LARGE-SCALE LABORATORY FIRE TESTS OF SMOKE DETECTORS

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From August 1973 to August 1974, I was sponsored by Underwriters' Laboratories as a research associate at the National Bureau of Standards Center for Fire Research. The purpose of the program to which I was assigned was to develop performance specifications for single-station residential smoke detectors.

At that time there were no published standards for residential smoke detectors. The only existing published standards covered commercial-type photoelectric detectors and commercial-type ionization detectors. In addition, there were different standards for each type of detector and greatly differing requirements among the several testing laboratories listing or approving such detectors. Residential detectors were being evaluated under these two commercial detector standards.

Because impending legislation from many areas required residential or single-station smoke detectors in all newly constructed housing, the National Bureau of Standards considered it imperative, first, that a published standard for residential-type smoke detectors be developed and, second, that a uniform testing procedure be independently developed so that all testing and approvals laboratories could use the same methods.

During the development of these performance specifications, it was felt that all smoke detectors should be tested to the same requirements regardless of their principle of operation. Thus it was necessary to determine whether photoelectric-type detectors could respond to the full-scale fire tests required for the approval of ionization-type detectors in UL Standard 167 but not required for photoelectric detectors in UL Standard 168.

An attempt to answer this question stimulated the series of tests reported herein. NBS, in cooperation with Underwriters' Laboratories, conducted a series of 26 fire tests at the UL facilities in Northbrook, Illinois, during the period of February 11 to 15, 1974. The same test facilities and the same test fires as described in UL Standard 167 were utilized. In addition to the four standard test fires of UL Standard 167, a smoldering cotton fire and several flaming polyurethane flexible foam fires were added to the test series. The purpose in adding the smoldering cotton fire to the test series was to compare the performance of photoelectric detectors against ionization detectors in a nonflaming cellulosic fire. The polyurethane foam fires were included to evaluate this material as a possible smoke detector test material. Polyurethane is used as a fire test material in Europe for assessing the performance of smoke detectors.

Eight different photoelectric smoke detectors were chosen for the test series. Seven of these detectors were chosen because of their good response to slowly moving smoke, as determined by laboratory analysis at NBS. It was thought that this would be the key to whether these photoelectric smoke detectors would perform satisfactorily. The eighth photoelectric smoke detector was chosen as one noted for having entry problems to slowly moving smoke. It was thought this detector would experience great difficulty in detecting the full-scale fires. To give the detector the benefit of the doubt, its sensitivity was set as high as possible, without provoking false alarms. The sensitivity chosen for this detector was 0.5%/ft.

For correlation and comparison purposes, two ionization chamber smoke detectors were included in the test series. One was a so-called single-station model of the type sold for residential protection. The other was a unit type or commercial detector used as a detecting component of automatic fire detection systems of the type installed in warehouses, nursing homes, computer spaces, and the like.

Several U.S. detector manufacturers are selling smoke and/or fire detectors that use the Taguchi gas sensor. This sensor is manufactured by Figaro Engineering of Osaka, Japan. One detector employing the Taguchi gas sensor and sold as a single-station residential smoke and fire detector was added to the test series for evaluation purposes. The particular detector chosen is equipped with a meter that gives an analog indication of the detector's shift toward alarm threshold. The detector also includes a horn within the enclosure that sounds an alarm when the appropriate threshold is reached.

The fire test series was conducted in UL's east fire test room, shown in Figure 1. This room is 60 by 60 ft (18 by 18 m) by 15.75 ft (5 m) high. The test fires were positioned 3.75 ft (1.2 m) off the floor or about 12 ft (3.7 m) below the ceiling. The smoke detectors were placed on the ceiling approximately 21 ft (6.4 m) from the point directly over the fire center, which corresponds approximately to a 30-ft (9-m) spacing pattern for the detectors.

Two photoelectric beams were used to measure the visible smoke obscuration and optical density. These were fastened to the ceiling. One was placed about 5 ft (1.5 m) from and parallel to a line joining the fire center and the detectors, and the other was placed just in front of the detectors. Each photoelectric unit consisted of a barrier layer type of photoelectric cell spaced 5 ft (1.5 m) from a tungsten-filament automotive-type spotlight energized from a constant-voltage source. The outputs of the photocells were connected to a 2-pen chart recorder.

One thermocouple was placed directly over the fire and another at the detector location. The temperatures were recorded on a multi-point chart recorder.

Carbon monoxide concentrations in parts per million were continuously monitored, and the peak value was recorded during all tests. A pickup tube was placed on the ceiling and positioned just in front of the detectors. The tube was connected to an Ecoloyzer Model 2400 carbon monoxide monitor.

The time of detector actuation was recorded on a 25-clock elapsed time annunciator panel, which indicated the detector operation to the nearest second.

The test fires included six different materials, of which the first four were the same as those specified in UL Standard 167. The test fire materials were as follows:

1. The shredded paper fires consisted of 1/2 lb (227 g) of newsprint torn in strips approximately 3/8 in. (0.95 cm) wide and 6 to 24 in. (15 to 61 cm) long. The paper strips were placed in a cylindrical receptacle made of 1/4 in. (0.64 cm) mesh hardware cloth. The overall dimensions of the receptacle were 12 in. (30 cm) diameter by 24 in. (61 cm) high, with the hardware cloth bottom positioned 6 in. (15 cm) above the base. The paper was fluffed in such a way as to produce a sufficient volume of smoke before open flaming took place. Ignition was by a common match applied to the bottom center of the basket.

2. The polystyrene fire consisted of 2 oz (57 g) of spaghetti-type foamed polystyrene packing material with no flame inhibitor placed in the same wire basket used for the shredded paper fire tests. The polystyrene was ignited by 50 cm^3 of ethyl alcohol placed in a pan positioned under the bottom center of the basket.

3. The gasoline fires consisted of 200 cm^3 of regular, leaded motor gasoline placed in a 9-in. (23-cm) diameter stainless steel pan, 1½ in. (3.8 cm) deep. Ignition was by common match; the gasoline in the pan was kept covered until ignition to prevent evaporation.

4. The UL Class A Wood Brand Tests consisted of a wood crib composed of three layers of kiln-dried douglas fir wood strips. Each strip was 3/4 in. (1.9 cm) square by 12 in. (30 cm) long. Twelve strips were used for each layer and were stapled together. Each layer was placed at right angles to adjacent layers. Overall dimensions of the wood cribs were 12 by 12 by 2¼ in. (30 by 30 by 6 cm). The crib was ignited by 100 cm^3 of denatured alcohol consisting of 94% ethanol and 5% methanol. The alcohol was contained in the same pan as used for the gasoline test fire.

5. The smoldering cotton fire consisted of approximately 2 lb (907 g) of raw cotton placed in a 12-in. (30-cm.) square pan and placed on a 1000-W, 120-V ac hotplate.

6. The polyurethane tests consisted of pieces of flexible polyurethane foam, 12 by 12 by 3 in. (30 by 30 by 8 cm) placed in a pan constructed of aluminum foil. The pan was arranged to fit snugly around the base of the foam pieces. The sides of the pan flared out slightly, and were about 3 in. (8 cm) high. The polyurethane foam was ignited by 10 cm^3 of ethyl alcohol poured into the pan along one side of the foam. Ignition of the alcohol was by a kitchen match.

Table 1 gives the alarm response times of the various smoke detectors for each of the test fires. It can be seen from these data that most of the detectors performed admirably in all of the test conditions with the exception of photoelectric detector J, which was the detector selected for its poor smoke entry characteristics, and the TGS semiconductor sensor detector.

It is the opinion of the author that the seven photoelectric detectors could in all likelihood satisfactorily detect the four standard fires, with perhaps some slight modifications to these fires. If the results of the tests confirmed this opinion, then it would be possible to combine the requirements of UL 167 and UL 168 into one standard. One result of this combination of standards would be the new requirement for all photoelectric smoke detectors to detect the four full-scale fires before approval, a current requirement for ionization-chamber smoke detectors.

If photoelectric detector J had also managed to detect the four standard test fires, then either of two conclusions could have been drawn. One conclusion would have been that the standard test fires are not severe enough to separate detectors with marginal performance from better performing detectors. The other conclusion would have been that the laboratory test procedures, which show large differences in the performance of various smoke detectors to slowly moving smoke, are not realistic, as these differences are not reflected in the performance of the detectors in real fire conditions. This, however, is not the case, and from the poor performance of detector J, it would appear that the tests are sufficient to separate detectors with poor smoke entry characteristics.

From the general shape of the smoke buildup curve for the paper fires shown in Figure 2, it appears that adequate concentration of smoke is generated but that the high concentrations are only available to the detectors for a very short length of time. This should result in proper operation of detectors with little or no smoke entry difficulty and nonoperation of those that restrict smoke entry.

The smoke buildup curve for the polystyrene fires, Figure 3, shows a characteristic double-peaked shape. These two peaks are caused by the polystyrene material in the center of the wire basket burning first and then the material around the sides falling into the center and burning. Although the smoke density is fairly high for a longer period, the darker color of the smoke makes it more difficult to detect.

The shape of the smoke-time curve for the gasoline fires shown in Figure 4, is similar to the polystyrene without the double peak. The same comments would be appropriate in this case.

The general shape of the curve for the polyurethane fire (Figure 5) is almost identical with that for gasoline except for the much lower peak value.

The smoke curve for the wood brand test, shown in Figure 6 as originally required in UL 167, shows that almost no visible smoke is produced. This is because the alcohol burning in the 9-in. diameter pan generates flames immediately, engulfing the entire wood crib. This results in generation of almost entirely small, invisible particulates, to which the photoelectric detectors would not respond. As this is a rather unrealistic condition, a modification of the standard wood brand test was developed to produce more visible smoke.

The amount of alcohol used to ignite the brand was reduced to 10 cm^3 and and the size of the container was reduced to 3½ in. (90 mm) in diameter. The smoke buildup curve for this modified wood fire is shown in Figure 7. It can be seen from this figure that the smoke curve for this modified test is quite similar to the buildup curve generated by the paper fire. Thus it, too, will provide a high smoke concentration for a relatively short time, which should result in separation of detectors with entry problems.

The average air velocities generated by the test fires ranged from approximately 17 ft/min (5.18m/min) for the wood brand tests with 10 cm^3 of alcohol to 168 ft/min (51.22 m/min) for the polyurethane foam fires.

The temperatures recorded at the detector were never more than slightly above ambient.

I feel that the following conclusions can be made with respect to the four tests specified in UL 167 and the response of photoelectric smoke detectors to these test fires:

1. Most presently available photoelectric smoke detectors would be unable to pass the wood brand fire test, as presently specified in UL 167, because the test fire produces very little visible smoke. Since it is the purpose of the test to check response of detectors to wood smoke, and since a condition where the wood brand is forced into an immediate flaming made by the alcohol is somewhat unrealistic in practice, it seems reasonable to modify the test to produce more visible smoke. If the wood brand test were modified to use less alcohol as an igniter, as was done in this series of experiments, then more visible smoke would be produced. The result would be that many of the photoelectric detectors could then meet this test requirement. The suggested modification to this test to permit its use for evaluating photoelectric smoke detectors is to continue with the one wood brand but reduce the alcohol igniter from 100 to 10 cm^3. The size of the metal container for the alcohol should be reduced to a small shallow pan having a diameter of approximately 3½ in. (90 mm). This modification has now been made in UL 167.

2. The shredded paper test fires are extremely operator-dependent because the packing density of the paper is critical in producing a reasonable amount of visible smoke. It is quite difficult to obtain repeatability between tests and would be almost impossible to obtain reproducibility between laboratories. If the changes suggested above are made to the wood brand test, then the shredded paper test becomes redundant and can be deleted.

3. The gasoline test fire as now conducted is a satisfactory method for the evaluation of photoelectric smoke detectors, based on the results of experiments. Therefore, no modification is needed in this test to accommodate photoelectric detectors.

4. The polystyrene test fire, although satisfactory in terms of detectability by the photoelectric detectors, produces a smoke buildup at the detector location with two pronounced peaks. It is believed that this double-peaked buildup curve is somewhat undesirable as it would not commonly be found in burning of materials.

5. The polyurethane test fires should be included in the test series because this material is used in several European countries as a standard material for the evaluation of smoke detectors. Because of its widespread use in furnishings in this country, the results in these tests were good enough to suggest the possibility of this material as a replacement for the polystyrene test material. Additional experiments will be necessary, however, to establish the quantity, configuration, and specific type and density of the polyurethane to be used. It is apparent in these experiments that detectors with sensitivities of less than 2%/ft will have difficulty with this test, regardless of their response to slowly moving smoke.

6. Photoelectric smoke detectors found to have poor smoke entry characteristics at low velocities will respond to few, if any, of the test fires. The example of this is the performance of detector J, a single-station smoke detector widely sold as a residential smoke detector. This suggests that the test fires used are sufficiently discriminatory in this regard in that the smoke entry characteristics measured in laboratory smoke test tunnels at lower velocities do give a reasonably accurate portrayal of the detector's response to real but small fires.

7. The lack of responsiveness of the TGS sensor (detector K) to fires with relatively complete combustion should be noted. In open flaming fires, very little unburned hydrocarbons and carbon monoxide are produced, the two main combustion products to which the TGS sensor is sensitive. It had been thought that the TGS sensor would sound an alarm for the smoldering cotton fire. But even here, only a slight analog output was noted, which was far short of the alarm threshold of the detector.

8. For a fire detector employing a carbon monoxide-specific sensor to respond in a comparable manner to conventional smoke detectors, detection of approximately 75% of the test fires would have been necessary. This would have required an alarm threshold to carbon monoxide of approximately 25 parts per million. Since concentrations of carbon monoxide in excess of this are periodically experienced in urban areas, a detector with this alarm threshold might experience an undue number of false alarms.

9. In those tests where open flaming and little visible smoke predominated, the ionization smoke detectors demonstrated their superiority over photoelectric smoke detectors under these types of fire conditions. In those tests where open flaming and significant quantities of visible smoke were produced simultaneously, neither detector indicated any significant margin of superiority. In the one truly smoldering fire, the photoelectric smoke detectors demonstrated their superiority over ionization smoke detectors for this type of fire. The obvious conclusion is that neither detector does well in all types of fires in terms of response. If one could predict with some measure of

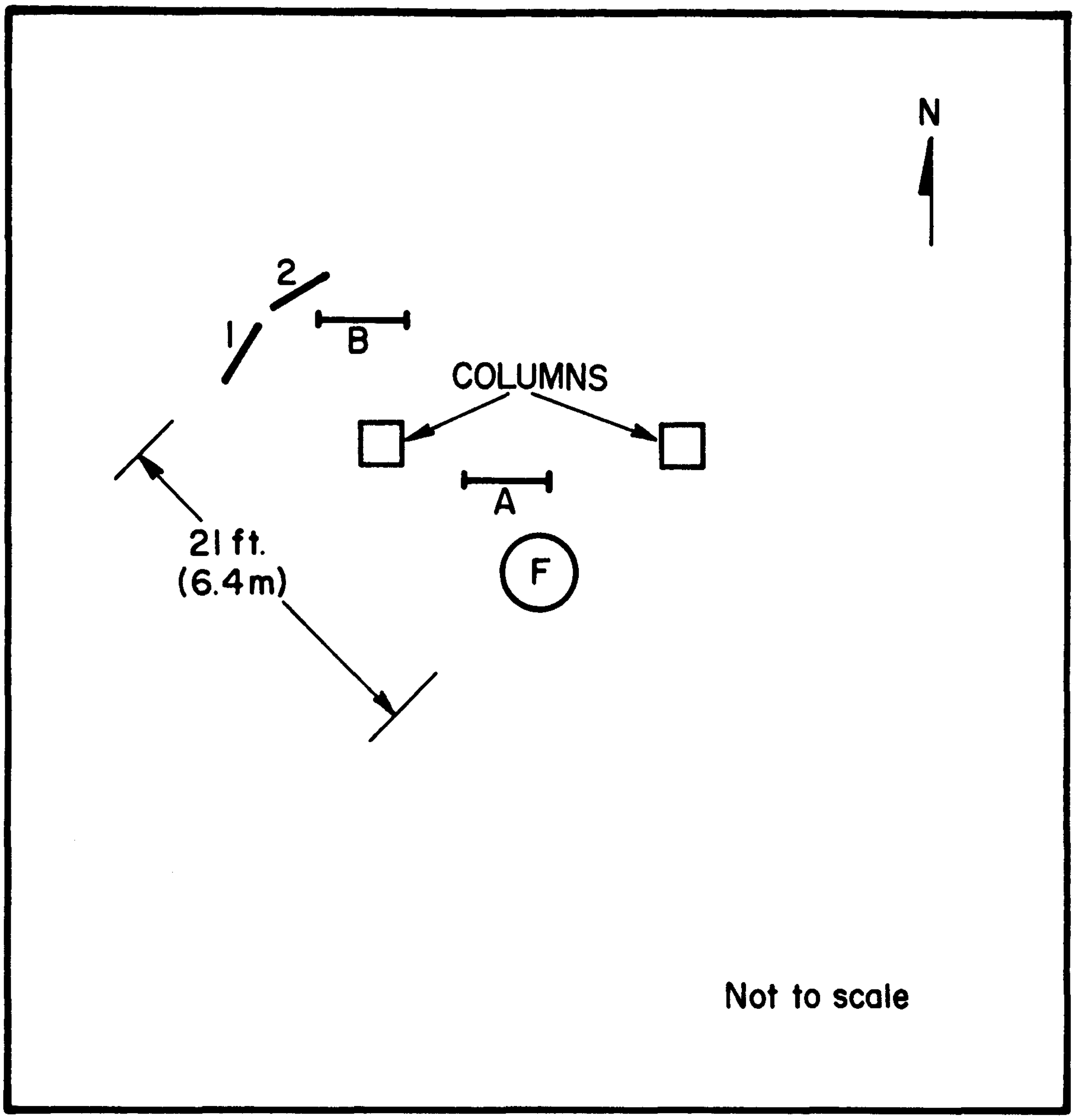
certainty the type of fire to be detected, then the appropriate detector could be selected. If this predictability is missing, then either type of detector should be able to satisfy the detection needs. The choice of which to use in this case should be based on other considerations, such as cost, reliability, aesthetics, and the like.

TABLE 1

Detector Alarm Response in Seconds

Test No.	A Photo-electric	B Photo-electric	C Photo-electric	D Photo-electric	E Photo-electric	F Photo-electric	G Photo-electric	H Ion Chamber	I Ion Chamber	J Photo-electric	K TGS Semi-conductor
1	30	46	27	29	28	36	34	33	30	56	36
2	--	29	--	--	--	--	--	32	27	--	--
3	28	30	26	28	27	32	31	30	27	--	--
4	--	45	--	--	--	--	--	45	38	--	--
5	--	42	--	--	--	41	--	45	35	--	--
6	62	52	55	72	58	57	107	44	39	--	--
7	63	55	76	76	59	64	132	46	NR	--	--
8	44	52	42	46	42	44	41	42	31	--	--
9	34	30	31	36	30	41	34	32	NR	--	--
10	28	28	27	28	28	34	31	30	28	--	--
11	49	51	53	58	58	49	--	52	43	--	--
12	48	56	49	55	*	51	46	49	47	--	--
13	49	49	54	119*	52	47	70	47	44	--	--
14	47	53	88	*	63	49	45	53	46	--	--
15	--	--	--	*	--	--	--	139	113	--	--
16	156	103	162	*	138	134	--	90	109	--	--
17A	154	108	163	*	138	170	--	85	108	--	--
19	123	102	124	*	124	119	--	97	109	--	--
20	1656	1582	--	1754	1762	1632	1690	--	1654	--	IND
21	74	67	76	103	111	74	74	72	73	160	--
22	103	97	103	130	118	102	103	106	110	--	--
23	96	92	101	124	102	100	95	102	101	--	--
24	138	111	141	134	136	138	--	92	114	--	--
25	134	109	145	134	132	141	--	104	120	--	--
26	127	137	138	131	133	134	--	118	113	--	--
27	51	51	52	55	54	58	--	50	48	--	--

Legend:
- -- No alarm or indication
- IND Indication but no alarm
- * Clock timer malfunction
- NR Not resettable



Notes:

1,2 Detector Board Locations

A,B Smoke Density Measuring Equipment

F Fire Location

FIGURE 1 Fire test room layout.

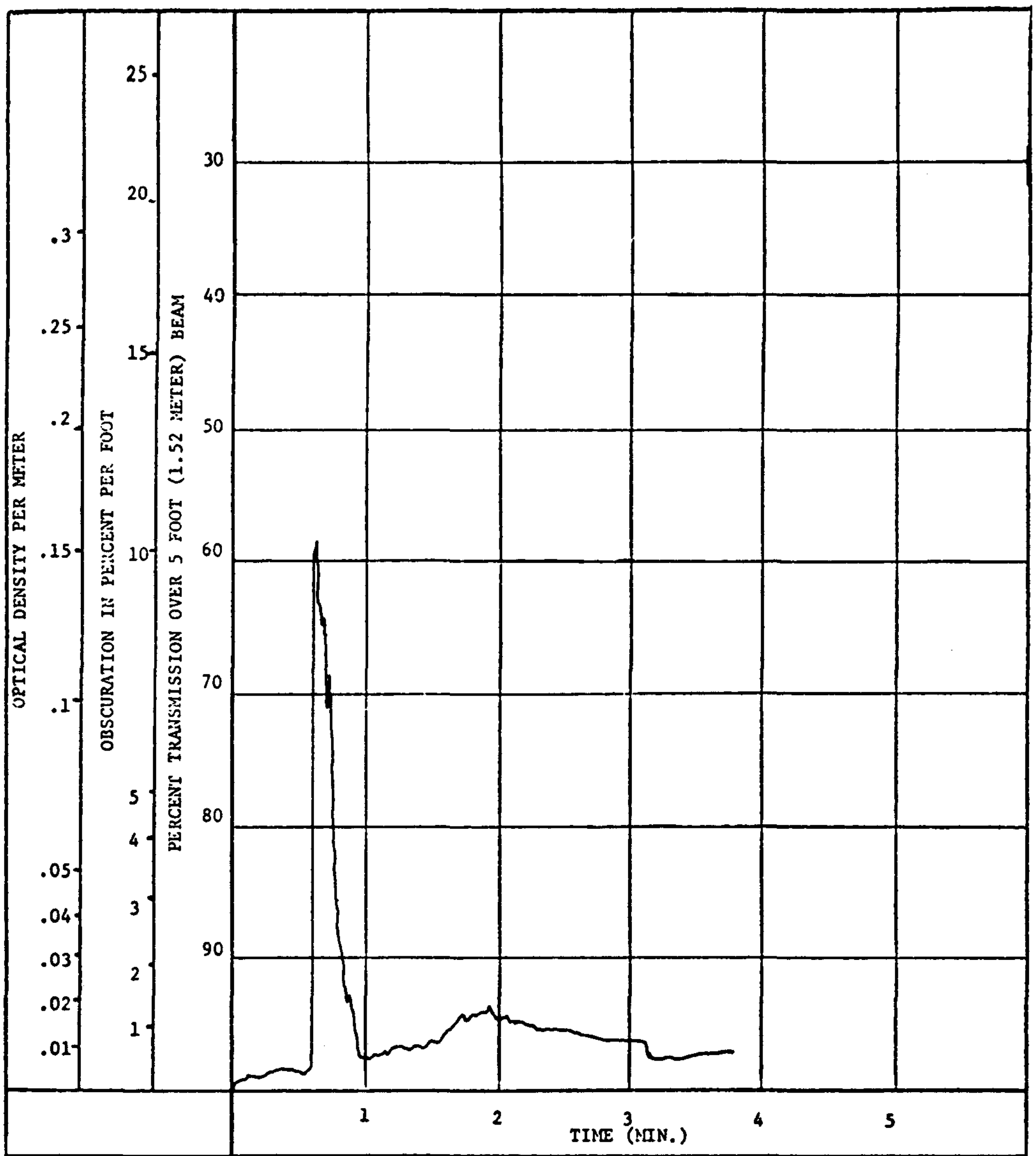


Photo-Electric Detectors	A	●
	B	●
	C	●
	D	●
	E	●
	F	●
	G	●
Ionization Detectors	H	●
	I	●
CO Level	PPM	63
Avg Velocity	a	60 (18.29)
Temp Over Fire	°C	46
Temp at Det	°C	21

Test No: 3	COMB: ½ # Paper	IGN: Match	DATE: 2/13/74

a VELOCITY IN FEET PER MIN (METERS PER MIN)

FIGURE 2 Smoke buildup curve for paper fire.

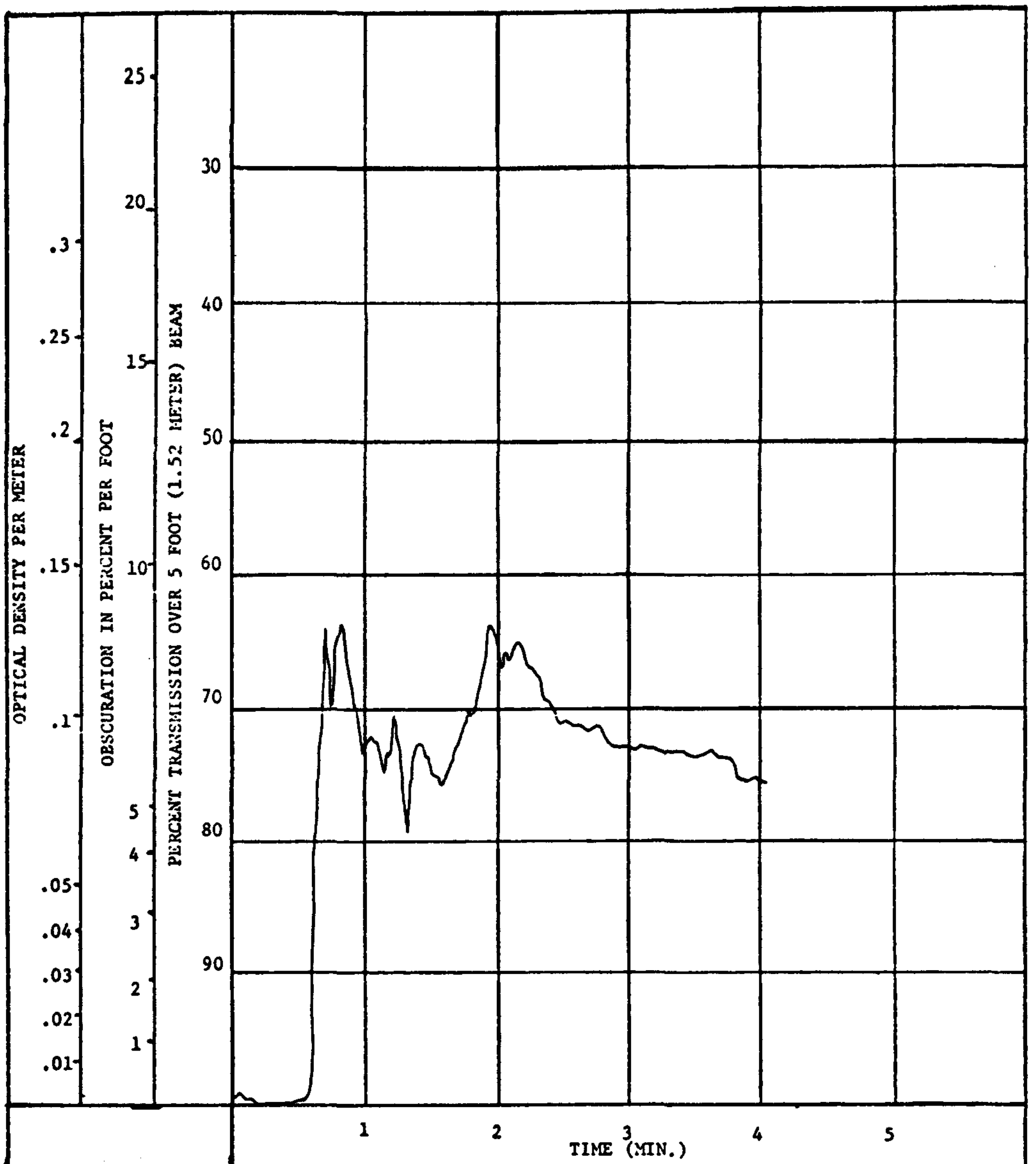


Photo-Electric Detectors	A	●
	B	●
	C	●
	D	●
	E	●
	F	●
	G	
Ionization Detectors	H	●
	I	●
CO Level	PPM	18
Avg Velocity	a	70 (21.34)
Temp Over Fire	°C	18
Temp at Det	°C	12
Test No: 27		COMB: 2oz Polystyrene · IGN: 50cc Alcohol · DATE: 2/15/74

a VELOCITY IN FEET PER MIN (METERS PER MIN)

FIGURE 3 Smoke buildup curve for polystyrene fire.

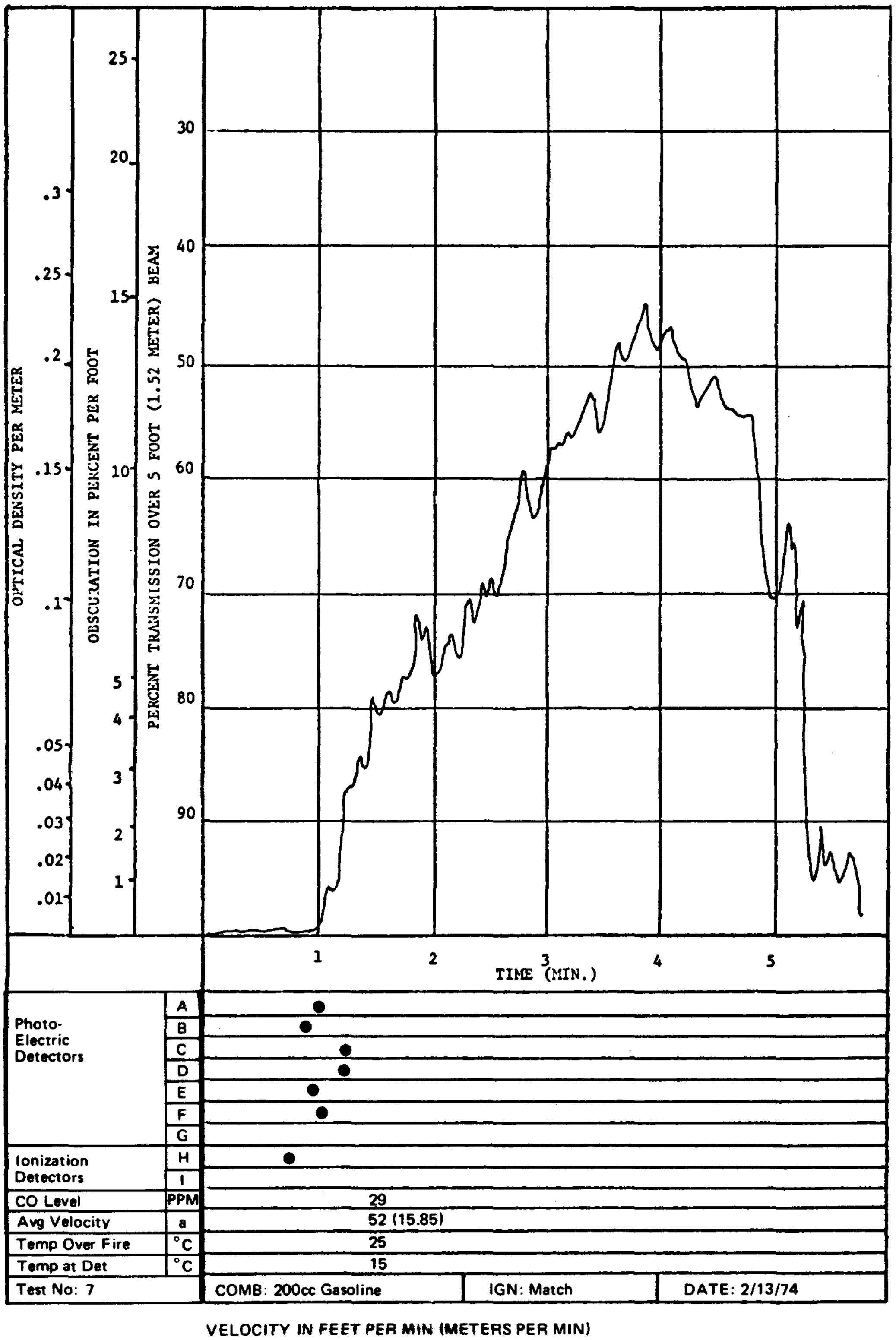
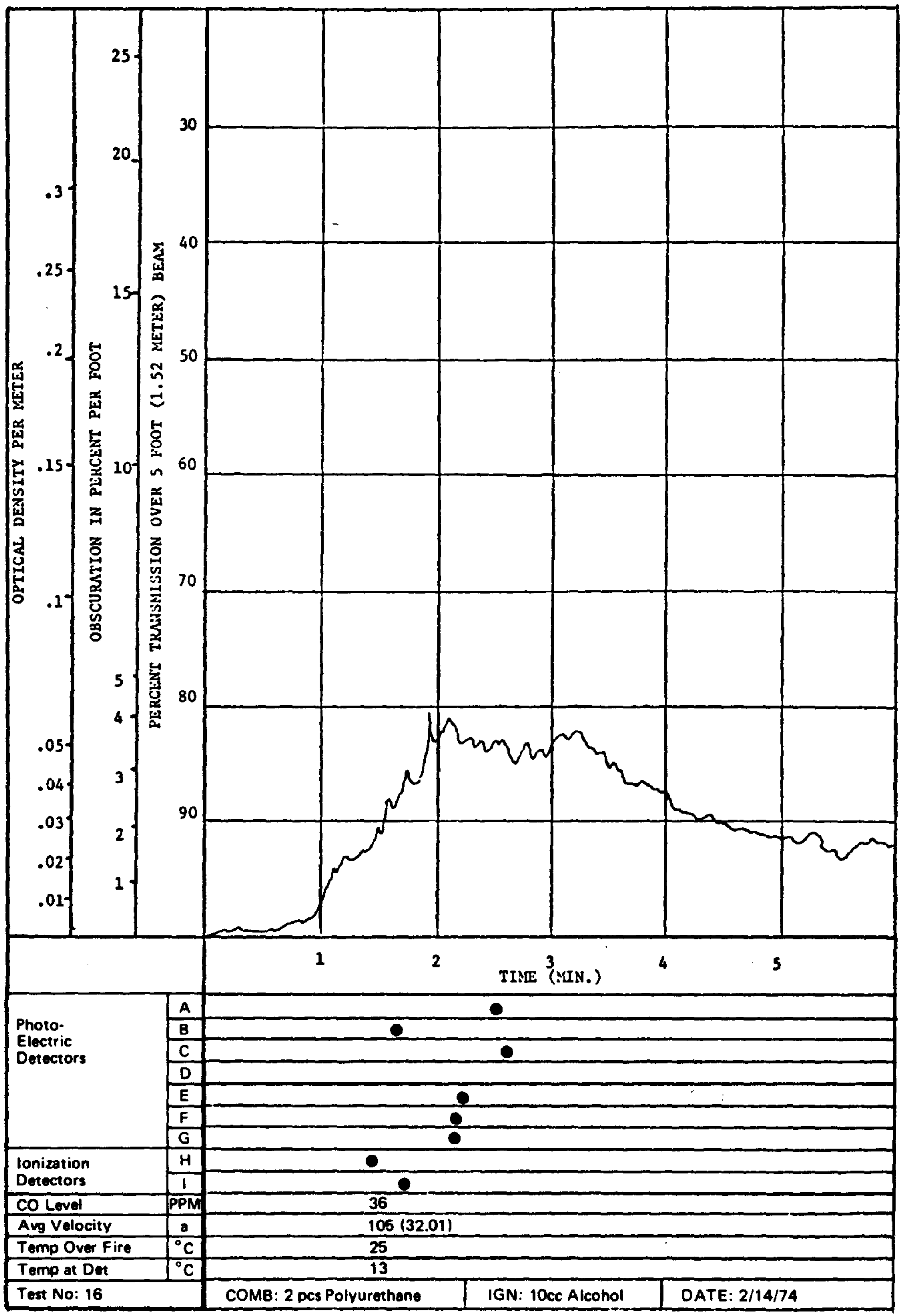


FIGURE 4 Smoke buildup curve for gasoline fire.



VELOCITY IN FEET PER MIN (METERS PER MIN)

FIGURE 5 Smoke buildup curve for polyurethane fire.

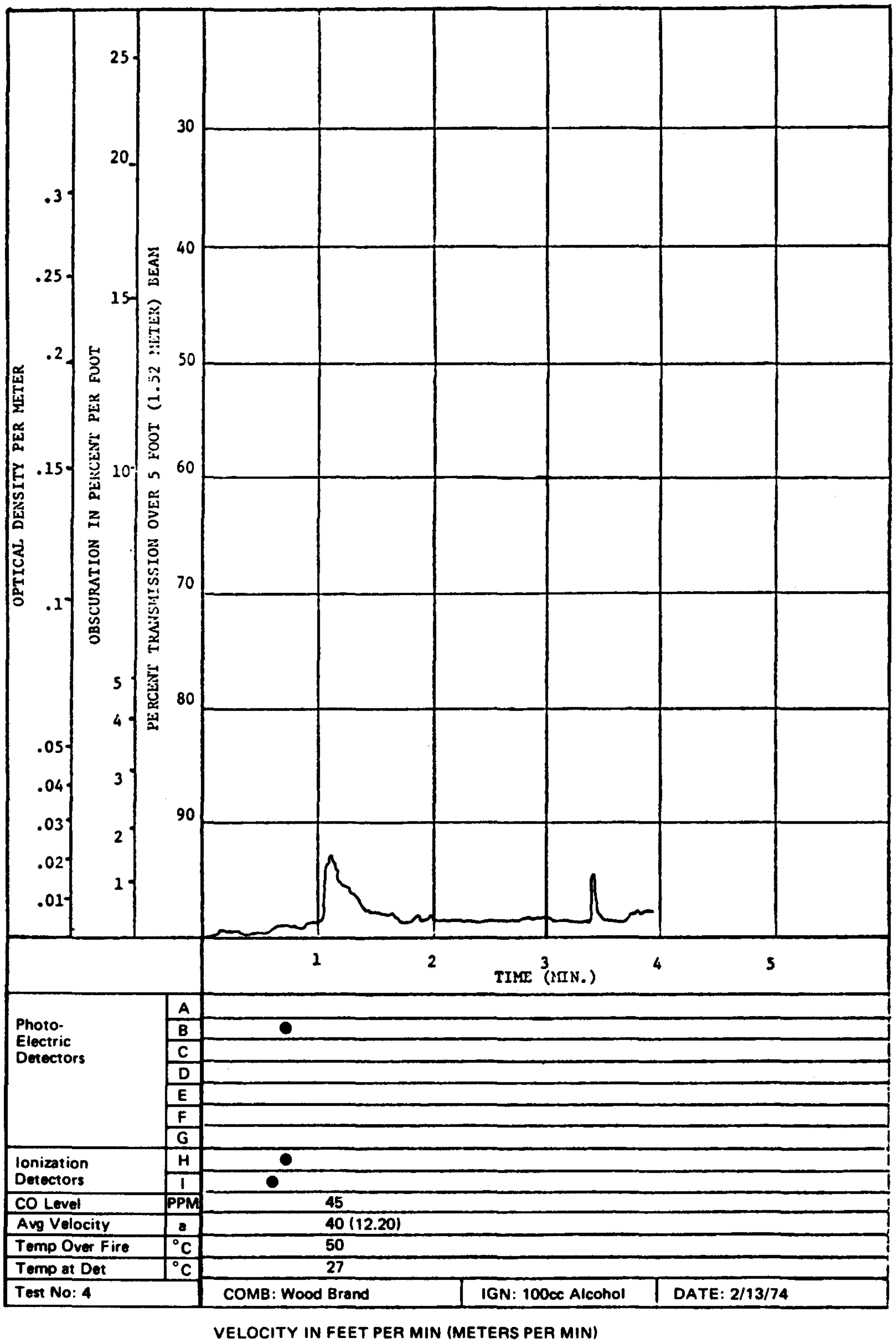
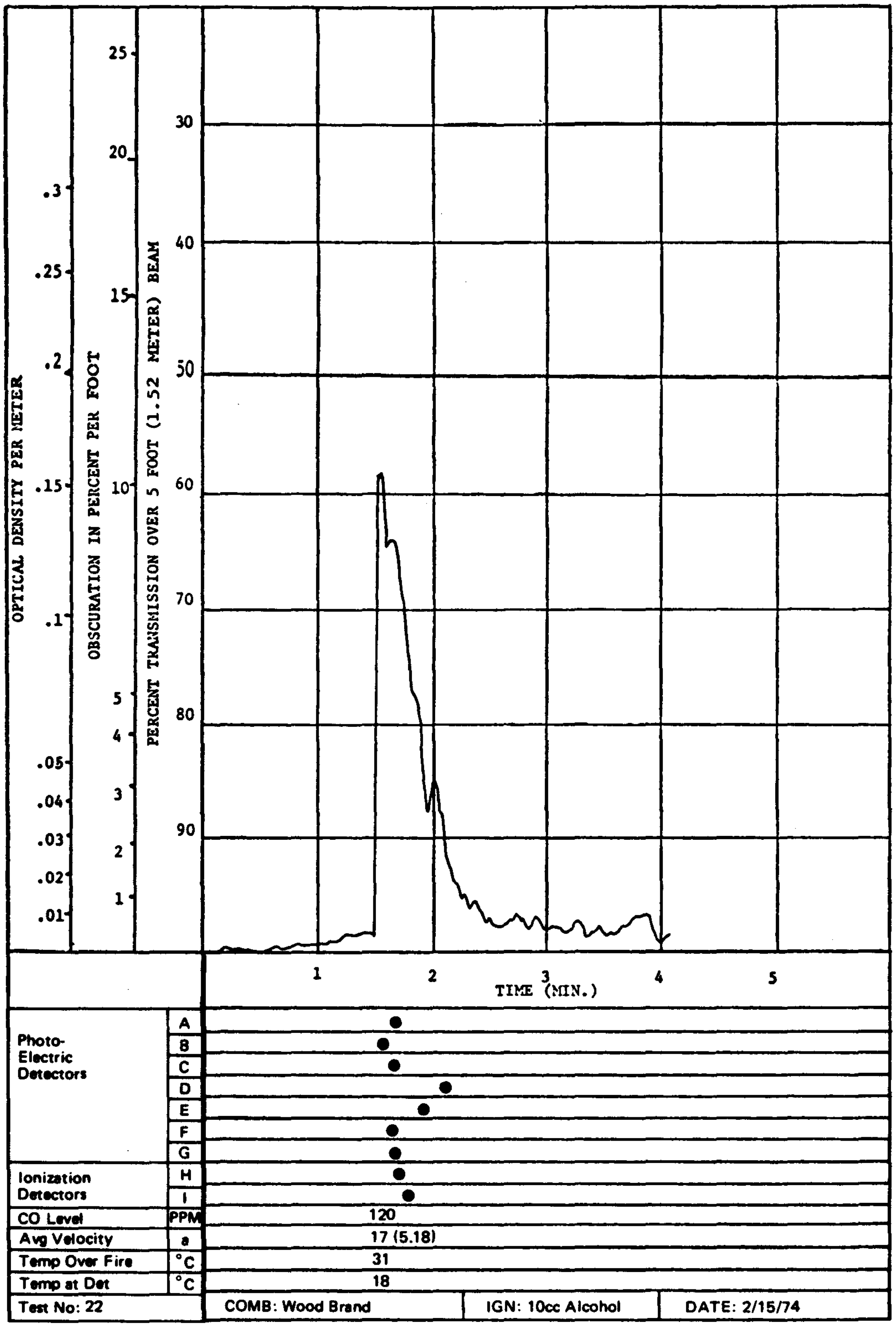


FIGURE 6 Smoke buildup curve for wood brand fire.



VELOCITY IN FEET PER MIN (METERS PER MIN)

FIGURE 7 Smoke buildup curve for modified wood brand fire.