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ST. LAWRENCE BURNS
SMOKE AND SOUND MEASUREMENTS

ANALYZED

BY

G. WILLIAMS - LEIR

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DECEMBER 1959

DBR INTERNAL REPORT NO. 151

NATIONAL RESEARCH COUNCIL

CANADA

DIVISION OF BUILDING RESEARCH

ST. LAWRENCE BURNS
SMOKE AND SOUND MEASUREMENTS

by

G. Williams-Leir

ANALYZED

Report No. 151

of the

Division of Building Research

OTTAWA

December 1959

PREFACE

The circumstances that led to the carrying out of fire tests on eight buildings in the project known as the St. Lawrence Burns, and the objectives and the ways in which these were achieved are fully described in a general report. It constitutes the complete record of the planning and execution of the experiments, together with all general information. The details on each kind of measurement made, including the results obtained, are contained in separate companion reports of which this is one. All the results are combined and are discussed and final conclusions drawn in a summary report.

Duplication has been avoided as far as possible, and it will be necessary to refer to the general report in reading any of the other reports including this one for any information which is pertinent to more than one of them. A listing of all reports on the project follows this preface.

The participation of the British Joint Fire Research Organization in the experiment, the interest and support of the Federal Civil Defence authorities, the assistance of the Ontario Fire Marshal and his staff, and finally the complete co-operation and very considerable assistance extended by the Hydro-Electric Power Commission of Ontario are all gratefully acknowledged. It is a pleasure also to be able to record the special contribution made by members of the staff of the Fire Section who worked long hours, often under trying field conditions and at great personal inconvenience, to meet the many deadlines and to complete the project in a most satisfactory manner.

The author of this report is Mr. G. Williams-Leir, research officer with the Fire Section of this Division who assisted in the initial planning of the project and was responsible for the measurements of temperature, smoke and sound.

Ottawa
December 1959

N. B. Hutcheon
Assistant Director

REPORTS ON THE ST. LAWRENCE BURNS

No.	Sub-Title	Author
150	General Report	G.W. Shorter
151	Smoke and Sound Measurements	G. Williams-Leir
152	Temperature Measurements	G. Williams-Leir
153	Radiometer Measurements	J.H. McGuire
154	Ventilation Rate Measurements	J.H. McGuire
155	Resistance Thermometer Measurements	J.H. McGuire
156	Radiant Temperature of Openings	D.G. Stephenson
157	Gas Analysis	J.R. Jutras
158	Summary Report	G.W. Shorter and J.H. McGuire

ST. LAWRENCE BURNS

SMOKE AND SOUND MEASUREMENTS

by

G. Williams-Leir

House-burning experiments carried out at Aultsville, Ontario, in January and February 1958 by the Division of Building Research, National Research Council, assisted by other organizations, have been generally described by G.W. Shorter in DBR Internal Report No. 150. Smoke measurements were made in the course of these experiments and Part I of this report describes the technique used and gives the results. Recordings were made also of the sounds in the buildings during the burns. These are described in Part II.

PART I - SMOKE MEASUREMENTS

EQUIPMENT

Smoke meters constructed according to the design shown in Fig. 9 were installed in the six houses to be burned (see Figs. 1 to 5,7) in order to observe the diminution of a beam of light passed through the smoke. The light was provided by an automobile sidelamp bulb. It passed in one direction through a lens which threw a roughly parallel beam along the smoke path and through a window onto a photocell; in the opposite direction it passed to the reference photocell. To bring the outputs of the two photocells into rough equality in the absence of smoke, a diaphragm with a suitably sized hole was placed before the reference photocell.

Power was supplied from a transformer with a secondary winding rated for 20 amps. at 6 volts. It received its 115-volt supply through a sola constant voltage transformer. Both transformers were housed in the trailer provided for the protection of the recorders and other instruments.

The photocells used were of the photovoltaic type (General Electric Company 8PV1AAF Sub 3), having a sensitive surface about 3/4 by 1 1/2 inches. Under the illumination received from the lamp in the smoke meter, their current output was sufficient to maintain rather more than 5 millivolts across a resistance of 500 ohms.

Each photocell was shunted with a Helipot calibrated variable resistance of 500 ohms and the potential across this was fed into a Leeds and Northrup self-balancing potentiometric millivolt recorder with 16 channels, printing at 4-second intervals on a scale of -0.5 to +5 millivolts. Each reference photocell was allotted one channel, so that its output was read at 64-second intervals. Each measuring photocell was allotted two channels so that its output was read at 32-second intervals. Thus, nine channels were required for the three smoke meters in simultaneous use; the remaining seven were used to record the outputs of radiometers and other instruments, as described in other reports of this series.

The variable-resistance shunt on each photocell was located beside the recorder and permitted adjustment of the input to the recorder to an exact 4.5 millivolts. This could be done immediately before the burn after all installation work (which was likely to disturb the alignment of the lamp and photocell) was complete.

This was the procedure with the two originally planned smoke meters. As an afterthought, smoke measurements in the cellar as well as in the two bedrooms were called for at a stage when it was too late to obtain more Helipots. Fixed shunt resistances of 220 ohms were used in the third smoke meter, with the result that it was not possible to use the whole scale span of the recorder; the inputs varied in different tests from 1.5 to 3 millivolts.

1. Installation of Smoke Meter

During the burn each instrument was housed inside a short piece of stove piping attached to a board that was cut to fit into the opening produced by raising the lower sash of a window. Since the photocells were sensitive to stray light other than that produced by the smoke meter lamp, it was necessary to exclude light from the rooms where the instruments were installed. This was done by stapling sheets of paper coated with aluminum foil over the inside of the windows and stuffing paper or cloth around the instrument where it passed through the stove pipe. The paper withstood the heat well and remained in position after the time when the smoke meters had to be recovered.

2. Recovery

Four smoke meters were made, the original intention being to provide two spares. Provision had to be made to recover each instrument during the course of the burn before it suffered damage by heat. As shown in Fig. 9, a loop of strip steel was attached to the reference-cell end of the smoke meter so that the loop projected outside the building. When it became necessary the instrument was recovered by means of a long hooked pole made from two 12-ft lengths of duralumin tubing.

SMOKE MEASUREMENTS

Light transmission through the 1.73-ft smoke path of the smoke meters, as computed from the recorder charts, is given in Figs. 10 to 15.

As is made clear in DBR Internal Report No. 150, some of the houses had incombustible wall and ceiling linings, some had linings of combustible materials, and others had mixtures of both. Where necessary, additional boards had been used to finish the walls, so that three were uniformly incombustible-lined and the other three were uniformly combustible-lined in the lower story, the stairway, and the upstairs hall. Buildings No. 3 and 5 were in fact wholly lined with combustibles but Building No. 2 had plaster in the bedrooms. Buildings No. 1,4 and 7 were wholly incombustible-lined. For brevity in this report the two groups of houses, incombustible-lined and combustible-lined will be referred to as I and C houses respectively.

From the transmission graphs in Figs. 10 to 15, two further graphs have been prepared. In Fig. 16 the mean transmission at each smoke meter for the three I houses is given; Fig. 17 gives the mean for the C houses. The means were taken of the logarithms of the transmissions, i.e., the mean as plotted in Figs. 16 and 17 is a geometric mean. Where, owing to the incompleteness of the individual transmission curves, the mean curve relies on but a single burn of the three, the mean curve is given as a broken line.

1. Critical Smoke Density

The treatment of the smoke measurements is modelled upon that used at the British Joint Fire Research Organization by Kingman and others (1). It originates with the assumption that a room may be regarded as smoke-logged and the escape of its occupants consequently prejudiced when visibility falls to 4 ft. Visibility here means the distance at which the holder of a fireman's handlamp can perceive objects by the light they reflect, and should be distinguished from the meteorological sense of the word. From the information given, it can be inferred that the JFRO workers considered that this limit had been reached when the light transmitted through the 2-ft smoke path of their instrument was reduced to 5 per cent of its intensity in the absence of smoke.

In smoke of the same density, the corresponding transmission through the shorter (1.73 ft) smoke path of the DBR smoke meters would be 7.5 per cent. The rooms at

Aultsville were consequently regarded as smoke-logged from the instant when transmission fell to 7.5 per cent.

2. Calibration of Smoke Meters

As Fig. 9 shows, provision was made for the insertion of optical filters in the light path of each smoke meter at the end remote from the lamp. Four graded and polished neutral glass filters, each about 2 inches square, were used for the calibration of the smoke meters; if necessary this could be done at any stage. Figure 18 shows the result of a calibration carried out in Building No. 2 immediately before the burn. Photocurrent from the measuring photocell is plotted against luminous transmittance for each of the four filters, as given in the report of calibration supplied with the filters.

It will be seen that the deviation from linearity is quite small, and in consequence was neglected. Transmittances of smoke were calculated directly from the outputs of the two photocells in each meter without reference to Fig. 18. Dr. W.E.K. Middleton of the Division of Applied Physics, N.R.C., gave helpful advice and arranged for the fabrication and calibration of a set of neutral glass filters.

3. Visibility in Smoke

The threshold of the smoke-logged condition was chosen to be 4 ft handlamp visibility. It was thought worth while to discover to what this corresponded in terms of the usual sense of the word visibility. From a series of experiments described in Appendix A it was found that this threshold level corresponded to a visibility of 11 ft, i.e., a 10-watt lamp could just be distinguished at a distance of 11 ft in total darkness.

4. Optimum Size of Smoke Meters

In a smoke meter with a path length of 20.8 inches the transmittance at the threshold of the smoke-logged condition was 7.5 per cent. Since the recording system was linear the significant part of the record was close to the zero of the scale. For optimum sensitivity the measured quantity should be about 50 per cent of full scale. If the system is to be linear (which is desirable) the smoke path should be shorter.

Let x = optimum path length in smoke meter

v = distance of limiting visibility

c = logarithm of critical transmittance

then $x = v \log 0.5 / c$

If $v = 11$ ft and $c = -6.6$ (Appendix A)

then $x = 6$ in.

If the main interest is in measuring smoke in which the visibility is around 11 ft, the path of the smoke meter should be about 6 inches.

It may be argued that it is desirable to average the density of the smoke, which may well be non-uniform, over a larger volume than a 6-inch cylinder, but a better way of doing this would be to have several meters and to provide for averaging their readings.

5. Effect of Choice of Threshold

It is instructive to consider how the conclusions of this report are affected if a different level of smoke density is equated to the smoke-logged condition. For example, the effect of setting the smoke density 50 per cent higher may be considered. By extrapolation of the transmittance curves in Figs. 16 and 17 new limiting times may be estimated; these are given in brackets in the last two lines of Table I.

It may be seen that this drastic change from the previously accepted smoke-logged condition does not greatly alter the corresponding time intervals, and the conclusion is that the choice of threshold is not critical.

RESULTS OF SMOKE MEASUREMENTS

Results are summarized in Table I. Smoke reaches first the room with the open door and not long after penetrates the closed room. It does not reach the cellar until much later when the fire is fully developed above. This can be said of houses with both combustible and incombustible linings.

However, smoke reaches each location in the houses with combustible linings earlier than in those with incombustible linings. Table I indicates the times at which the smoke-logged condition was reached during the experiments.

Although smoke of this density will hardly be fatal of itself, vision cannot be relied upon to guide a trapped person to a possible escape route after the smoke-logged stage has been reached. Some would doubtless be able to feel their way to safety, and rescue is a possibility, but a trapped person is likely to become a victim.

It will be seen, therefore, that although all the times are short, incombustible linings give an extra half-minute in which to see the way out of an open bedroom and a whole minute for escape from a closed bedroom. Of itself closing the door of a bedroom provides two extra minutes.

PART II - SOUND RECORDINGS

It was decided to record the noise made by fire in the two bedrooms where smoke was being measured, and since both smoke meters and microphones had to be recovered for use in succeeding burns, they were combined in a single instrument. Thus the microphone was mounted on the measuring cell end of the smoke meter as shown in Fig. 9.

The microphone was connected by means of separately sheathed cable and Cannon XL plugs to a tape recorder in the trailer. It was a binaural model by Magnecorder, with two channels to record simultaneously the sounds picked up in the two bedrooms on the same piece of magnetic tape. Unfortunately, on some of the windier days the microphone detected some crackling from the aluminum-foil covered paper on the windows. Since the recordings were made in rooms which lacked furniture they were consequently rather reverberant; sound in an inhabited house would be somewhat more muted.

RESULTS OF SOUND MEASUREMENTS

The noise recordings were compared with the level of sound from an alarm clock situated 3 ft from the sound level meter. Results are listed in Table II. The last column has been included because it is believed that it is the noises in the higher frequency range which are most likely to waken a sleeping person. It may be seen that the higher frequencies are attenuated much more than the lower frequencies by the closing of the bedroom door. Working on the premise that an alarm clock would rouse a sleeper, there seems little doubt that fire noise would waken the occupant of a room with the door open. Taking the second column as the more significant, however, there is some doubt as to whether a person would be wakened in a bedroom with the door closed.

It must be emphasized that the experiment is rather crude. The sharp crackling sounds produced right from the start of these fires may not be typical of a dwelling house fire, but instead may be associated with the nature of the igniting cribs. There is the additional psychological factor that a person may be habitually wakened by a certain special sound such as that of a baby crying, but remain completely undisturbed by the noises created by fire.

The author is indebted to Dr. T.D. Northwood for the analysis of the sound recordings.

CONCLUSION

Further discussion of these results, considered together with the results obtained from other measurements, is contained in the Summary Report, DBR Internal Report No. 158.

REFERENCE

1. Kingman, F.E.T., E.H. Coleman, and D.J. Rasbash. The Products of Combustion in Burning Buildings. J. Appl. Chem. 3: 463-468. 1953.

TABLE I

TIME FOR HOUSES TO BECOME SMOKE-LOGGED

Burn Number		Time: Open Bedroom	Time: Closed Bedroom	Time: Cellar
			decimal minutes	
Incombustible-lined houses:				
1		-	3.9	16.7
4		2.4	5.2	-
7		2.0	5.7	17.6
Combustible-lined houses:				
2		1.9	-	10.7
3		1.5	4.4	11.2
5		2.2	3.4	-
Times taken from mean transmission curves for the two groups:				
1, 4, 7	Incombustible	2.1 (2.9)	4.4 (5.1)	17.1 (18.8)
2, 3, 5	Combustible	1.6 (2.0)	3.4 (3.8)	10.7 (12.3)

N.B. The figures in brackets are those that would have been obtained if the smoke density level had been set 50 per cent higher.

TABLE II

	Frequency range c/s	
	60 - 20,000c/s	600 - 20,000c/s
Fire Noise, open door, average	69db	67db
Fire Noise, open door, peak	72db	72db
Fire Noise, closed door, average	65db	55db
Fire Noise, closed door, peak	67db	58db
Alarm Clock	--	63db

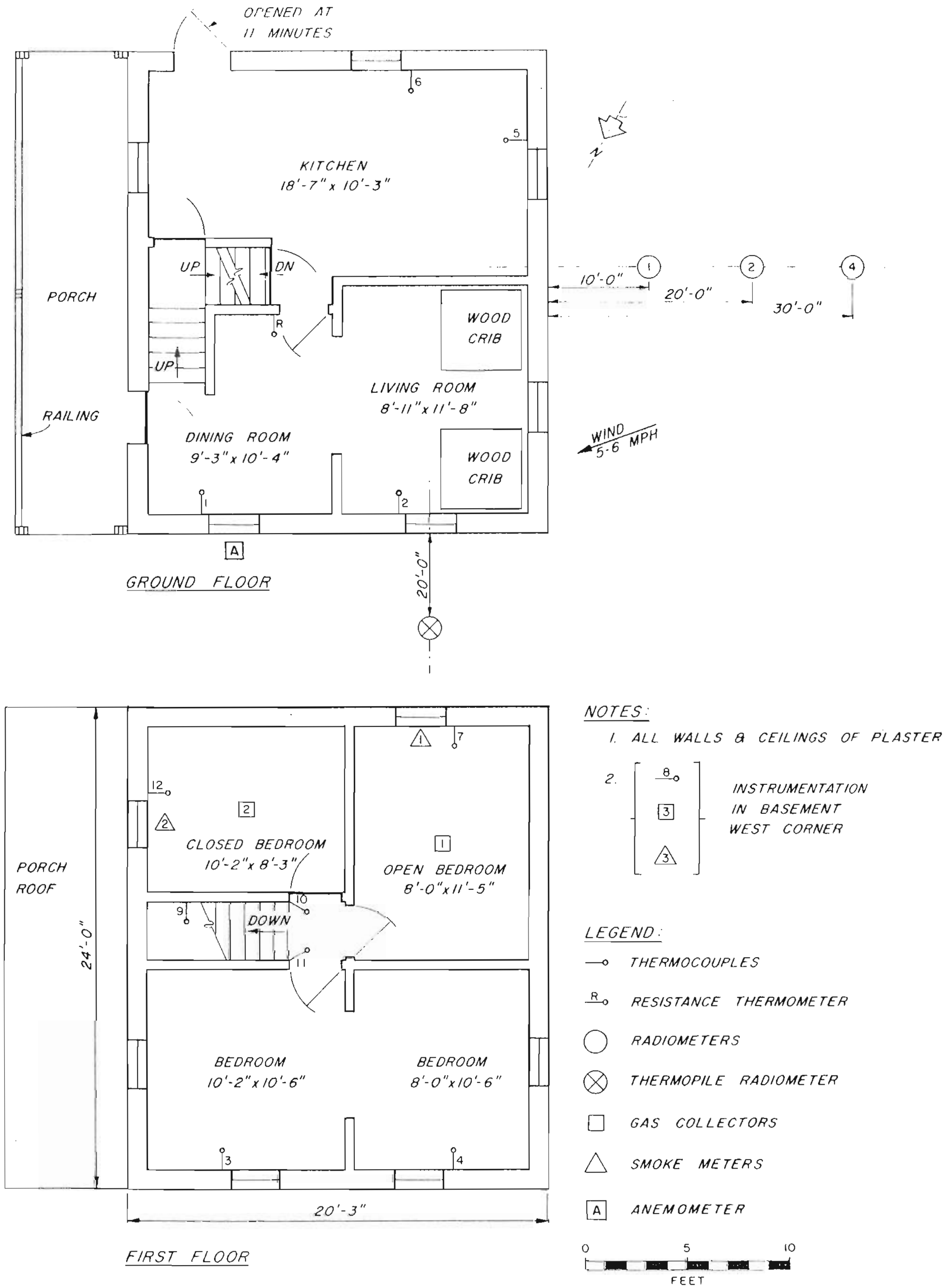

FIGURE 1 - BUILDING No. 1 - TWO-STOREY SOLID BRICK DWELLING

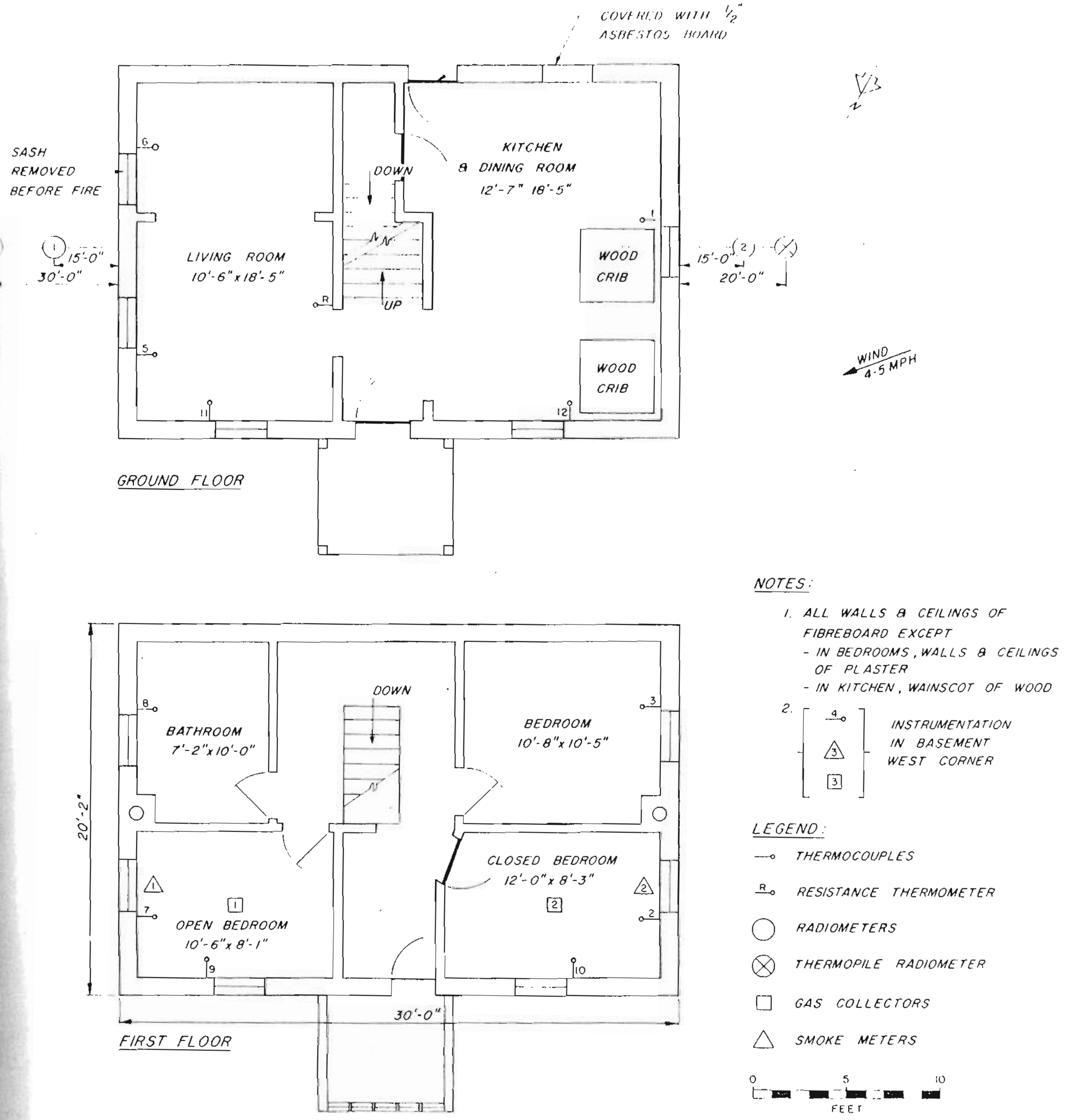

FIGURE 2 - BUILDING No. 2 - TWO-STOREY SOLID BRICK DWELLING

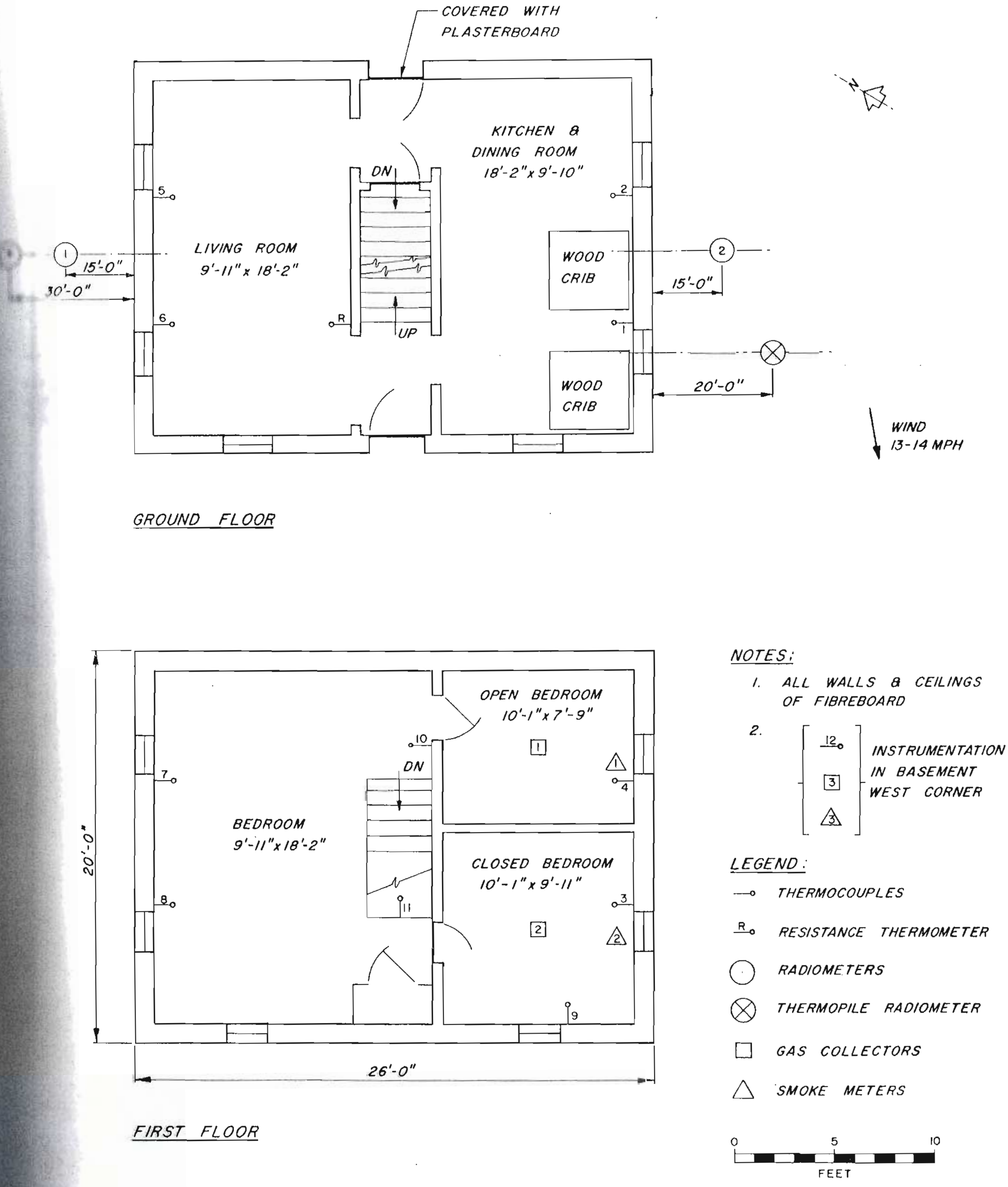

FIGURE 3 - BUILDING No. 3 - TWO - STOREY SOLID BRICK DWELLING

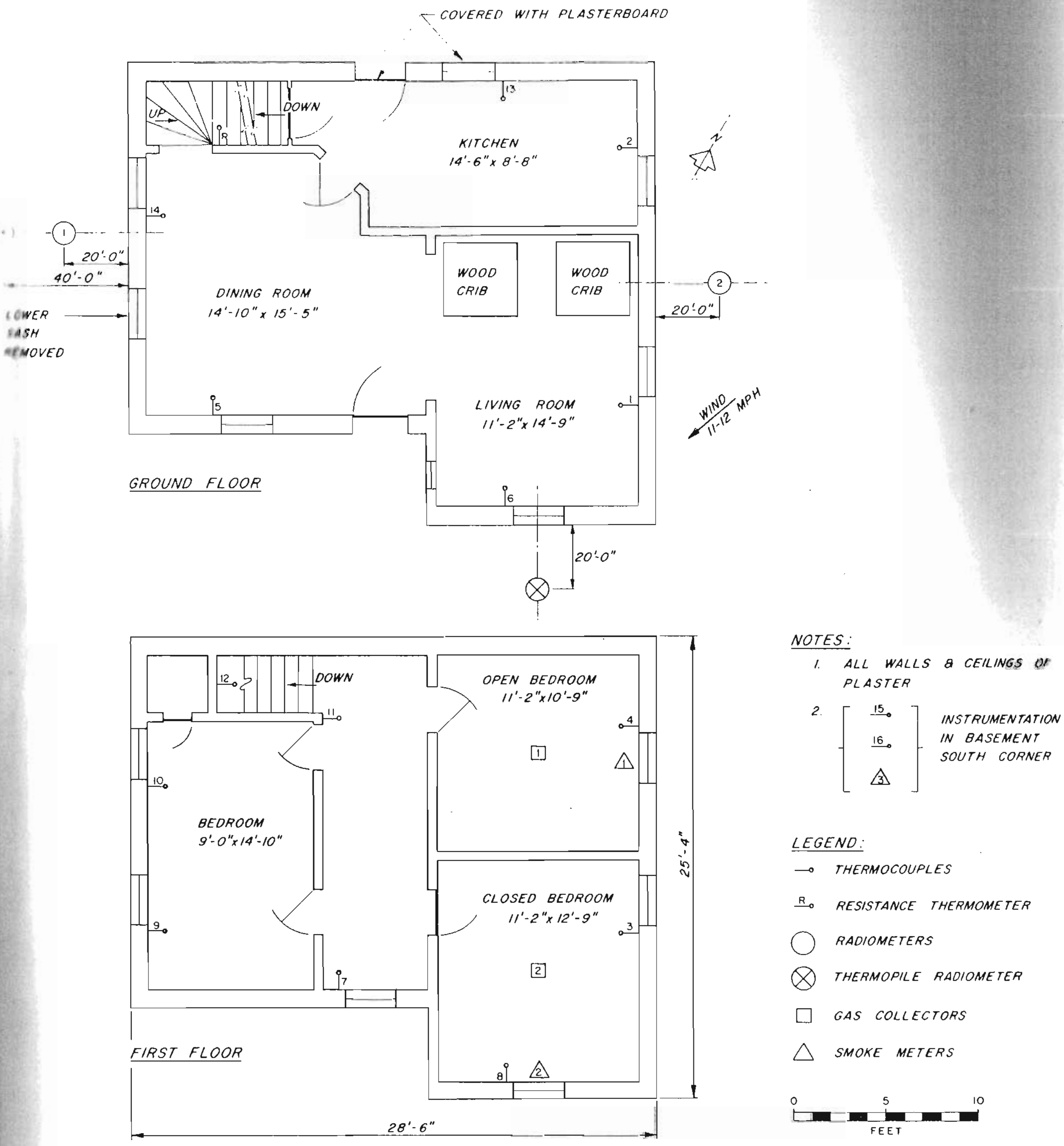

FIGURE 4 - BUILDING No. 4 - TWO - STOREY WOOD FRAME DWELLING WITH CLAPBOARD EXTERIOR AND BRICK INFILLING

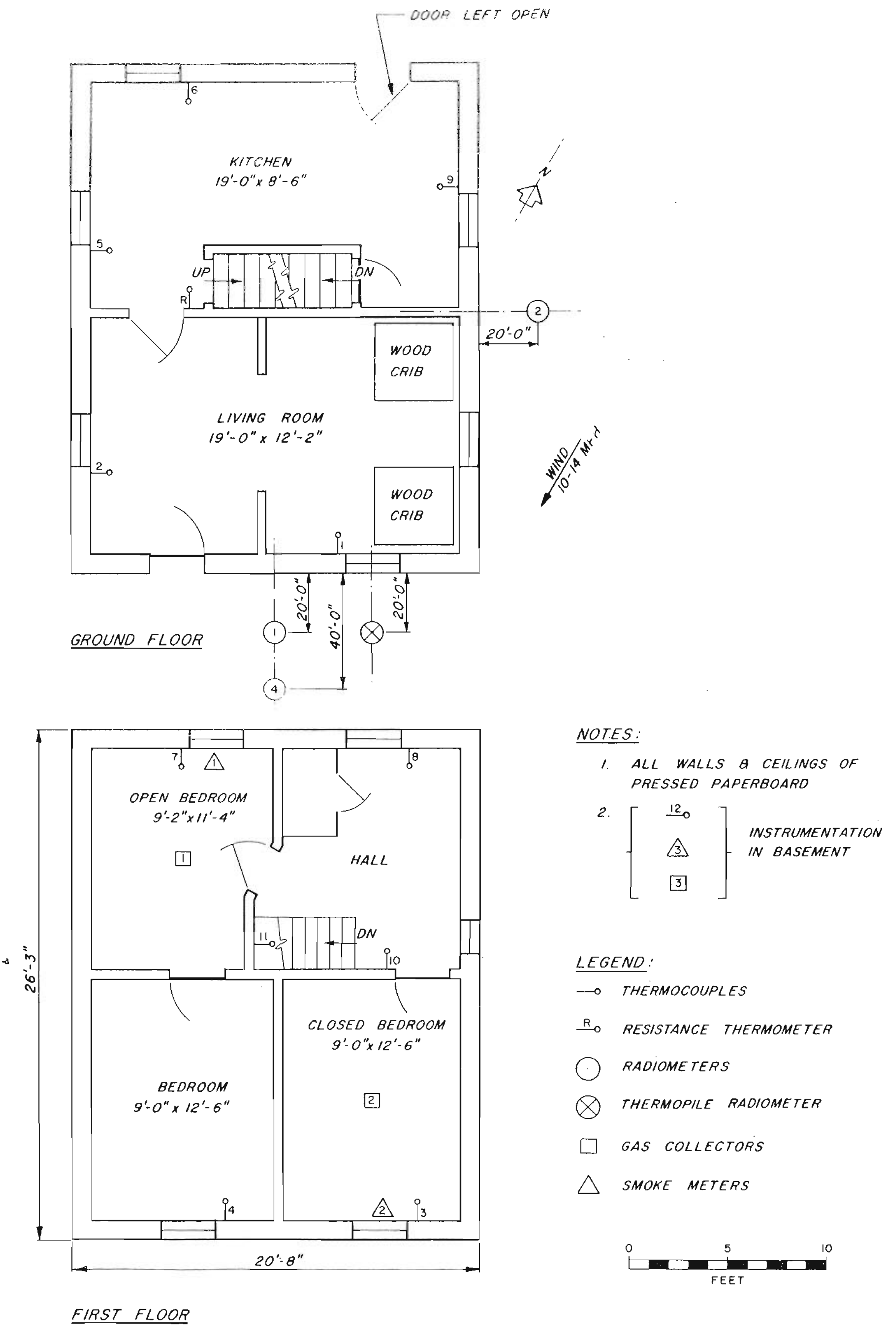

FIGURE 5 - BUILDING No. 5 - TWO - STOREY WOOD FRAME DWELLING WITH CLAPBOARD EXTERIOR

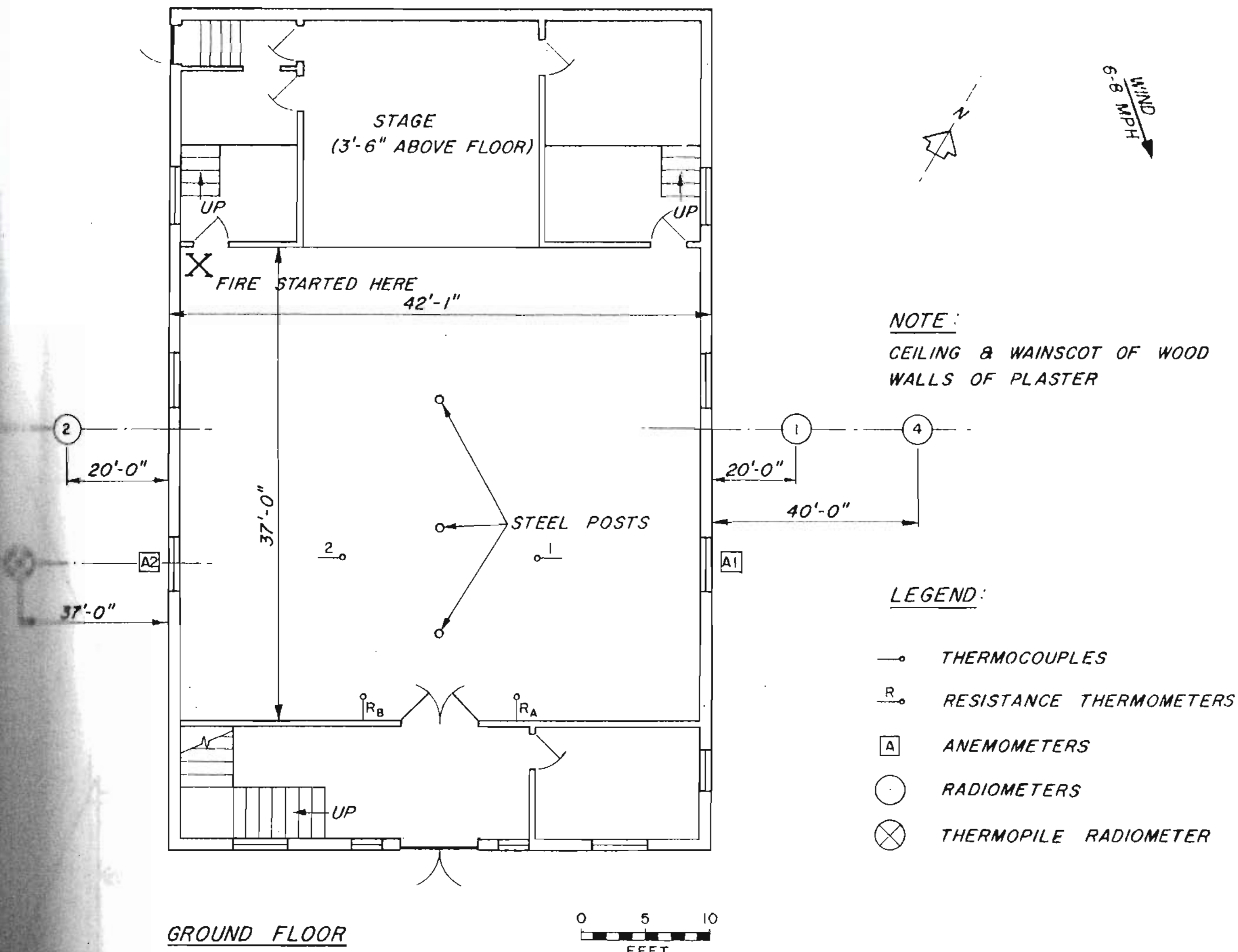

FIGURE 6 - BUILDING No. 6 - TWO - STOREY SOLID BRICK FRATERNITY HALL

FIGURE 6a - ELEVATIONS OF BUILDING No. 6 (FRATERNITY HALL)

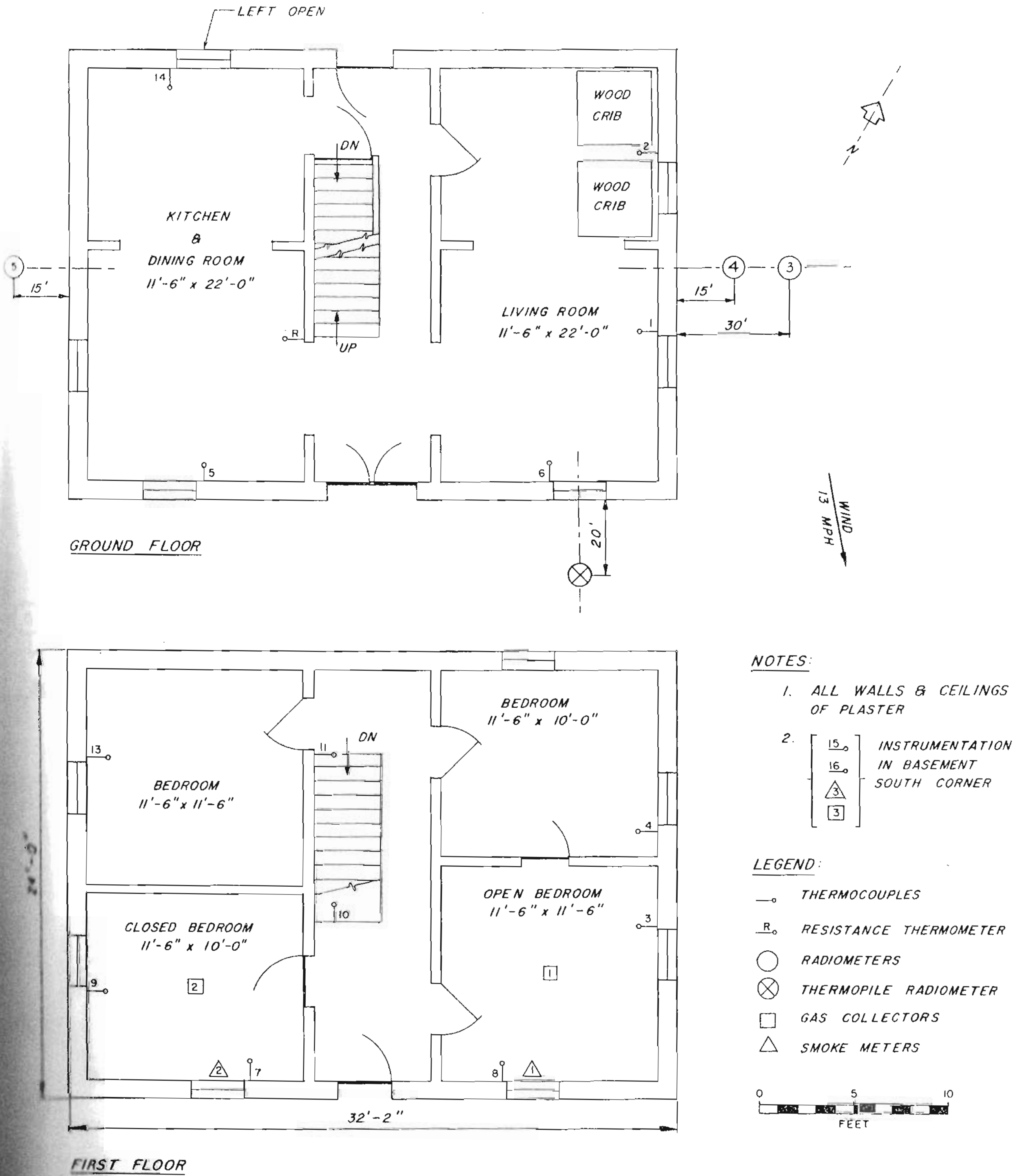

FIGURE 7 - BUILDING No. 7 - TWO - STOREY SOLID BRICK DWELLING

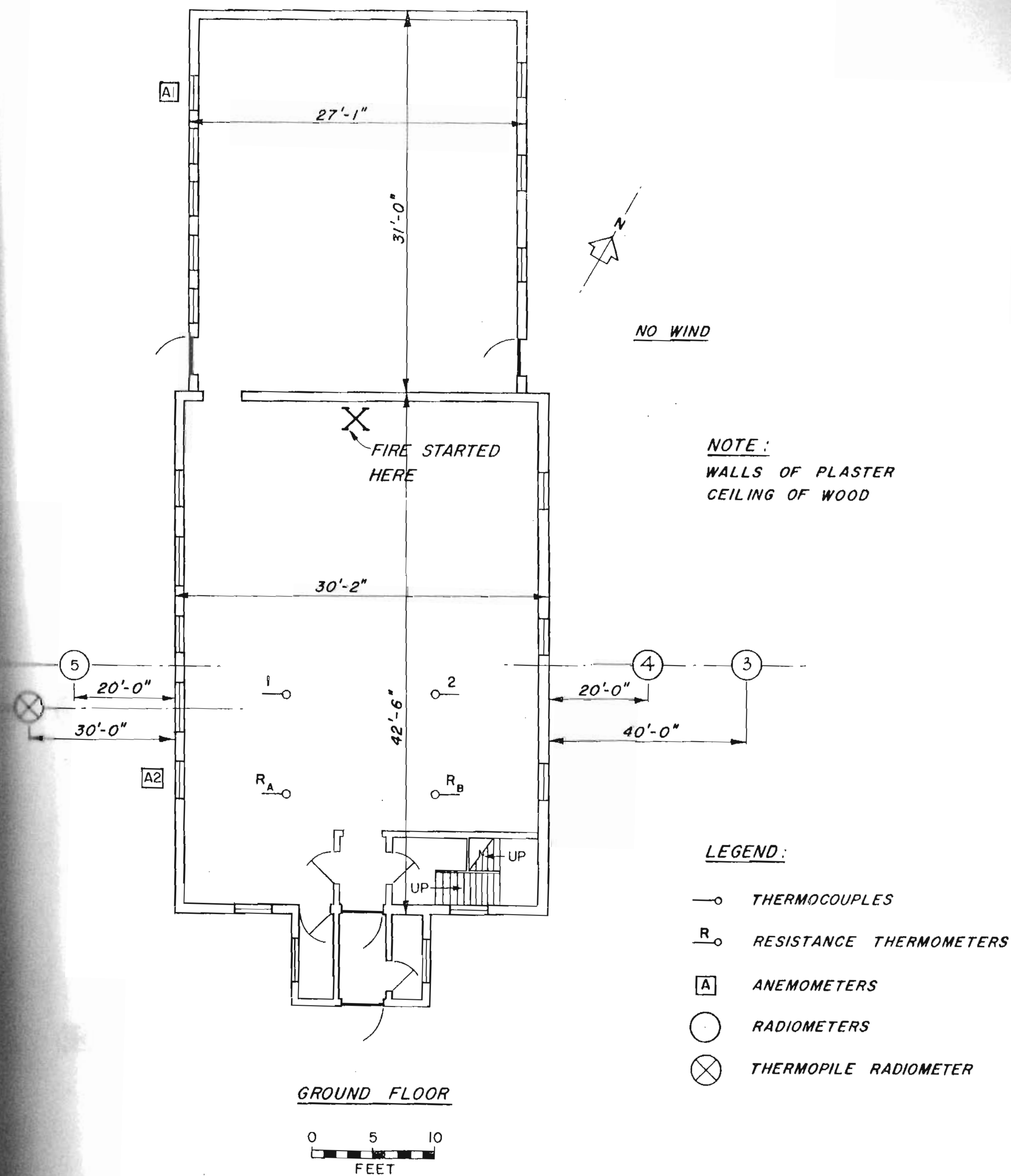

FIGURE 8 - BUILDING No. 8 - TWO - STOREY SOLID BRICK SCHOOL WITH ONE - STOREY EXTENSION AT REAR

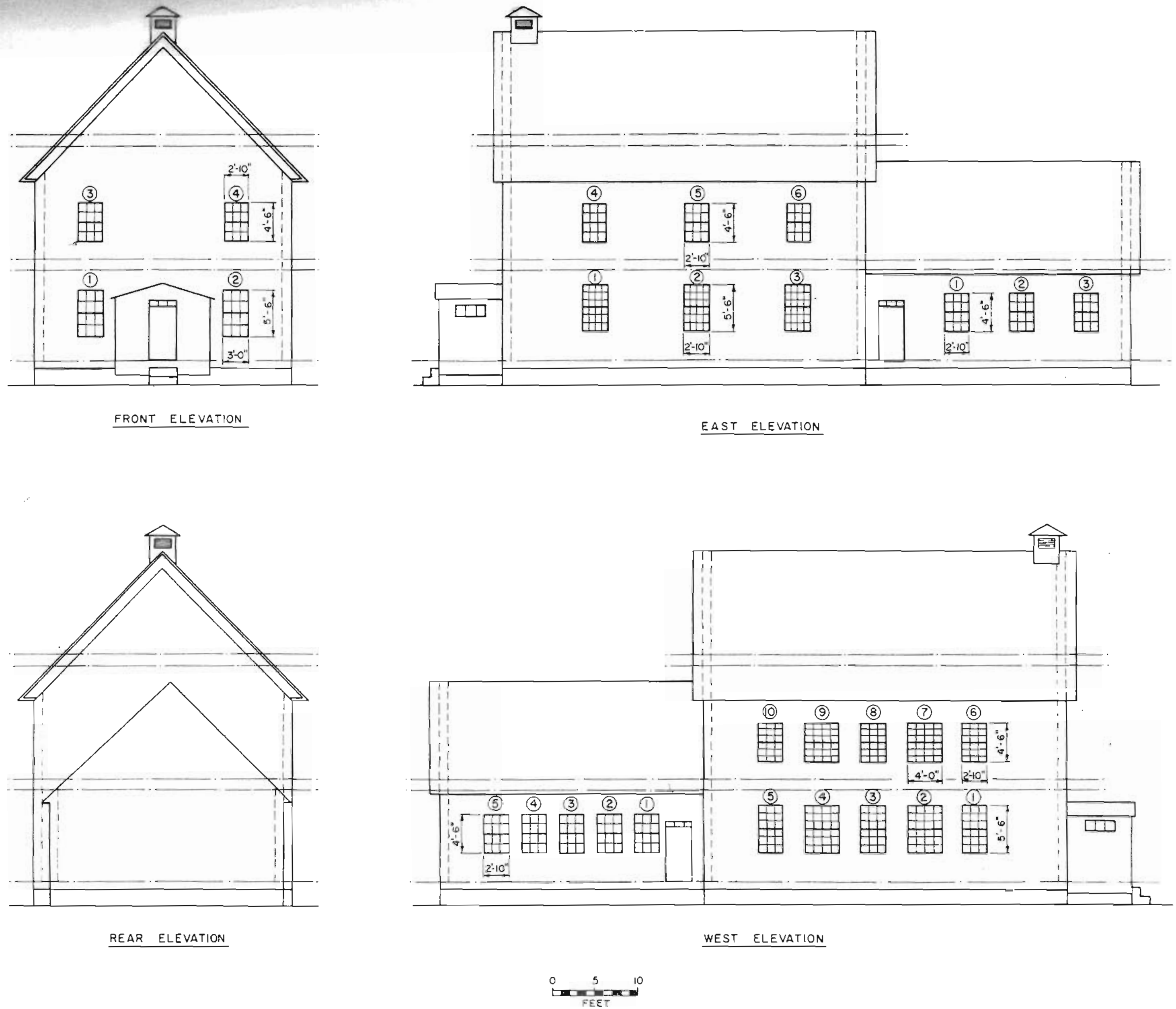

FIGURE 8a – ELEVATIONS OF BUILDING No 8 (SCHOOL)

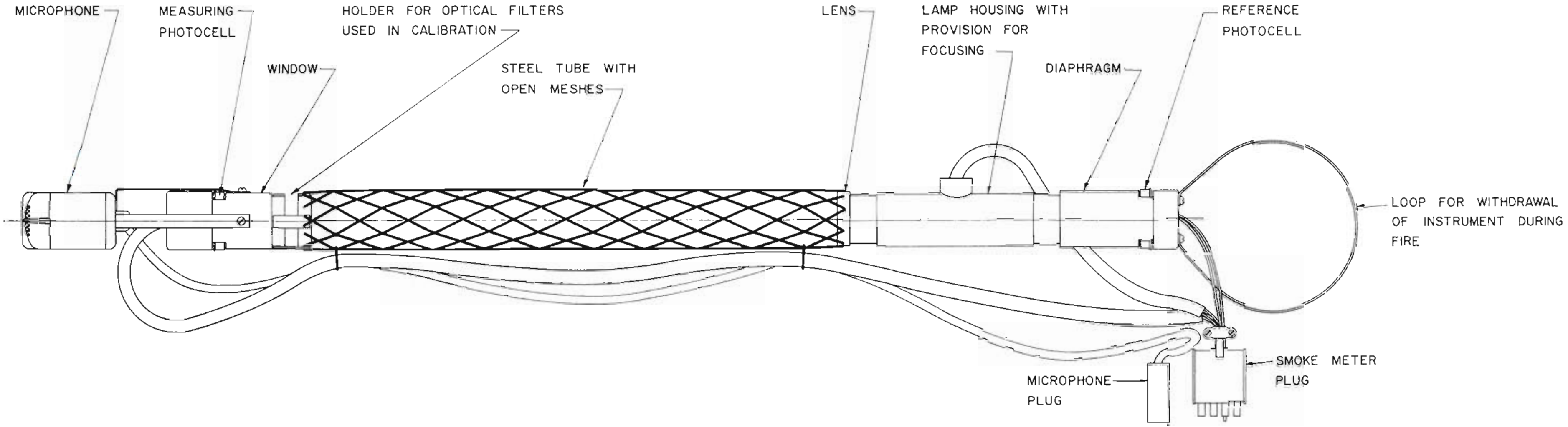

FIGURE 9 RECOVERABLE SMOKE - METER AND MICROPHONE COMBINATION

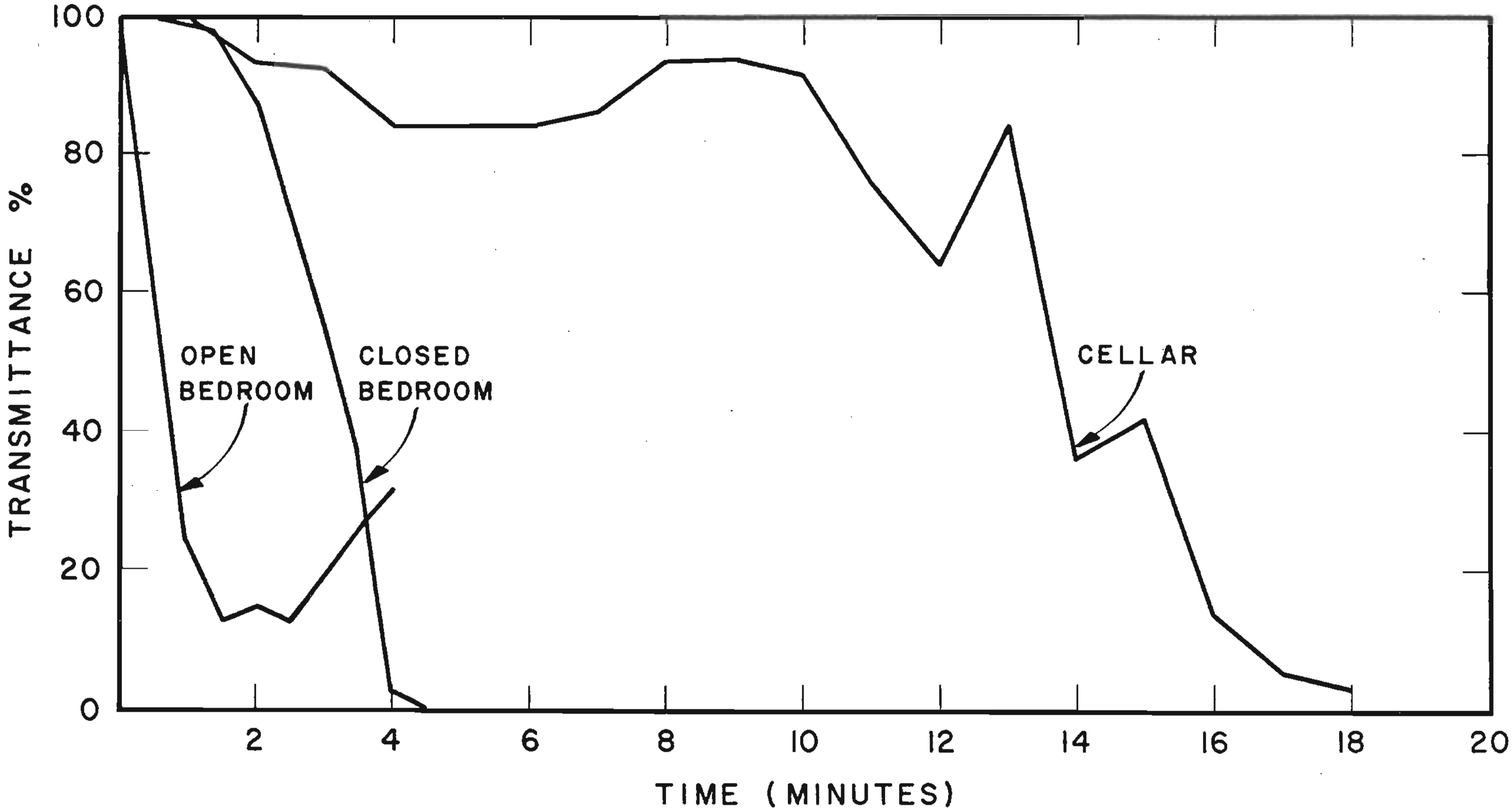

FIGURE 10

LIGHT TRANSMITTANCE IN SMOKE METERS AT BURN I

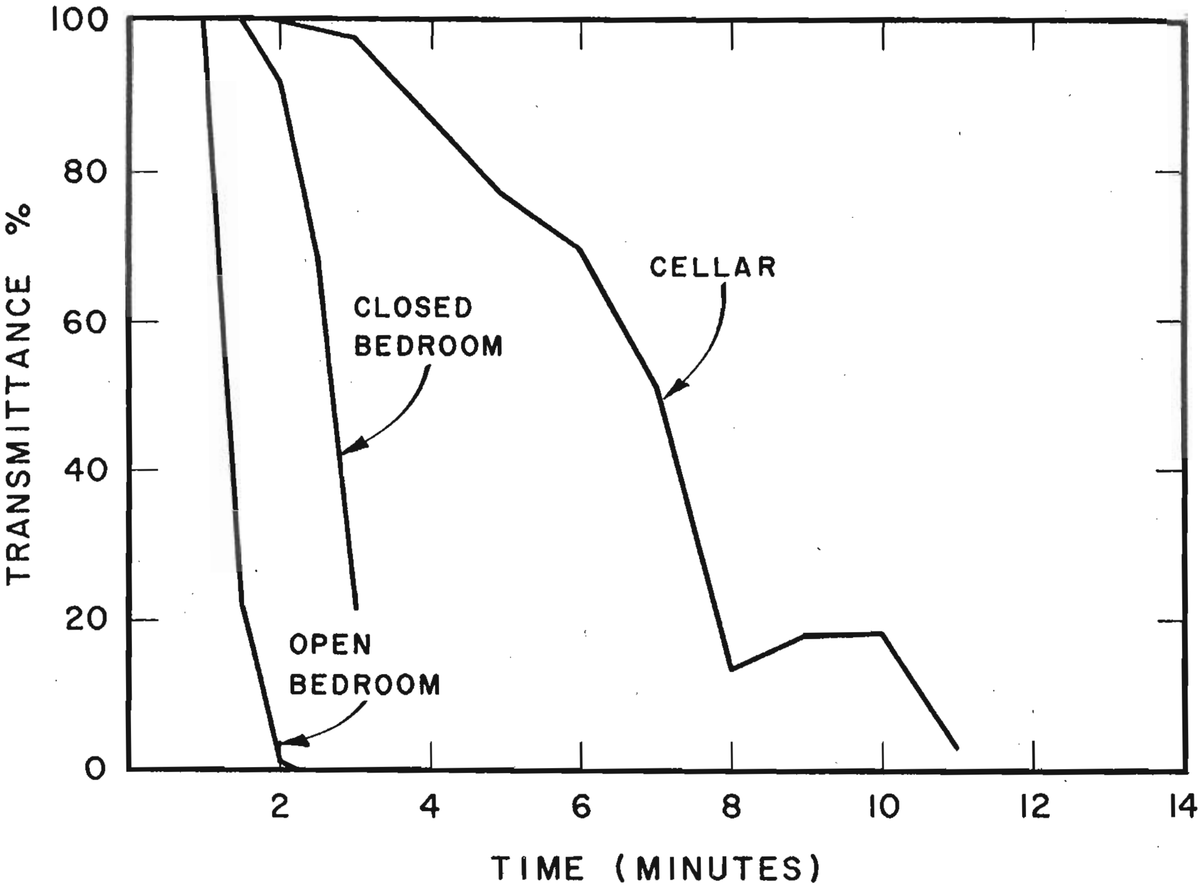

FIGURE 11

LIGHT TRANSMITTANCE IN SMOKE METERS AT BURN 2

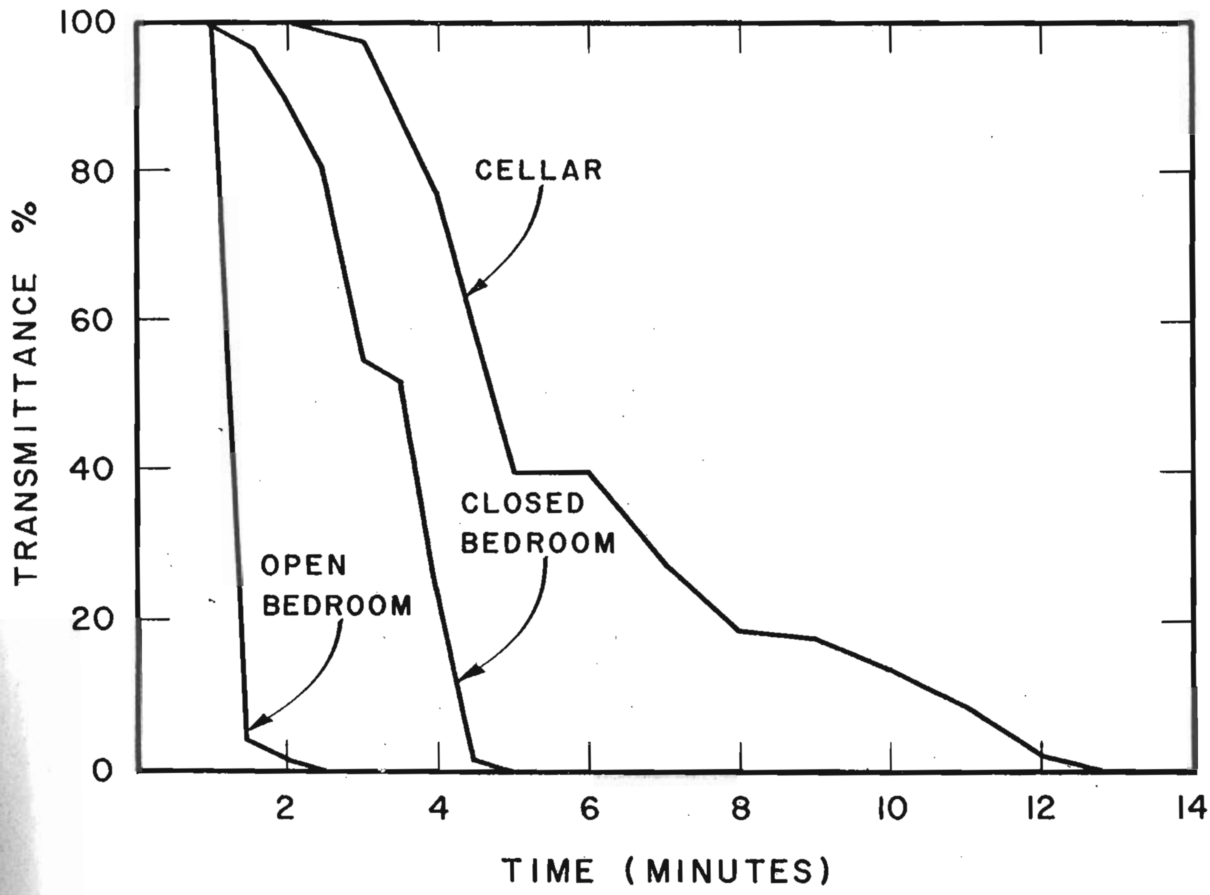

FIGURE 12

LIGHT TRANSMITTANCE IN SMOKE METERS AT BURN 3

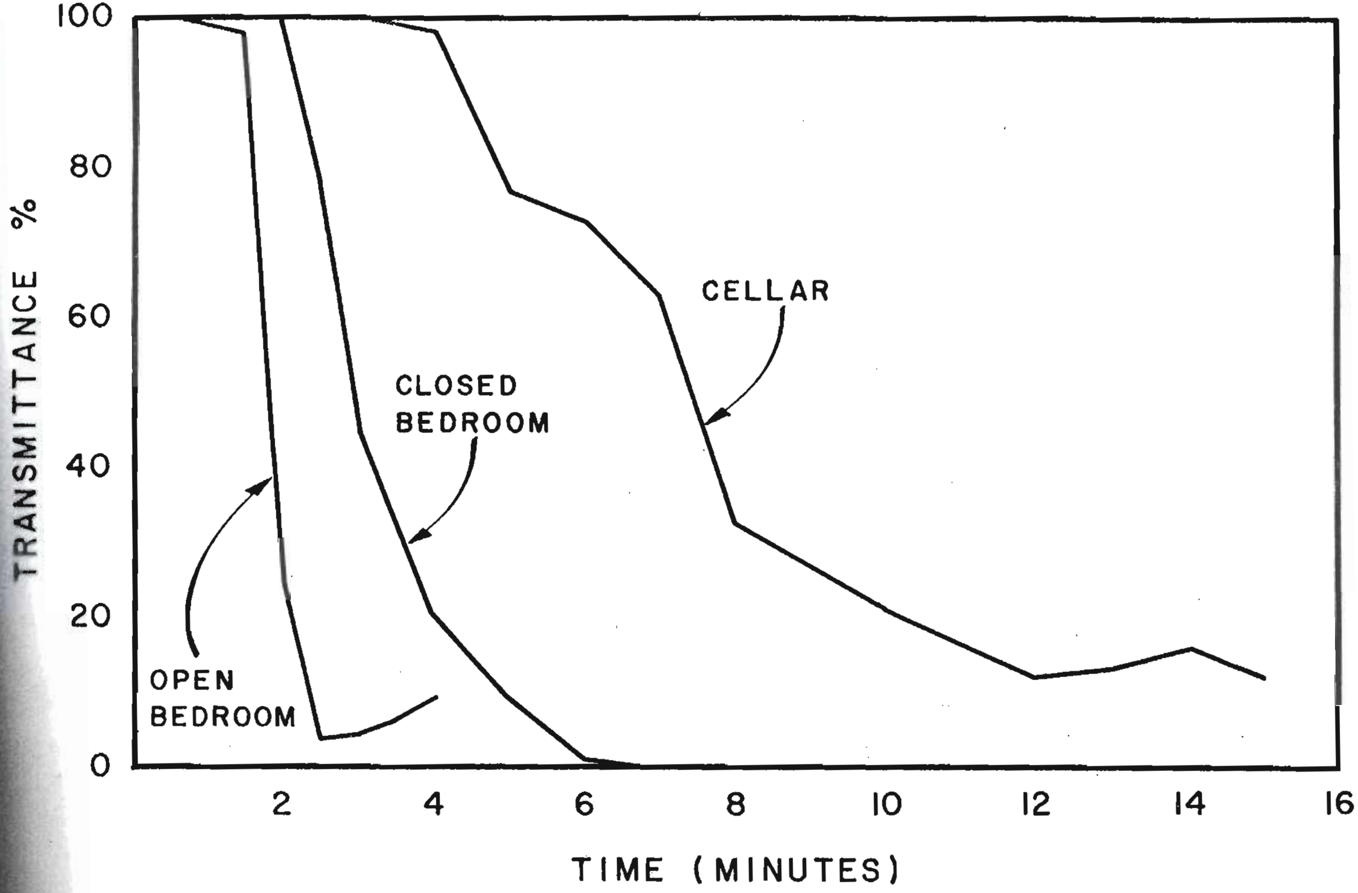

FIGURE 13

LIGHT TRANSMITTANCE IN SMOKE METERS AT BURN 4

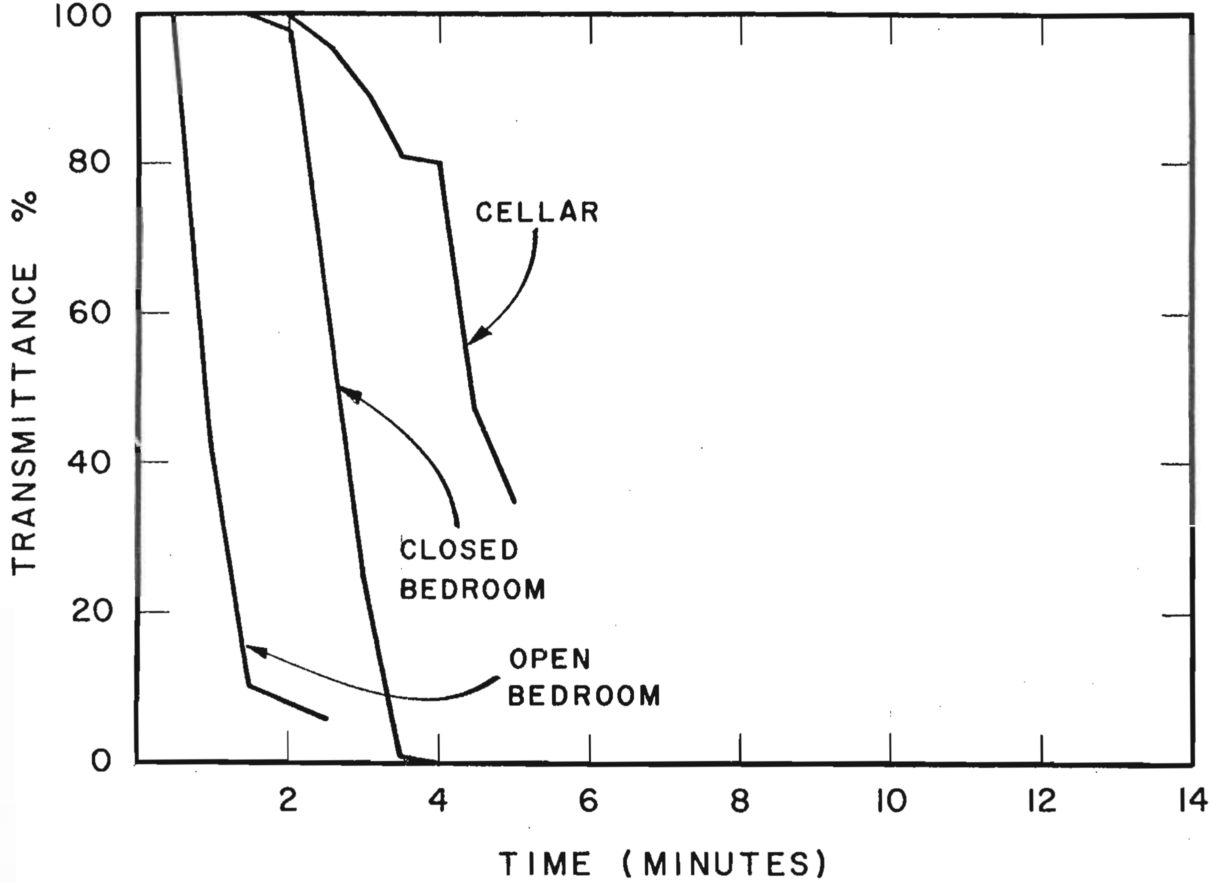

FIGURE 14

LIGHT TRANSMITTANCE IN SMOKE METERS AT BURN 5

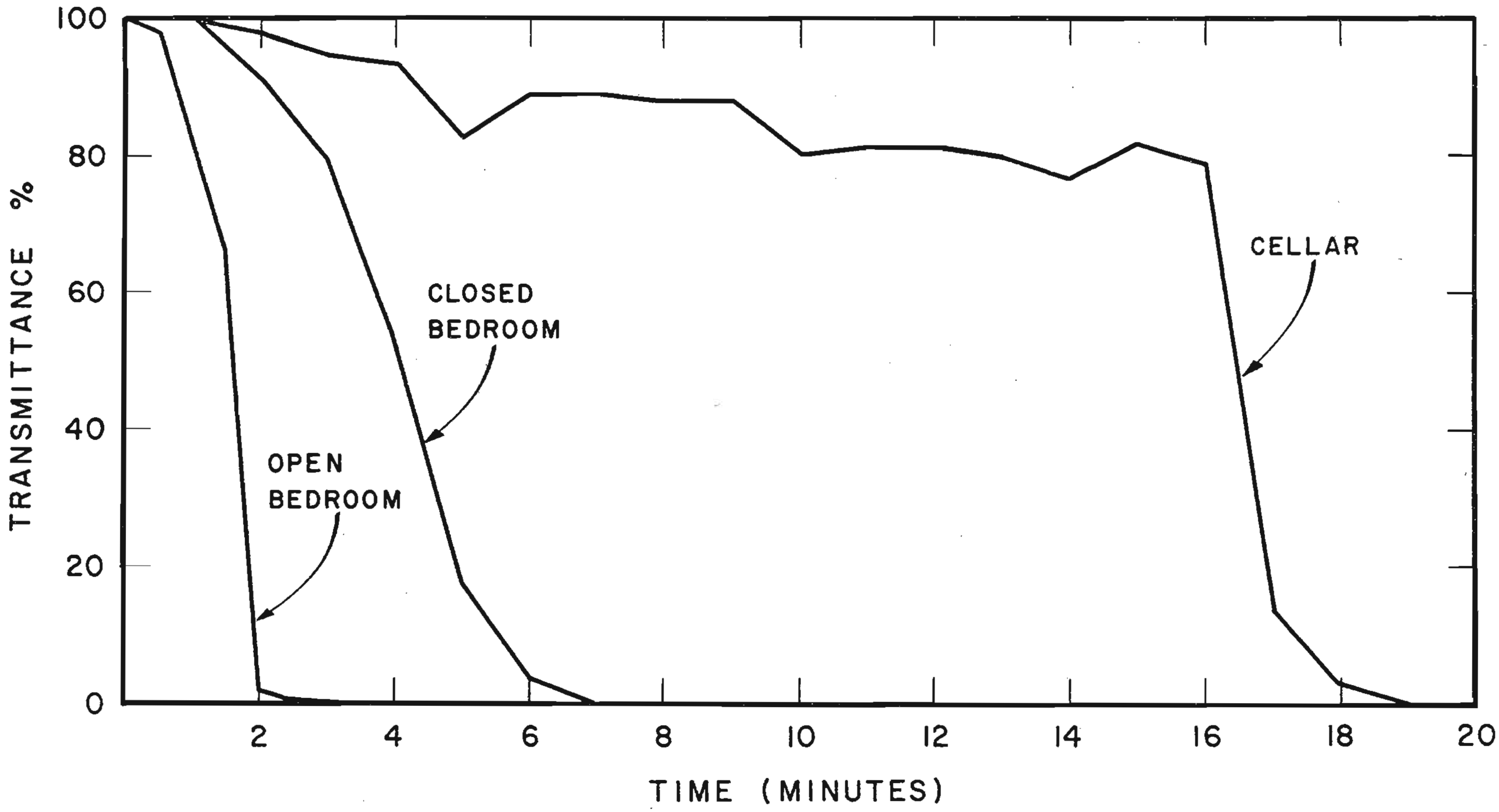

FIGURE 15

LIGHT TRANSMITTANCE IN SMOKE METERS AT BURN 7

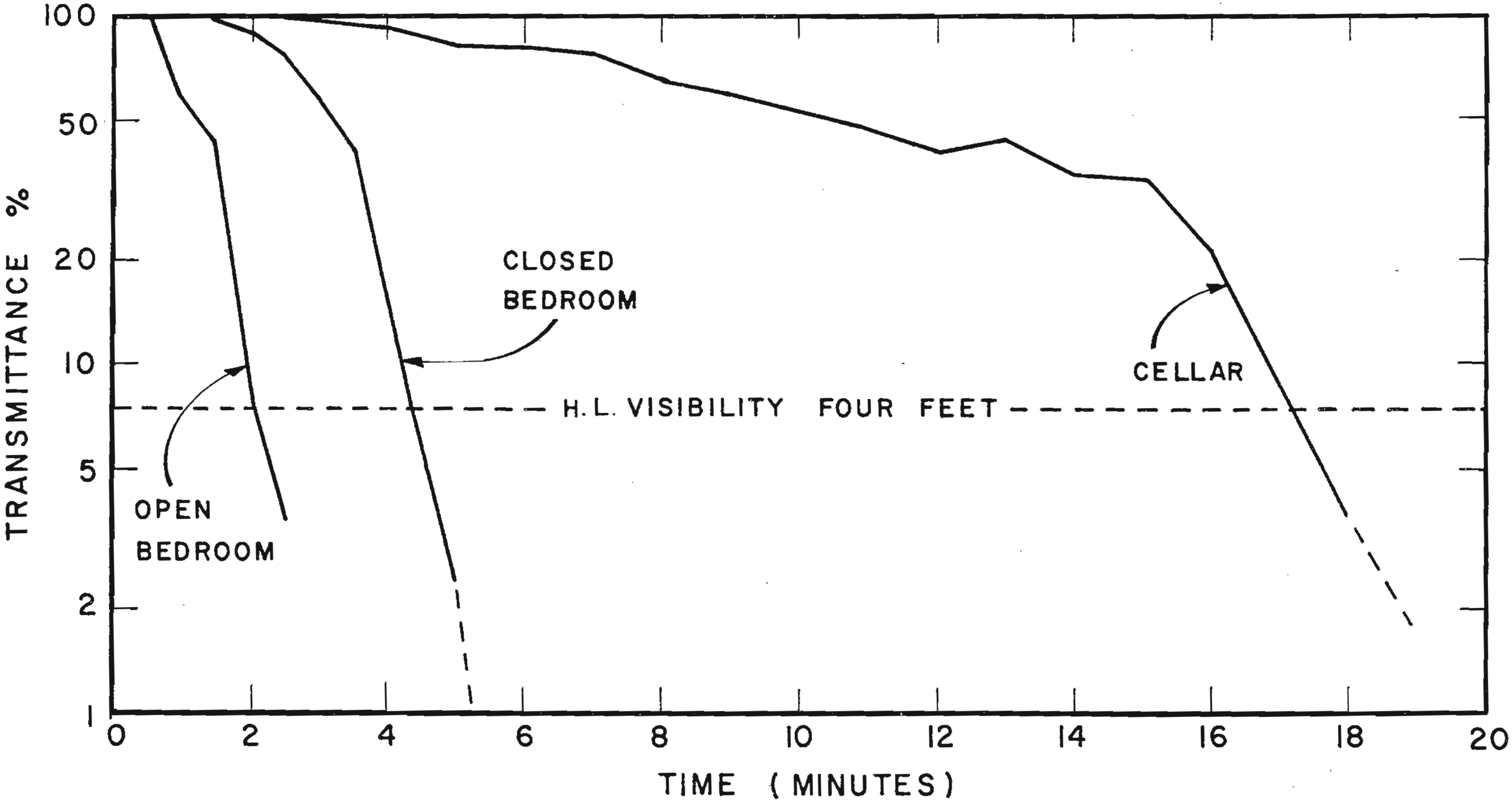

FIGURE 16

MEAN LIGHT TRANSMISSION IN SMOKE METERS IN THREE HOUSES WITH INCOMBUSTIBLE LININGS

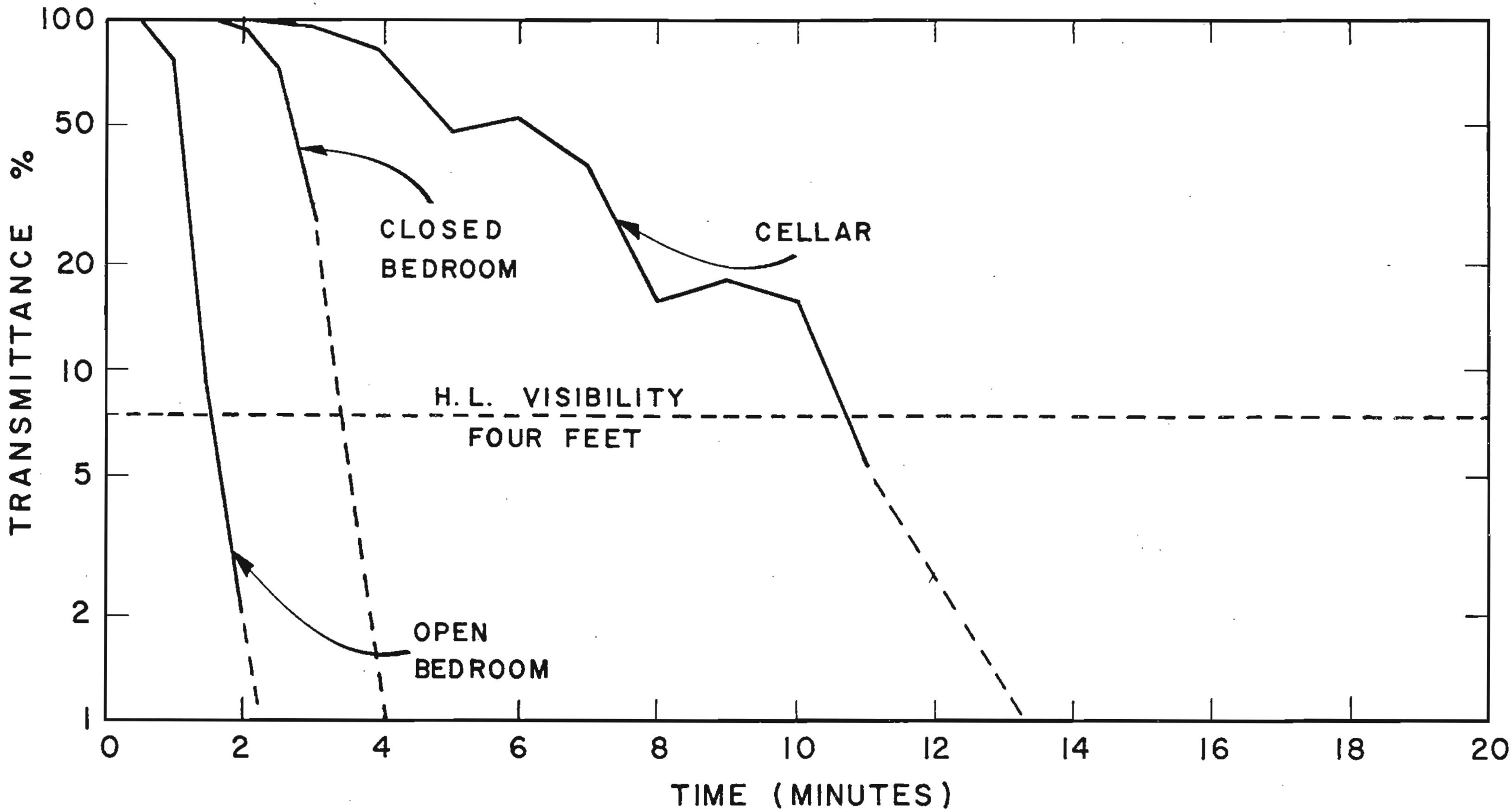

FIGURE 17

MEAN LIGHT TRANSMISSION IN SMOKE METERS IN THREE HOUSES WITH COMBUSTIBLE LININGS

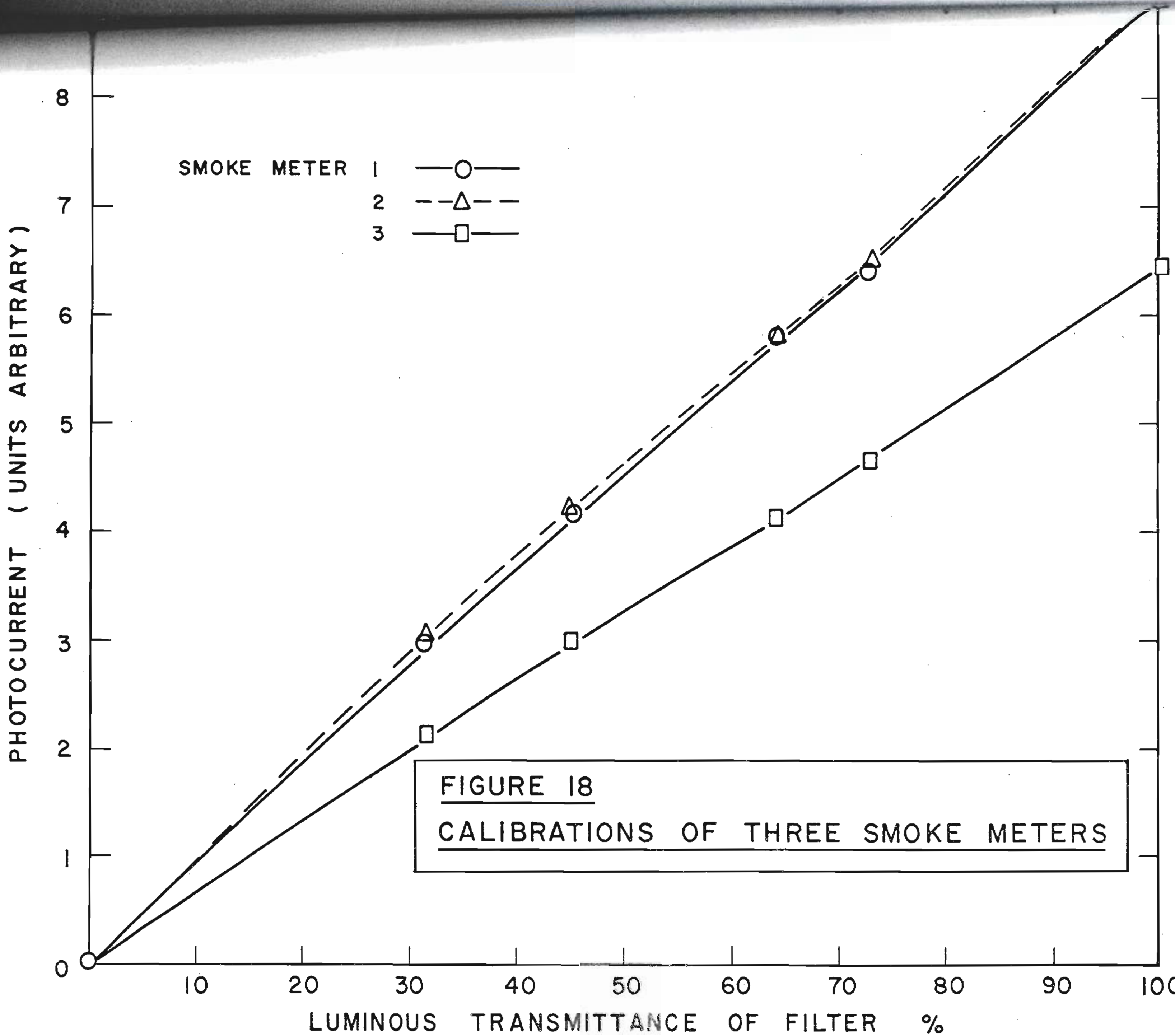

FIGURE 18

CALIBRATIONS OF THREE SMOKE METERS

APPENDIX A

VISIBILITY IN SMOKE

House-burning experiments at Aultsville are described in DBR Internal Reports No. 150 to 158. Smoke measurements in particular are described in Report No. 151, where results are given in terms of percentage transmission of light through a given distance in the smoke, the distance being the smoke path of the smoke meter used.

It was desired to interpret these results in terms of visibility. From Reference 1 it has been inferred that the value adopted as threshold of the smoke-logged condition, i.e. 4-ft visibility, corresponded to a transmittance of 5 per cent through the 2-ft smoke path of the smoke meter. Visibility here means the distance one can see by the reflected light of a fireman's handlamp held by an observer. Naturally this distance is reduced by reflection of light from the smoke, so that the distance at which one can see a lamp by its own light is greater. In this note the expression handlamp visibility will be applied to the quantity as measured by Kingman, and lighted-object visibility will be applied to the distance at which one can see a lamp.

A smoke chamber was constructed of hardboard sheets on a wooden frame, the whole being 4 by 24 by 8 ft high. The access opening was covered with tarpaulin. Five 10-watt frosted lamps were set in the ceiling in staggered positions so that none impeded a view of the others. They were wired for independent remote control. Two of the original smoke meters used at Aultsville were suspended in the chamber and connected in the manner described in the report. Two small desk fans were set up to mix the smoke. A small panel of glass was provided in one end for observation. A green baize curtain hung over this on the outside to exclude light while observations were being made, and a hinged cover on the inside protected the glass from smoke deposition until it was lifted by means of wire.

The experiments were in two series:

A. The observer went into the smoke-filled chamber, held his breath for long enough to take a quick look, and reported the most distant lamp he could see as the smoke gradually thinned out.

B. The observer watched through the glass panel, with the baize over his head, and reported when each lamp first became visible.

Three kinds of smoke were used: two different types of smoke bomb, one producing orange smoke and one white, and smoke from burning fibreboard. The three smokes gave somewhat different results, but the differences were small compared with that between series A and B.

The difference between the two series was easy to understand. In series A the observer's eye was adapted to room daylight and observation was intermittent, so that often a lamp was first seen a minute or two after it first became visible. In series B the observer was under the baize for long enought to have developed adaptation to the dark and he was able to observe continuously. The difference in comfort must also have had an effect, especially in the case of smoke from fibreboard which has an irritant action on the eyes.

The optical transmittance of an absorbing layer, I/I_o, is related to the thickness and properties of the layer in the following manner:

$$I/I_o = e^{-kx} \qquad (1)$$

where I_o = intensity of light incident on an absorbing layer

I = intensity transmitted

k = a constant depending on the density and properties of the absorber

x = thickness of the layer

The output of the photocell in the absence of smoke was adjusted to 4.5 millivolts (9 scale divisions of the recorder) in the manner described in the report. It was closely proportional to light intensity. Thus if

P = scale reading of recorder

then $P/9$ = transmittance of smoke

$$= e^{-kl} \qquad (2)$$

where l = length of smoke path in smoke meter.

If c is the logarithm to the base 10 of the critical transmittance, i.e. of a transmittance such that light from a lamp bulb is at the limit of vision, and V is the distance through which it is just visible, then

$$10^c = e^{-kV} \qquad (3)$$

Eliminating k between equations (2) and (3)

$$c = \frac{V}{l} \log_{10} (P/9) \qquad (4)$$

This equation has been used to derive estimates of critical transmittance from the measurements described above. The results are given in Table A-I.

An estimate that 4-ft (handlamp) visibility corresponds to 5 per cent transmission through a 2-ft smoke path has already been referred to. Putting these values into equation (1) gives $k = 0.125 \text{ in.}^{-1}$. More precise information has since been supplied by private communication, from which handlamp visibility 4 ft corresponds to transmission 0.003 through a smoke path of 50 inches, whence $k = 0.116 \text{ in.}^{-1}$. Putting this value and $c = -6.61$ from the Series B experiments into equation (3) leads to V = 131 inches.

Thus handlamp visibility 4 ft corresponds to lighted-object visibility 11 ft.

CONCLUSIONS

1. The limiting distance at which one can see a lighted object in smoke is such that $10^{-6.6}$ of the incident light is transmitted.

2. Handlamp visibility 4 ft, as defined by Kingman, corresponds to lighted-object visibility 11 ft.

3. The suitability of the value adopted as threshold of the smoke-logged condition, i.e. $k = 0.12 \text{ in.}^{-1}$, is considered to be confirmed.

TABLE A-I

VISIBILITY DISTANCES AND CALCULATED CRITICAL TRANSMITTANCE

	V (inch)	P (division)	C
Series A			
1. Orange smoke	271	3.6	-5.19
	191	2.6	-4.95
	147	1.5	-5.49
	97	0.8	-4.90
Mean			-5.13
2. White smoke	271	3.0	-6.21
	191	2.0	-6.00
	147	1.2	-6.19
Mean			-6.13
3. Smoke from fibreboard	271	2.8	-6.61
	191	2.3	-5.43
	147	1.4	-5.70
Mean			-5.91
	Over-all mean		-5.72
Series B			
1. Orange smoke	105	0.4_8	-6.43
	155	1.2	-6.52
	199	1.9_5	-6.35
	279	2.9	-6.60
Mean			-6.47
2. White smoke	105	0.5	-6.33
	155	1.0_5	-6.95
	199	1.7_5	-6.81
	279	2.6_5	-7.12
Mean			-6.80
3. Smoke from fibreboard	105	$0.6, 0.5_5$	-6.04
	155	$1.2, 1.0_5$	-6.75
	199	1.9, 1.8	-6.57
	279	$2.8_2, 2.7_5$	-6.84
Mean			-6.55
	Over-all mean		-6.61