic chemicals reported here were considered only for their effects on the quantity of visible smoke produced from plywood. The toxicity of these materials and their degradation products were not considered a basis for their selection.

HOW NINE INORGANIC SALTS AFFECTED SMOKE YIELD FROM DOUGLAS-FIR PLYWOOD

By
JOHN J. BRENDEN, Chemical Engineer
Forest Products Laboratory,[1] Forest Service
U.S. Department of Agriculture

INTRODUCTION

In surveying the potential use of building materials, surface flammability and fire resistance of the assemblies, in the past, have been the principal fire performance characteristics considered. Now increased emphasis is being placed on the potential for smoke development of acceptable materials. Thus, it is important that the potential smoke development characteristics of wood and wood products be determined as well as methods to reduce smoke production.

This report is the third in a series of applications of a smoke chamber test method developed by the National Bureau of Standards (NBS).[2] The first report[3] was on the performance of several wood species and panel products exposed to fire in the chamber. The second reported3 the effect of 14 types of coatings on smoke yield from Douglas-fir plywood measured by the test method. In addition to giving the results from several types of materials and surface-coated plywood specimens tested in the apparatus, the reports also contained discussions of the results in relation to how to use the test method to differentiate among treatments. It is this differentiation that is useful in separating promising from nonpromising treatments for reducing the smoke yields from wood and wood products.

Specifically, this, the third, report deals with applying the smoke chamber test method to plywood treated with various inorganic chemical salts. Some of the salts are used as components of commercially available fire-retardant treatments, whereas others are non-fire-retardant. The data will help answer the following questions: (1) How does wood impregnated with inorganic chemicals behave in the smoke chamber test apparatus and (2) can inorganic chemicals be used to reduce the smoke yield from wood?

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] Gross, D., Loftus, J.J., and Robertson, A.F. A method for measuring smoke from burning materials. ASTM Spec. Tech. Pub. No, 422. American Society for Testing and Materials. Philadelphia, Pa. 1967.

[3] Brenden, J.J. Determining the utility of a new optical test procedure for measuring smoke from various wood products. U.S. Dep. of Agric. For. Serv. Res. Pap. FPL 137. For. Prod. Lab., Madison, Wis. 1970.

[4] Brenden, J.J. How 14 coating systems affected smoke yield from Douglas-fir plywood. U.S. Dep. of Agric. For. Serv. Res. Pap. FPL 214. For. Prod. Lab., Madison, Wis. 1973.

DESCRIPTION OF EQUIPMENT

Apparatus

The equipment for this work is essentially the same as the original NBS smoke chamber[2] with a few of the modifications made in the most recent commercial model.[5] This equipment has been described in two Forest Service publications.[3,4] The most recent reports describes some modifications of the earlier apparatus.[3]

The apparatus used in this study consisted of a closed, instrumented chamber containing an electric furnace. The furnace was mounted in a furnace holder that also served as a mounting for the test specimen and for an air-cooled radiometer. A light source was mounted above the chamber ceiling and a light receptor mounted opposite the source below the chamber floor. The light receptor was electronically equipped to measure the amount of light from the light source that passed through the chamber. An overall view of the apparatus is shown in figure 1.

Chamber. — The chamber, 2 feet deep by 3 feet wide by 3 feet high, was fabricated from stainless steel. The inside of the chamber was coated with flat black paint to reduce light-scattering effects. The front wall of the chamber had a steel-framed glass door equipped with a shade. Mounted near the upper rear left side of the chamber (fig. 1) was an exhaust fan with a capacity of 50-60 cubic feet per minute. The fan inlet was covered with a retractable door.

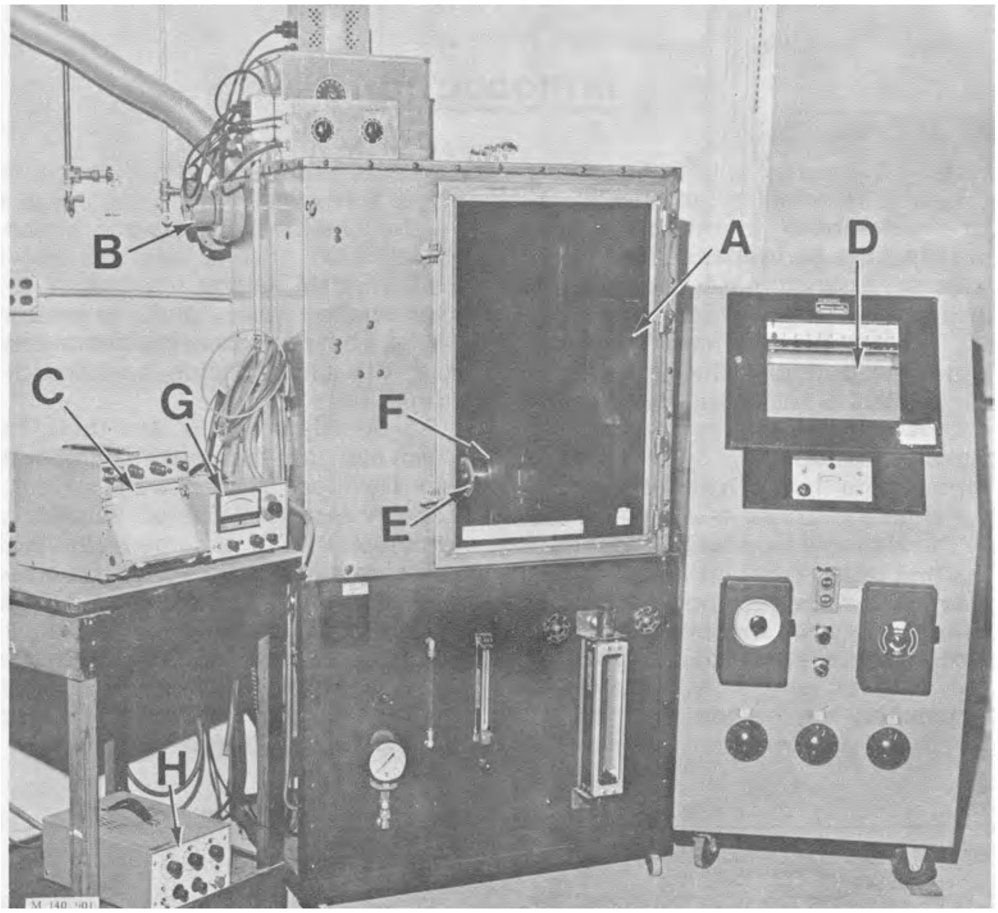

Figure 1. —Smoke collection chamber with controls and smoke-measuring devices: A, Blowout panel covered with aluminum foil; B, exhaust fan; C, recorder; D, controller; E, furnace; F, holder; G, picoammeter; and H, power supply.

(M 140 901)

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[5] Lee, T.G. Interlaboratory evaluation of smoke density chamber. U.S. Dep. Commerce, NBS Tech. Note 708. 1971.

Photometric system.- The photometric system consisted of a light source mounted in a box on the top rear left side of the chamber and a light receptor mounted in a box under the bottom of the chamber opposite the light source. The light-path length was 3 feet. The light source, a 30-watt type BLC film viewer lamp, was adjusted for intensity by using two variable resistors. The light receptor, or light sensor, was a 1P39 phototube that conducts an electric current proportional to the incident light intensity. In the circuit with the phototube were a 200 volt d-c power supply and a picoammeter. The picoammeter was equipped to produce an output voltage proportional to the current in the phototube circuit. A system of lenses and a diaphragm were used to ensure the rays of light passing through the chamber would remain almost parallel and that no extraneous light would be received by the receptor.

Furnace. —The furnace (fig. 2) used to irradiate the test materials consisted of a 525-watt circular heating element mounted in a section of stainless steel sanitary pipe with an outside diameter of 4 inches. The furnace was 4-1/8 inches long. A chromel-alumel thermocouple, placed close to the core of the heating element, was connected to a controller (fig. 1) to control power to the furnace.

The fire-exposure system permitted the test material to be exposed either to flaming or to nonflaming conditions. For the flaming exposure, in addition to furnace irradiations, a natural gas flame from a stainless steel burner (fig. 3) was impinged on the bottom of the test material. For the nonflaming exposure, the pilot flame was turned off and the specimen was exposed only to radiant energy from the furnace.

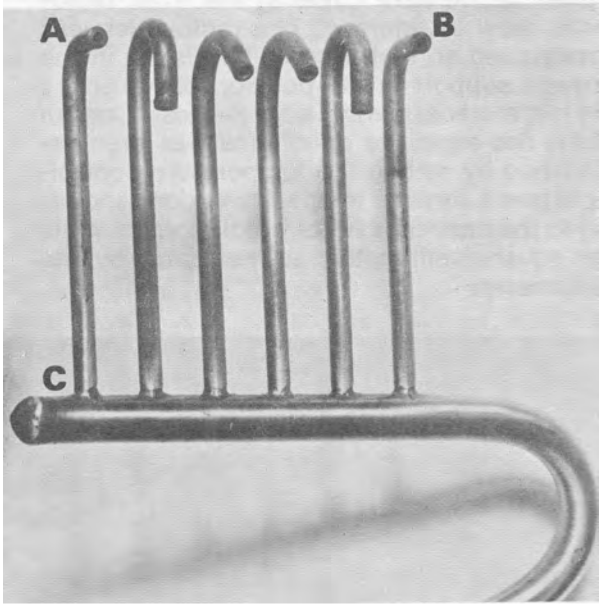

Figure 3. - Burner to apply flaming exposure to test specimen (AB is 2 in; AC, 1-7/8 in).
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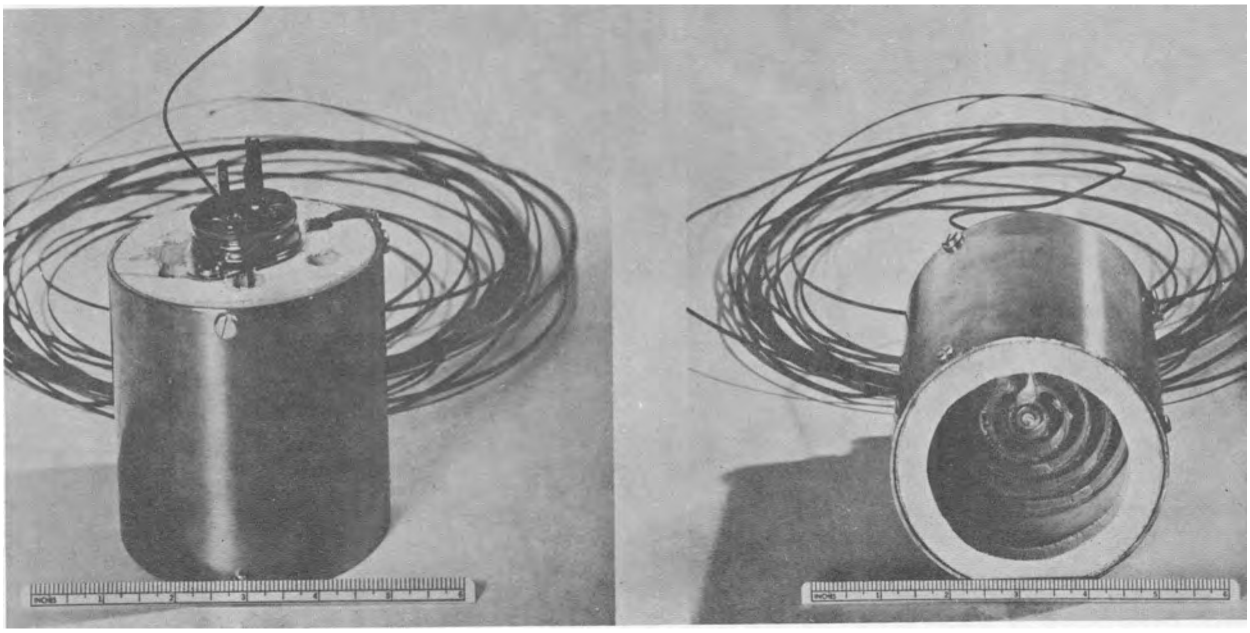

Figure 2. — Furnace to irradiate materials in smoke chamber.
(M 134 335)

Radiometer.- To measure the radiant energy output of the furnace, a circular foil radiometer (fig. 4) was built according to the method suggested by the NBS.[2] A calibration curve was made for the radiometer relating its output voltage as a function of the energy (in watts per square centimeter) incident on the heat-sensitive surface. This surface is shown as the dark circle in the front radiometer view in figure 4. The radiometer was constructed so that it could be placed in the furnace support in the position occupied by the test material during a smoke test. Control of the fire-exposure conditions was then established by setting the temperature controller to give a furnace temperature corresponding to the desired level of irradiation (in watts per square centimeter) as measured by the radiometer.

Specimen holder.—The specimen holder (fig. 5) was fabricated from stainless steel to hold a specimen 3 by 3 inches. With the front edges turned inward toward the center of the exposed specimen face (to hold the specimen in place), an area 26.55 square inches (42.2 cm^2) was subjected to irradiation from the furnace. The specimens were held in place by a piece of asbestos millboard plus a vertical pin and spring assembly. Except for the surface to be subjected to furnace irradiation, specimens were wrapped snugly in aluminum foil. Thus the smoke was released only through the face of the specimen oriented toward the furnace. During a smoke test the specimen surface was 1-1/2 inches away from, and parallel to, the circular furnace opening. The specimen holder in figure 5 is equipped with a trough along the bottom to collect samples that sag and melt.

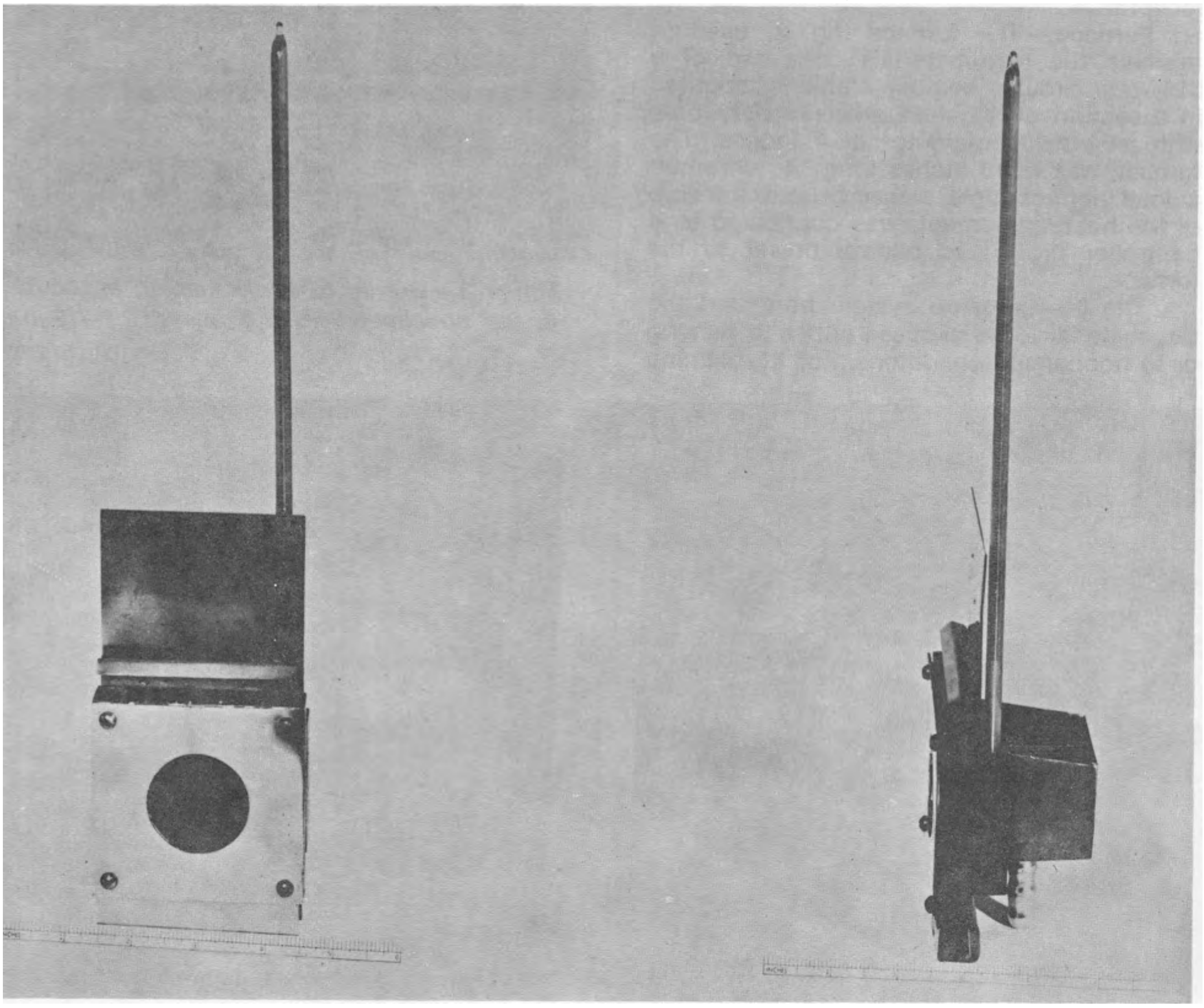

Figure 4. - Radiometer used to measure the radiant energy output of the furnace: Front view (left), side view (right).

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TREATMENT OF SPECIMENS AND TEST PROCEDURE

Treatment of Specimens

Specimens for this study were produced by treating 3/8-inch thick, exterior grade, A-C quality Douglas-fir plywood with nine inorganic salts. For treating, essentially a full-cell vacuum-pressure process was used to impregnate water solutions of the chemicals into 15- by 12-inch panels of plywood. For each salt, four solution concentrations (by anhydrous weight) were used: 15, 10, 5, and 1.25 percent. The panels (one panel for each salt solution) were first conditioned to moisture equilibrium at 80° F and 30 percent relative humidity (RH), then impregnated with the water solutions, and finally reconditioned again at 80° F and 30 percent RH. After the last conditioning step, the perimeter of the panels was trimmed to reduce edge effects, and each panel was cut into 16 specimens 3 inches square for use in the smoke chamber apparatus. To obtain data on the treatment levels of the specimens, the 15- by 12-inch panels were weighed three times during the treatment process: After the original conditioning; after impregnation (to determine the weight of solution pickup); and after the final conditioning step. Table 1 lists the inorganic salts, the solution concentrations, and the treatment levels of the panels.

Test Procedure

The test procedure in this study was similar to that used previously;[3,4] slight modifications will be noted. A run consisted of exposing a specimen to irradiation from the furnace in the smoke chamber either with the pilot flame lighted (flaming exposure) or with the pilot flame not lighted (nonflaming exposure). All smoke developed during the course of a run was collected in the chamber and subjected to photometric measurement.

To begin a run, the furnace was adjusted to give an irradiation level of 2.5 watts per square centimeter as measured by the radiometer. As noted, the heat-sensitive surface of the radiometer was placed in a position relative to the furnace opening geometrically similar to the position occupied by the specimen surface during fire exposure. Equilibrium conditions in the chamber were then established as evidenced by only minor fluctuations in furnace temperature, radiometer output, and chamber wall temperature. The chamber wall temperature measurement, determined with a chromel-alumel thermocouple in the geometric center of the rear wall, is a modification of previous procedures. The light-source intensity was adjusted to give a picoammeter output of 1 volt full scale on a current measurement range at least four orders of magnitude greater than the phototube dark current.

After preliminary adjustments were completed, a specimen was wrapped in aluminum foil and placed in a holder with the specimen front exposed. If flaming combustion was to be used, the gas flow through the pilot burner was lighted and adjusted to 350 British thermal units per hour (103 W). The radiometer was then removed from the chamber, the door to the exhaust fan inlet closed, and the holder containing the specimen was placed in front of the furnace opening. As quickly as possible after placing the specimen in the test position, the door to the chamber was closed, and the potentiometric recorder started. To complete the run startup, the shade was pulled down over the glass window of the chamber door.

The main part of the run consisted of recording the picoammeter output (in volts) versus time. The run was allowed to proceed until the smoke in the chamber had reached a maximum (minimum picoammeter output) and then declined somewhat for a few minutes.

Triplicate runs were made with each type of specimen (chemical and treatment solution concentration) and exposure (flaming or nonflaming). The results for each treatment and exposure are therefore the arithmetic mean of three determinations. The runs were in random order to permit a possible statistical analysis of the results.

The calculations of the test procedure involved converting the picoammeter output voltage values to values of a parameter known as the specific optical density, $\underline{D_S}$. The mathematical derivation of $\underline{D_S}$ is discussed in two publications.[3,4] Briefly, $\underline{D_S}$ is a characteristic smoke density parameter based on the geometry of the test apparatus and the percentage of light transmitted from the light source to the light receptor. It is given by the equation:

$$D_S = \frac{V}{LA} \log \frac{100}{\%T} \qquad (1)$$

Table 1.—Treatment levels of salt-Impregnated plywood

Treatment		Treatment level[1]			
Chemical salt	Solution concentrations	1	2	3	4
	Pct	Pct	Pct	Lb/ft^3	Lb/ft^3
Ammonium sulfamate	15	14.8	14.0	6.21	5.87
	10	12.5	11.1	4.74	4.20
	5	6.7	5.5	2.54	2.07
	1.25	3.2	1.5	1.13	.52
Ammonium sulfate	15	19.1	17.5	7.34	6.71
	10	11.4	10.0	4.62	4.05
	5	7.9	7.0	2.65	2.35
	1.25	3.3	1.7	1.07	.55
Borax	15	9.0	8.9	3.10	3.07
	10	5.0	3.6	1.81	1.29
	5	5.8	5.4	2.09	1.96
	1.25	2.6	1.4	.90	.50
Boric acid	15	6.5	11.9	2.43	4.44
	10	7.1	9.1	2.82	3.62
	5	4.1	4.6	1.52	1.70
	1.25	2.0	1.4	.73	.51
Diammonium phosphate	15	15.1	15.5	5.98	6.14
	10	10.9	10.8	4.12	4.07
	5	6.4	5.9	2.31	2.15
	1.25	2.6	1.6	.90	.54
Monoammonium phosphate	15	15.1	14.9	6.26	6.32
	10	10.8	10.4	4.40	4.21
	5	6.3	5.8	2.26	2.09
	1.25	2.4	1.4	.90	.51
Sodium chloride	15	17.5	15.3	7.05	6.15
	10	13.1	10.8	4.97	4.09
	5	7.9	5.4	2.93	1.99
	1.25	4.2	1.6	1.35	.51
Sodium dichromate	15	19.2	15.9	7.39	6.12
	10	15.0	10.2	5.70	3.87
	5	9.6	5.7	3.27	1.94
	1.25	3.9	1.5	1.35	.51
Zinc chloride	15	21.7	16.5	9.03	6.87
	10	16.7	12.5	6.15	4.59
	5	8.8	5.9	3.16	2.13
	1.25	3.5	1.5	1.24	.52

[1] Level 1—salt expressed as percentage of treated specimen weight (based on conditioned specimen weight before and after impregnation). Level 2—salt expressed as percentage of treated specimen weight (based on weight of solution pickup). Level 3—salt expressed in pounds per cubic foot of wood (based on conditioned specimen weight before and after impregnation). Level 4—salt expressed in pounds per cubic foot of wood (based on weight of solution pickup).

where

V is the chamber volume,
L is the light path length,
A is the exposed specimen surface area, and
$\%T$ is the percentage of transmitted light.

%T is given by the equation:

$$\%T = \frac{V_t}{V_o} \times 100 \qquad (2)$$

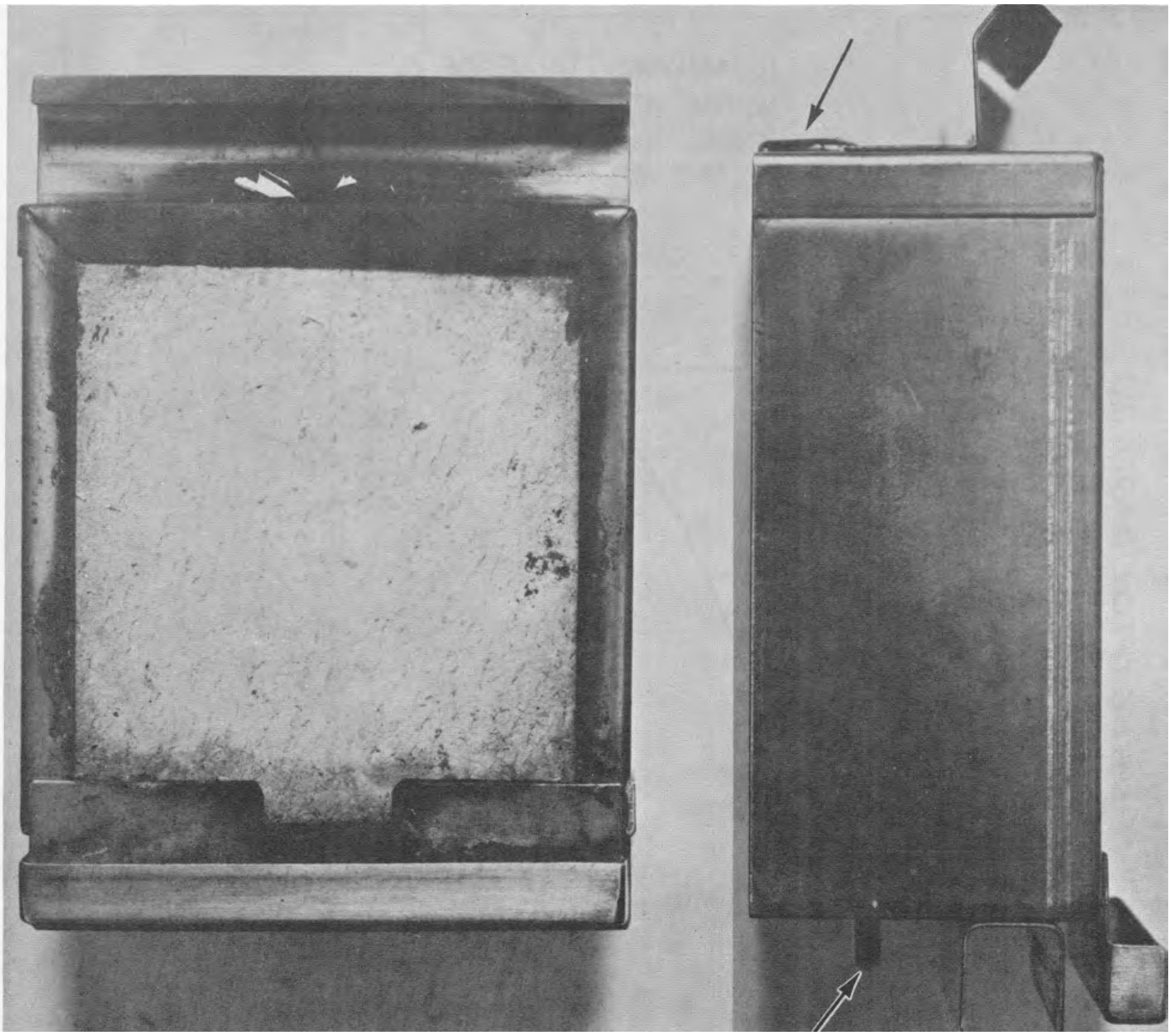

Figure 5.—Specimen holder: Front (left) and side (right) with arrows showing spring-pin assembly to keep specimen in place.

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where

V_o is the picoammeter voltage corresponding to a smoke-free chamber, and

V_t is the voltage at any time during the run.

By noting that for this smoke chamber $V = 18$ cubic feet, $L=3$ feet, and $A = 0.0456$ square foot and substituting these values in equation (1) it is possible to arrive at the working equation for the chamber as:

Values of V_t, read at 1-minute intervals from the potentiometric recorder chart record of the picoammeter output voltage, were machine-plotted as D_s values versus time. This procedure resulted in smoke accumulation curves (or D_s-time curves) similar to the curve shown in figure 6.

Of interest on the D_s-time curves is the maximum value of D_s, designated D_m. The time in the run at which D_m occurs is denoted by t_m. Experience has shown that it is frequently difficult to assign an exact value to t_m because many of the D_s-time curves have

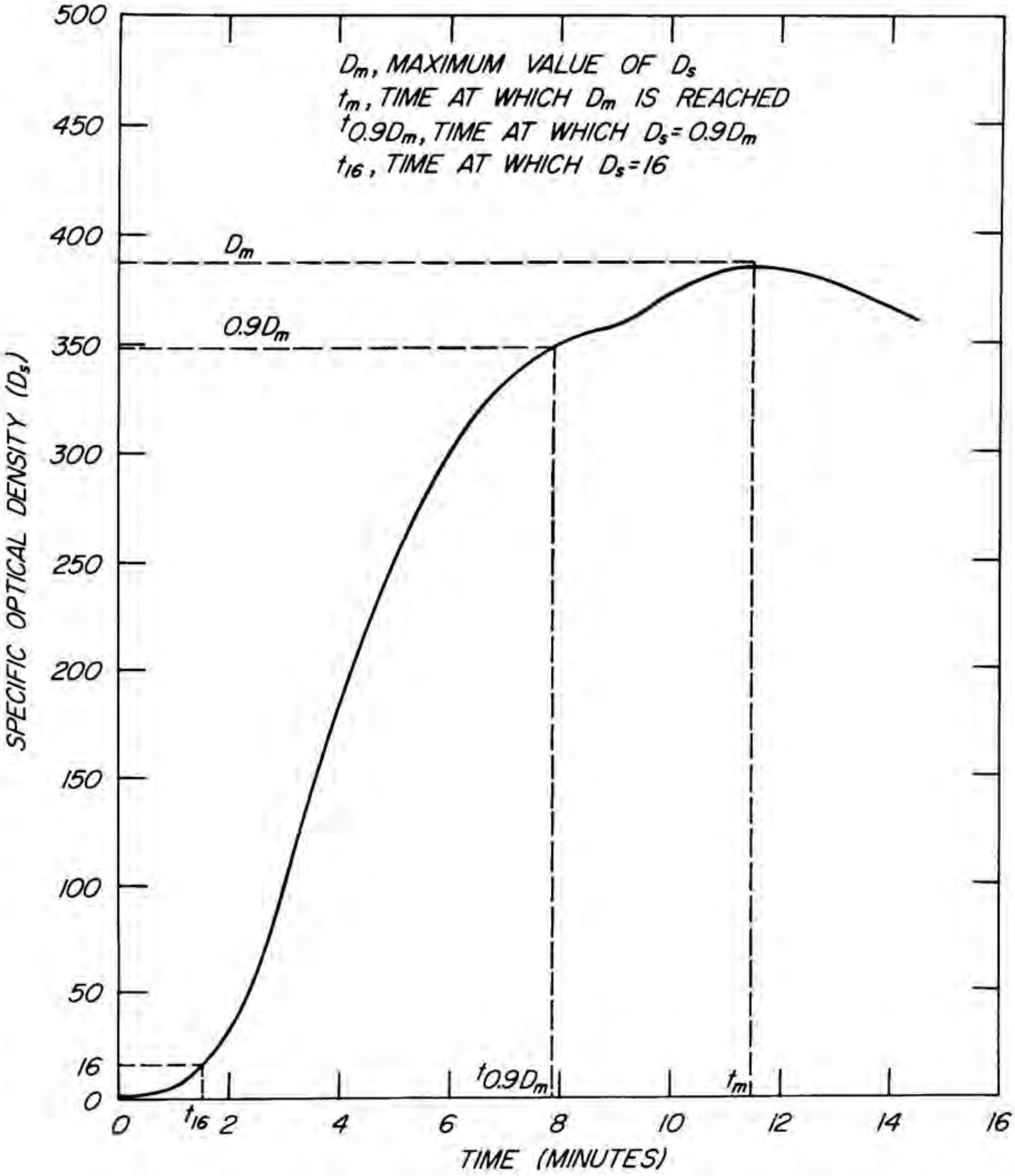

Figure 6.—Relationship of specific optical density to time (D_s curve) for untreated Douglas-fir plywood.

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plateaus in the region of D_m; hence it is current practice to report $t_{0.9Dm}$ the time when $D_s=0.9D_m$, since the curves are still changing rapidly enough in this area to assign a relatively accurate Value to $t_{0.9Dm}$. Values of D_m are the smoke values most frequently found in the literature.

Another value obtained from the D_s–time curves is t_{16}, the time when $D_s= 16$. The value $D_s = 16$ corresponds to an arbitrarily chosen room size of 12.5 by 20 by 8 feet in which an area of 10 square feet is burning, the light-path length from source to observer is 10 feet, and the limiting light transmission, %T, is assumed to be 16 percent.

Still another method to interpret the information represented by the D_s–time curves is to combine several characteristics of the curves into a single parameter. One attempt at such a combination is the smoke obscuration index (SOI) originally formulated by the NBS. The equation for calculating the SOI is:

$$SOI = \frac{D_m R}{100 t_{16}} \qquad (4)$$

where

D_m is the maximum value of D_s,

t_{16} is the time at which $D_s = 16$, and

R is the average rate of increase of D_s between the start of a run and $t_{0.9D_m}$.

Further details on calculating the SOI are given in a previous publication.[3] An additional attempt to combine the information in the D_s–time curves is represented by the smoke obscuration number at 5 minutes (SON_5). The SON_5 is obtained by adding the D_s values at the end of 1-minute intervals for the first 5 minutes of the run. Thus, this parameter emphasizes the behavior of the test material during the first 5 minutes of fire exposure.

RESULTS AND DISCUSSION

Smoke Yields

Smoke yields from the chemically treated plywood are given in tables 2 and 3. It should be recognized that the plywood specimens were treated with varying amounts (treatment levels) of the inorganic salts. Moreover, the same water solution concentration of different chemicals resulted in somewhat different treatment levels. Thus, for example, a 15 percent (by weight) solution of diammonium phosphate produced plywood specimens containing 5.98-6.14 pounds of chemical per cubic foot of wood; a 15 percent solution of zinc chloride, 6.87-9.03 pounds per cubic foot. These differences in treatment level occur because the individual chemical solutions have unique physical properties that influence the solution penetration and retention in wood. Hence, when the water fraction of the solution is evaporated, varying amounts of chemicals remain deposited in the wood structure. Thus the results discussed here should be considered in relation to the computed treatment level data of table 1.

In assembling the tables, arithmetic means of three smoke-yield determinations were used at each combination of treatment solution concentration and exposure (flaming or nonflaming). Determinations were in random order so that the results might be analyzed statistically. However, preliminary statistical work showed that the variation in results was too great to allow significant comparisons between the various salts and treatment levels. Therefore, the discussion that follows is based on a visual inspection of tables 2 and 3.

Calibration

To check the calibration of the smoke chamber apparatus and the operating techniques, a standard smoke-generating material with fairly constant smoke yield, α-cellulose paper, can be used. For this lot of the paper, the NBS determined that a sheet 0.030 inch (0.76 mm) thick exposed to nonflaming conditions in the chamber at 2.5 watts per square centimeter should give a D_m value of 150 ± 5. Before starting this work, the standard material was run in four consecutive runs with the D_m value in the range $D_m = 145$ to $D_m = 154$. Another standard smoke-generating material, acrylonitrile-butadiene-styrene plastic, in sheets 0.032 inch (0.81 mm) thick, is available to check the operation of the smoke chamber under flaming exposure conditions. The NBS reports a value of $D_m = 455 \pm 26$ for this material. Before starting this work, two smoke determinations were made on the plastic; the results were $D_m = 466$ and $D_m = 510$.

Maximum Specific Optical Density

When the specific optical density, D_s, reaches a maximum, the maximum value is denoted by D_m. D_m is important in understand-

Table 2.-Smoke yield[1,2] from treated plywood—nonflaming exposure (2.5 W/cm^2)

Treatment		Smoke yield measurements					
		D_m	Range of D_m[3]	$t_{0.9D_m}$	t_{16}	SOI	SON_5
Chemical salt	Solution concentrations	Dimensionless	Dimensionless				Dimensionless
	Pct			Min	Min	Min^{-2}	
Diammonium phosphate	15	159	118-200	12.2	2.0	22	193
	10	172	156-182	11.3	2.1	14	181
	5	232	187-271	10.1	1.3	56	397
	1.25	400	382-414	9.8	1.1	157	483
Boric acid	15	106	79-127	10.2	2.4	6	149
	10	163	148-175	9.7	2.6	14	184
	5	207	185-246	9.4	1.8	34	310
	1.25	345	290-386	7.9	1.7	117	523
Monoammonium phosphate	15	138	132-148	11.5	1.8	9	133
	10	148	109-170	10.2	1.6	14	198
	5	244	195-277	10.1	1.4	44	293
	1.25	496	400-660	10.9	2.1	151	279
Ammonium sulfate	15	122	104-134	9.9	2.0	8	160
	10	206	179-224	7.2	1.9	40	321
	5	288	272-301	8.3	1.6	74	398
	1.25	523	509-531	7.4	1.5	309	749
Borax	15	244	79-469	10.2	2.3	87	330
	10	411	337-455	6.2	1.4	289	876
	5	202	196-210	8.6	1.9	31	282
	1.25	314	275-342	9.1	1.4	105	535
Sodium chloride	15	388	377-407	10.7	1.9	78	329
	10	336	194-422	8.6	1.4	106	466
	5	365	285-423	9.0	1.4	121	513
	1.25	365	337-408	8.2	1.1	167	614
Sodium dichromate	15	42	21- 55	10.8	5.8	0	45
	10	62	50- 68	10.8	3.3	1	66
	5	192	98-303	9.2	2.2	27	180
	1.25	269	47-438	8.8	1.8	102	356
Zinc chloride	15	231	212-244	15.8	3.4	12	72
	10	173	158-187	13.0	2.8	10	88
	5	231	191-291	9.3	2.0	36	232
	1.25	457	373-597	6.9	1.2	311	879
Ammonium sulfamate	15	200	95-317	12.8	4.3	16	50
	10	185	139-219	5.6	1.3	67	468
	5	302	203-380	7.8	1.3	134	583
	1.25	525	451-593	7.7	1.6	313	789
Untreated	—	440	376-494	7.9	2.1	163	383

[1] Each value is mean of 3 test runs in random order.

[2] D_s, specific optical density; D_m, maximum specific optical density; $t_{0.9D_m}$, time at which $D_s = 0.9D_m$, t_{16}, time at which $D_s = 16$; SOI, smoke obscuration index; SON_5, smoke obscuration number (first 5 min of run).

[3] Range of values of D_m in 3 replicate test runs.

Table 3.—Smoke yield[1,2] on treated plywood—flaming exposure (2.5 W/cm2)

Treatment		Smoke yield measurements					
		D_m	Range of D_m[2]	$t_{0.9D_m}$	t_{16}	SOI	SON_5
Chemical salt	Solution concentrations	Dimensionless	Dimensionless				Dimensionless
	Pct			Min	Min	Min^{-2}	
Diammonium phosphate	15	97	70-113	11.5	2.3	4	117
	10	96	49-139	11.0	3.5	5	111
	5	72	46- 92	10.1	3.8	2	64
	1.25	56	34- 87	12.4	5.5	2	49
Boric acid	15	33	31- 37	10.9	6.2	0	28
	10	27	18- 39	9.3	7.5	0	19
	5	63	37- 79	10.0	4.9	1	47
	1.25	43	33- 52	11.0	7.7	0	16
Monoammonium phosphate	15	78	56-101	11.7	2.1	3	104
	10	103	75-133	9.6	2.6	8	114
	5	78	40- 99	9.8	4.2	2	60
	1.25	62	37- 75	10.9	6.8	1	19
Ammonium sulfate	15	49	25- 75	10.2	4.3	1	67
	10	66	59- 71	11.0	4.3	1	54
	5	50	23- 96	10.6	7.7	1	18
	1.25	46	33- 62	10.7	7.9	0	22
Borax	15	89	69-123	11.1	5.9	2	24
	10	73	63- 79	11.4	4.3	3	56
	5	29	8- 55	11.0	5.1	0	16
	1.25	28	16- 35	12.5	10.8	0	13
Sodium chloride	15	56	36- 69	12.1	6.8	1	23
	10	134	26-253	11.0	6.2	10	50
	5	106	48-143	11.2	6.4	4	25
	1.25	68	49- 89	10.2	6.3	2	34
Sodium dichromate	15	7	5- 11	11.4	—	0	6
	10	8	4- 12	8.8	—	0	8
	5	11	9- 13	8.8	—	0	9
	1.25	39	13- 67	8.8	3.7	1	23
Zinc chloride	15	178	157-192	10.0	2.4	15	139
	10	96	80-117	9.5	3.0	4	85
	5	53	46- 65	9.3	5.7	1	39
	1.25	58	34- 92	9.6	5.0	2	37
Ammonium sulfamate	15	108	64-175	13.1	5.8	3	29
	10	53	30- 82	8.2	3.9	1	66
	5	61	45- 77	11.7	5.1	1	40
	1.25	89	60-109	13.0	4.5	2	39
Untreated	—	106	60-159	13.5	8.1	3	15

[1] Each value is mean of 3 test runs in random order.

[2] D_s, specific optical density; D_m, maximum specific optical density; $t_{0.9D_m}$, time at which $D_s = 0.9D_m$, t_{16}, time at which $D_s = 16$; SOI, smoke obscuration index; SON_5, smoke obscuration number (first 5 min of run).

[2] Range of values of D_m in 3 replicate test runs.

ing the smoke yield properties of materials because it relates to the maximum smoke yield (or maximum obscuration of vision) during relatively long fire exposures. It is therefore important that if the smoke yield of wood is to be reduced, the D_m parameter must be lowered. Because of the importance of the D_m values, tables 2 and 3 give the range of D_m as well as the arithmetic mean of D_m for the three replicate smoke determinations made on each combination of inorganic salt and solution concentration.

Nonflaming exposure.—Table 2 shows that variation is wide in D_m and that, increasing solution concentrations tend, in general, to result in lower D_m values. All of the solutions except the 1.25 percent solutions of ammonium sulfate, monoammonium phosphate, zinc chloride, and ammonium sulfamate produce D_m values that are lower than those for untreated wood. For some of the chemical treatments difference is not great in the amount of reduction of D_m for the 5, 10, and 15 percent treatments. The data for borax appear unusual because the D_m values were D_m=202 (5 pct solution), D_m=411 (10 pct solution), and D_m = 244 (15 pct solution), which show a maximum in D_m at the 10 percent solution concentration. These data may be better understood by referring to table 1 that for an unknown reason shows a lower treatment level for the sample with borax using a 10 percent solution than with a 5 percent solution.

In table 2 the most effective chemical for reducing D_m under nonflaming exposure conditions is sodium dichromate. Boric acid, monoammonium phosphate, and diammonium phosphate (all at higher solution concentrations) are also shown effective.

Flaming exposure.—Table 3 shows that variation of mean D_m values with treatment solution concentration is much less under flaming exposures than under nonflaming. Table 3 also shows that all of the treatment solutions give D_m values below those for untreated plywood except for the 5 and 10 percent solutions of sodium chloride, and the 15 percent solutions of zinc chloride and ammonium sulfamate.

The chemical salt that apparently is the most promising for reducing D_m during flaming exposures is sodium dichromate, followed by boric acid (10 and 15 pct solutions).

Time at Which $D_s = 0.9D_m$

The parameter $t_{0.9D_m}$ is important in investigating the smoke yield from wood because this parameter is related to the time necessary for maximum smoke obscuration to occur. Thus, larger values of $t_{0.9D_m}$ show longer times to reach D_m; hence longer time for escape and for firefighting.

When this test method was being developed, it was common practice to report t_m, the time (in minutes) from the start of a test at which the maximum value of D_s (D_m) was reached. This practice was followed in the previous work.[4] On accumulating experience with the smoke chamber, it became apparent that the D_s curves for many materials had plateaus in the region of D_m. This means that as the test proceeds, and D_m is approached, the rate of change of D_s with time becomes smaller and smaller. (This effect probably occurs because a more-or-less dynamic equilibrium is established between the rate of smoke generation and the rate of smoke agglomeration and deposition on the chamber walls.) The practical effect is that it is difficult to pick an accurate value for t_m, the time at which D_m occurs. Consequently what is reported is $t_{0.9D_m}$, the time at which D_s reaches a value of $0.9D_m$. In the region of $0.9D_m$, D_s is usually changing rapidly enough with time to permit a more accurate estimate of $t_{0.9D_m}$ than t_m.

Nonflaming exposure.—Table 2 shows that most of the chemical salt treatments tend to increase $t_{0.9D_m}$ as compared to untreated plywood. The only salt and solution concentrations that do not confirm this are ammonium sulfamate (1.25, 5, and 10 pct), borax (10 pct), ammonium sulfate (1.25 and 10 pct), and zinc chloride (1.25 pct). There also is evidence that, as the salt solution concentration is increased for each salt, the $t_{0.9D_m}$ period is increased, although there exceptions, notably, ammonium sulfamate, borax, and ammonium sulfate. The most effective chemicals for lengthening the $t_{0.9D_m}$ period (as compared to untreated wood) apparently are zinc chloride (other than a 1.25 pct solution), monoammonium phosphate, diammonium phosphate, sodium dichromate, and ammonium sulfamate (15 pct solution only).

Flaming exposure.—None of the inorganic salt treatments used in this investigation helped increase the $t_{0.9D_m}$ time for treated wood compared to untreated wood. This means that all of the treated wood specimens reached their maximum smoke yield more quickly than the untreated specimens. However, in interpreting these data it should be remembered that the D_m values for wood tend to be much lower under flaming exposure conditions than under nonflaming.

Time at Which $D_s = 16$ (t_{16})

The time from the start of a test until $D_s = 16$ is the parameter t_{16} (in minutes). It is sometimes referred to the critical time factor in smoke chamber work. As such, it enters into the calculation of the smoke obscuration index (SOI) to be discussed. This parameter provides a convenient reference point at which to compare the treatments because this value $D_s = 16$ occurs on the D_s-time curves and can be related to a model room. However, a criticism of the t_{16} value is the arbitrary nature of the hypothetical room on which it is based. In practice, for many materials, $D_s = 16$ is so low compared to D_m that t_{16} is very short. As a result, determining t_{16} from the D_s-time curves is sometimes a problem. On these occasions, the operator must go back to the original percent transmission versus time data to get an accurate value for t_{16}.

Nonflaming exposure.—Table 2 shows first that as concentration of the treatment solution is increased, the differences between the mean t_{16} times for the individual salts increases. Thus, at 1.25 percent solution concentrations the mean t_{16} values range from 1.1 to 2.1 minutes (lower than untreated wood) whereas at 15 percent concentrations the t_{16} values range from 1.8 to 5.8 minutes (higher than untreated wood). The implication of this observation is that, to decrease the smoke yield of wood for the critical time parameter, solutions in the range of 10 to 15 percent must be used. A second implication is that lower solution concentrations may lead to treated wood that has a shorter critical time than untreated wood. The treatments that apparently are most effective in increasing t_{16} are sodium dichromate, zinc chloride, boric acid, and ammonium sulfamate (15 pct only).

Flaming exposure.—The t_{16} data for flaming exposures (table 3) are much more scattered than those for nonflaming. The only treatments that apparently are promising to increase the critical time under these conditions are borax (1.25 pct solution) and sodium dichromate (5, 10, and 15 pct solutions.) It should be noted that for sodium dichromate (5, 10, and 15 pct solutions), a value of $D_s = 16$ was never attained (D_m<16) for plywood specimens treated with these solutions, thus the t_{16} values corresponding to these treatments cannot be given in table 3. All of the other solutions used in this study caused the treated wood to have a shorter critical time than the untreated. Thus, it appears that these other treatment solutions may be actually harmful to some of the smoking properties of wood.

Smoke Obscuration Index (SOI)

Details for calculating the SOI are given in “Treatment of Specimens and Test Procedure” and in a previous publication3 The index was developed to represent the salient features of the D_s-time curves by a single number or index. Thus, materials could be either accepted or rejected by this test method using a single criterion. It was thought that to base acceptance or rejection on a single factor such as D_m or t_{16} would disregard other pertinent information yielded by the apparatus in the form of the D_s-time curves. In formulating the SOI, the following factors were considered important in representing the smoke buildup in rooms: (1) The maximum smoke accumulation (D_m); (2) the average rate of smoke buildup R_{av}; and (3) a critical time factor (taken as t_{16}). These were then combined in the form shown in “Treatment of Specimens and Test Procedure” and as has been described.[3] R_{av} is calculated as the average rate of increase of D_s between time zero and $t_{0.9D_m}$. It follows of course, that in considering the effect of the salt solutions on wood, low SOI values, and decreasing the SOI are desirable whereas high SOI values and increasing the SOI are undesirable.

Nonflaming exposure.—Many of the chemicals helped reduce the smoke obscuration index (table 2). Greatest reductions in SOI were observed for sodium dichromate, boric acid, monoammonium phosphate, and diammonium phosphate. In addition, the data show that increasing the treatment levels gives consistently lower SOI values. Borax-treated wood, however, has a much higher SOI value at 10 percent solution concentration than at either 5 or 15 percent. The high value might be partially explained by referring to table 1 in which the treatment level of wood treated with the 10 percent solution was lower than the treatment level for either 5 or 15 percent solutions. Also, some specimens treated with 1.25 percent solutions, particularly those of ammonium sulfamate and zinc chloride, had SOI indexes greater than those for untreated wood.

Flaming exposure.—Under flaming exposure conditions, all of the treatments produced wood that gave a very low SOI index (table 3). It is therefore impossible to differentiate among the smoke yield characteristics of the treated wood with this formulation of an index under flaming exposures.

Smoke Obscuration Number, First 5 Minutes

The parameter, smoke obscuration number, first 5 minutes, SON_5, is another attempt to represent the salient features of the D_s-time curves by a single number. Here, the D_s values are taken at 1-minute intervals, and are added for the first 5 minutes of the run. This technique emphasizes the first short period (5 min.) of fire exposure.

Nonflaming exposure.—Table 2 shows that except for borax, monoammonium phosphate, and diammonium phosphate, increasing the treatment solution concentration lowers SON_5 values. For monoammonium phosphate (comparing 1.25 and 5 pct solution treatments) and diammonium phosphate (compar-

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ing 10 and 15 pct solution treatments) the increases in SON_5 seem to be minor. For solutions of borax, the SON_5 value is greatest for specimens treated with a 10 percent solution. The observed variations in the SON_5 values for borax may be partly explained with reference to the treatment level data in table 1. The SON_5 data also indicate that except for monoammonium phosphate and sodium dichromate, treatment of wood with 1.25 percent solutions of the inorganic salts increases the smoke obscuration number at 5 minutes. Thus the evidence is low concentrations of these salts should probably be avoided in trying to improve the smoke yield properties of wood for nonflaming exposures. The most effective chemicals in reducing SON_5 (using solutions in the range of 5 to 15 pct) apparently are sodium dichromate, zinc chloride, monoammonium phosphate, and diammonium phosphate.

Flaming exposure.—Data in table 3 show that SON_5 varied much less for flaming exposures than for nonflaming. Except for sodium dichromate, all of the chemicals used in this study increased the SON_5 values above those for untreated wood. For sodium dichromate, the SON_5 for wood treated with a 1.25 percent solution was 23 (above untreated wood), whereas the 5, 10, and 15 percent solutions showed SON_5 values of 9, 8, and 6 (below untreated wood) respectively. Thus, except for sodium dichromate, none of the salts used in this study lowered the SON_5 for wood, but, under flaming exposure conditions, wood already has a relatively low SON_5 without treatment.

CONCLUSIONS

1. Values for smoke development of replicate samples varied considerably, but definite trends were observed.

2. The inorganic salts used had a greater effect on the smoke yield from wood under nonflaming exposure conditions than under flaming. The effectiveness of the chemicals under flaming conditions was difficult to detect because wood normally gives off little smoke under this condition.

3. Sodium dichromate (an oxidizing chemical and a glow promoter) was the chemical most effective in reducing smoke yield from wood under both flaming and nonflaming conditions. This chemical improved all smoke development parameters except for the time to reach $0.9D_m$ under flaming exposure ($t_{0.9D_m}$). None of the treatments improved this characteristic.

4. Under nonflaming exposure, chemicals other than sodium dichromate were also partially effective in improving smoke yield as shown by lower maximum specific optical densities, longer times to reach a specific optical density of 16 (t_{16}), and lower smoke obscuration indexes. The performance usually improved with increased solution concentration. Paradoxically some of these chemicals that reduce smoke development under the nonflaming exposure are considered good glow inhibitors, in contrast to the sodium dichromate that promotes glow.

5. Under flaming exposure, some evidence indicates boric acid and some treatment levels of ammonium sulfate and borax also seem to lower the smoke yield from wood. The trends did not consistently indicate better performance with increased concentration. For the other treatments the results did not differ greatly from those of the untreated samples.