No. 909

AIR INFILTRATION THROUGH DOUBLE-HUNG WOOD WINDOWS

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This paper is the result of research conducted at the University of Wisconsin in cooperation with the A. S. H. V. E. Research Laboratory.

AIR infiltration through various types of building constructions has been the subject of research carried on at the University of Wisconsin for the past several years in cooperation with the AMERICAN SOCIETY OF HEATING AND VENTILATING ENGINEERS. The previously reported work has been on walls of brick and wood frame constructions.[4] The primary purpose of the investigation reported in the present paper was to aid in the establishment of figures for both plain and weather-stripped windows of the double-hung wood type for use in the calculation of heat losses from buildings. As secondary aims, it was desired to study the variation to be expected from one window to another for various cracks and clearances, for locked and not-locked conditions, and for several representative weatherstrips as applied to plain windows showing both low and high resistance to air leakage.

PROGRAM AND WINDOW USED

For the investigation, fourteen windows having a sash opening of 3 ft 0 in. by 6 ft 0 in. were purchased. The thickness of the sash was 1⅜ in. in all cases, and for convenience in testing, box frames were used. These differed from standard masonry frames in the additional use of box construction at the head and sill and the use of steel corner plates to stiffen the frames for test purposes. Some of these windows are shown in Figs. 1 and 2.

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[4] See Air Infiltration through Various Types of Brick Wall Construction by G. L. Larson, C. Braatz and D. W. Nelson (A. S. H. V. E. TRANSACTIONS, Vol, 35, 1929) and Air Infiltration through Various Types of Wood Frame Construction by G. L. Larson, D. W. Nelson and C. Braatz (A. S. H. V. E. TRANSACTIONS, Vol. 36, 1930).

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escapes into the atmosphere by thin-plate, square-edged orifices. The drop in pressure through the orifice is measured on a Wahlen gage. Access doors are provided in each of the two chambers so as to be able to open, close, lock or seal the window during the progress of a test without disturbing the rubber seal between the two halves of the machine.

Test Procedure

Each time a window was placed in the machine for testing, 4 runs were made. Two runs were made with the window closed but not locked. This was done to obtain a better average value than from one test. Before each of these tests, both sash were raised and lowered several times and the closure made with ordinary effort as it would be in actual building occupancy. Access to the inside of the window was secured through the bolted and gasketed door in the collecting chamber. Since locking places the sash in a definite position, only one run was made at this condition. The air leakage observed at the orifice in the aforementioned runs was the sash perimeter leakage plus a certain amount of leakage through the window frame joints, through the rubber seal joint between the window frame and the machine partition, and leakage occurring through whatever minute cracks existed in the machine partition itself. The latter leakage was kept at a low value by sealing all visible cracks with calking compound and by the application of asphalt paint.

Each time a window was placed in the machine for test, a fourth run was made in which the entire sash perimeter was sealed on the outside of the window to prevent all leakage of air at the joints between the sash and the frame at the head, sides or jambs, meeting rail and sill. The leakage obtained in this run was the leakage entering the window at the frame joints, and at the rubber seal, and that passing through the partition itself. This leakage was subtracted from the total leakage in the locked and not-locked runs to secure the net leakage occurring through the sash perimeter. The leakage in this sealed run is the leakage of the test set-up obtaining when a perfect weatherstrip is applied, hence the name of 100 per cent weatherstrip is applied to this run. In all of the tables and curves of this paper, this sealed run leakage has been subtracted except in the runs shown in Fig. 4 which illustrates methods of sealing. It should be noted that only a part of this sealed run leakage is window frame leakage and that there are no values for frame leakage obtainable from a study of the 14 frames built for the testing of sash perimeter leakage. Later in this paper, frame leakage is discussed as determined on frames built into wood frame and masonry wall sections.

One Hundred Per Cent Weatherstrip

The purpose of a window is to admit light, to allow the entrance of air when it is wanted, and at other times to prevent all air leakage or infiltration. When the joints between the sash and the frame permit no entrance of air, the cash perimeter is perfect in so far as infiltration is concerned. This condition is secured by the sealing of the sash perimeter on the outside of the window.

To approach this condition in actual building construction, weatherstripping is generally applied. There are two major factors in weatherstripping that influence the effectiveness of the installation. One of these is the ability of

the strip to stop all air that reaches it and the other is the placing of the strip with respect to the sash perimeter joint so that it is in a position to stop all leakage entering this joint. Fig. 3 at *c* and *d* shows the two extreme positions for the placing of the strip. When placed as at *c* on the upper sash, it is possible for air that enters the sash perimeter joint to enter the upper sash pulley holes. When once in the weight spaces, access to the room is gained through the lower sash pulley holes and through cracks in the frame such as at the sash weight doors or around the window trim. Were the strip and its

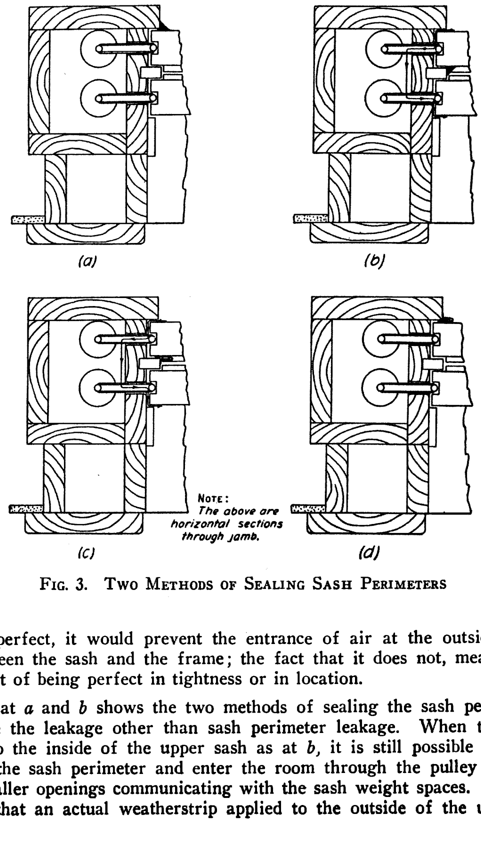

Fig. 3. Two Methods of Sealing Sash Perimeters

location perfect, it would prevent the entrance of air at the outside contact line between the sash and the frame; the fact that it does not, means that it falls short of being perfect in tightness or in location.

Fig. 3 at *a* and *b* shows the two methods of sealing the sash perimeter to determine the leakage other than sash perimeter leakage. When the seal is applied to the inside of the upper sash as at *b*, it is still possible for air to enter at the sash perimeter and enter the room through the pulley holes and other smaller openings communicating with the sash weight spaces. It is conceivable that an actual weatherstrip applied to the outside of the upper sash

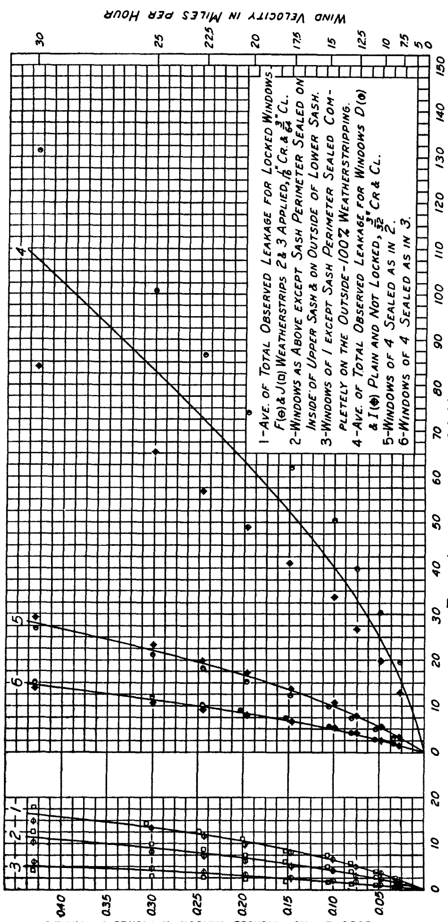

FIG. 4. COMPARISON OF RESULTS FOR TWO METHODS OF SEALING SASH PERIMETERS

as at *d* would stop more leakage than the perfect seal placed on the inner side where it could not prevent air reaching the pulley holes. The actual weatherstrip would then be more perfect than the seal set up as 100 per cent perfect. This obviously indicates a mis-location of the seal and points to the propriety of placing the seal on the outside of the upper sash as well as on the outside of the lower sash.

Fig. 4 shows a comparison of results using the two methods of sealing two plain windows having a high leakage and two weatherstripped windows having a low leakage. The difference between curves *1* and *2* is the leakage obtained for the weatherstripped window perimeter if the seal on the inner side of the upper sash represented 100 per cent weatherstripping. Likewise, the difference between curves *4* and *5* is the leakage through the sash perimeter for the plain window under the same conditions. The differences between curves *2* and *3*

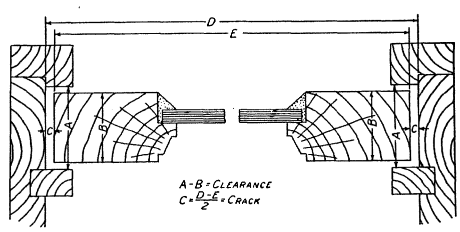

FIG. 5. DIAGRAM ILLUSTRATING CRACK AND CLEARANCE

and between *5* and *6* represent the leakages that originated in the sash perimeter and found a way into the room through the pulley holes and other smaller openings. This properly should be charged against the sash perimeter whether plain or stripped. It is included as sash perimeter leakage when the seal is made on the outside of both sash. This method of sealing was used in all tests reported in this paper except in the case of two illustrated in Fig. 4 to show the difference in the two methods. In comparing window tests, it is important to know which method of sealing was used. Fig. 4 shows that the leakage charged against the weatherstrip is only about one-half of that entering the sash perimeter if the seal is applied to the inside of the upper sash in the case of the two weatherstripped windows represented in this figure.

SETTING OF CRACK AND CLEARANCE

The 5 windows of a poor grade *D*, *H*, *I*, *M*, and *N* fitted loosely when received and were fitted to a uniform 3/32 in. crack and clearance before testing. Fig. 5 illustrates crack and clearance. It is important to note that the crack is one-half of the difference of the horizontal width between runways and the horizontal width of the sash. In the judgment of all who tried them, including a building carpenter boss and a construction inspector, these 5 windows were considerably looser than the average window in buildings. In the opinion of several weatherstripping mechanics, they were as loose as the usual loosely-fitted window they were called upon to weatherstrip in old build-

TABLE 2. FIELD MEASUREMENTS OF CRACK AND CLEARANCE IN INCHES

LOCALITY	NUMBER OF WINDOWS	AVERAGE FOR UPPER SASH		AVERAGE FOR LOWER SASH		MEETING RAIL	TYPE AND NUMBER OF BUILDINGS
		CRACK	CLEARANCE	CRACK	CLEARANCE		
MINNEAPOLIS, MINN.	91	0.0362	0.0465	0.0531	0.0520	0.0757	3 UNIV. - 2 RES.- 1 APT.
HARTLAND, WIS.	42	0.0395	0.0290	0.0603	0.0372	0.0471	5 RESIDENCES.
OCONOMOWOC, WIS.	16	0.0615	0.0415	0.0894	0.0264	0.0283	1 OFFICE
MILWAUKEE, WIS.	32	0.0220	0.0340	0.0720	0.0394	—	2 RESIDENCES
MILWAUKEE, WIS.	80	0.0984	0.0531	0.0765	0.0484	—	1 HIGH SCHOOL GROUP
MADISON, WIS.	16	0.0550	0.0527	0.0840	0.0733	—	1 UNIVERSITY
MADISON, WIS.	96	0.0373	0.0339	0.0659	0.0635	0.0804	6 UNIVERSITY
MADISON, WIS.	64	0.0373	0.0594	0.0694	0.0655	0.0847	1 UNIV.-3 FRATERNITY
WATERFORD, WIS.	46	0.0615	0.0508	0.0544	0.0382	0.0577	3 RESIDENCES
MADISON, WIS.	64	0.0553	0.0510	0.0776	0.0905	0.0992	4 UNIVERSITY
MADISON, WIS.	32	0.0385	0.0437	0.0553	0.0609	0.0515	2 FRATERNITY
WEIGTED AVERAGE	TOTAL 579	0.0500	0.0455	0.0666	0.0567	0.0734	
EQUIVALENT IN FRACTIONS		3/64+	3/64 -	1/16+	1/16 -	5/64-	
CR.& CL. USED ON 9 WINDOWS		1/16	3/64	1/16	3/64	—	

ings, although at times they encountered some that fitted more loosely. All sash would rattle badly except a few with sash members warped to such an extent as to prevent rattling. These 5 poor windows were tested as plain windows when the crack and clearance were first set at 3/32 in. and again 6 months later without any alteration to the fit except that which occurred in standing. They were then weatherstripped according to the schedule in Table 1 and again tested.

The 9 windows, *A, B, C, E, F, G, J, K,* and *L,* of a good grade were received fitted as closely as possible for free movement of the sash in opening and closing the window. They were tested after a standing period of 3 months. The crack was found to be approximately 1/64 in. and the clearance 1/32 in. By the definitions of crack and clearance, this means the windows had a tolerance of 1/32 in. in the two directions of sash fit; the difference of the distance between the runways and the width of the sash was 1/32 in. and between the width of the runway and the thickness of the sash was 1/32 in. In the judgment of those trying the windows, they were considered tighter than would be permissible in actual building construction, although under the conditions in the laboratory, they worked easily and smoothly. When they were retested after a standing period of 6 months from the date of the original tests, it was found that the crack and clearance had increased considerably. The measured crack and clearance were found to average slightly less than 1/16 in. and slightly more than 3/32 in. respectively. They were tested under this condition before a manual change in crack and clearance was made. During the entire 6 months, the windows were sheltered in the laboratory and were carefully handled in the few feet of moving to and from the machine and storage space. The original tests were made in a long dry period of the late summer, and the final tests were made under late winter and early spring heating conditions. After the original tests were completed and before the beginning of the heating season there was a rainy period when the humidity was considerably higher. The increase in crack and clearance during the 6 months' period was observed to be largely an opening up of joints in the frame, which increased the frame leakage and also allowed leakage that started at the outside of the sash perimeter to enter into the weight spaces. Some of this opening of frame joints was considered to be due to the warping of frame members and some to the effect on the frame members of the warping of the closely fitted sash members.

The 5 loosely fitted windows of a poor grade (*D, H, I, M,* and *N*) showed very little increase in crack and clearance and only a slight increase in leakage during the 6 months' standing period. This was considered to be due to the sash and frame members having sufficient room to warp without opening up joints and to the longer aging period of 1 yr instead of 3 months between the time of entering the laboratory to the time of testing. Before the final cracks and clearances were set for the final plain and the weatherstripped tests, the frame joints were closed by using larger nails with heads to supplement the finishing nails originally used.

Since in the judgment of those who tried the windows the 3/32 in. crack and clearance of the five windows of a poor grade were more than the average for old building construction, it was decided to actually measure the fit of a large number of windows. A total of 579 plain double hung wood windows was measured on buildings at least 5 yr old by about a dozen observers within

Table 3. Results of Tests on Five Windows with 3/32 in. Crack and Clearance, Plain and Weatherstripped, in Cubic Feet per Hour, per Foot of Sash Perimeter

	Window	Crack	Clearance	Sash Pulls (Pounds) Upper		Lower		Average for 1st and 2nd Closures — Wind Velocity-Miles per Hour										Locked — Wind Velocity-Miles per Hour									
				Up	Dn.	Up	Dn.	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	30.0	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	30.0
Sept. Tests	D	3/32	3/32	5	2	5	0	36.6	65.5	98.7	131.1	164.7	198.6	231.2	262.0	294.3	357.7	13.4	30.0	51.7	76.6	102.8	131.8	161.8	192.3	223.2	271.0
	H	3/32	3/32	2	5	5	0	29.3	52.6	77.8	102.8	127.5	152.2	176.1	199.2	222.7	268.2	19.4	33.7	48.9	64.9	79.4	92.8	104.6	116.0	127.2	148.9
	I	3/32	3/32	6	3	7	2	28.0	48.0	67.7	87.2	106.7	126.6	146.5	165.8	186.1	228.2	18.0	32.9	47.4	62.3	76.8	91.7	106.5	120.8	136.0	166.6
	M	3/32	3/32	5	2	4	2	23.0	43.3	64.6	86.8	109.7	131.5	153.2	175.4	198.6	246.8	11.1	23.1	37.4	53.7	71.2	89.4	108.3	128.0	148.5	190.4
	N	3/32	3/32	6	1	5	1	24.7	42.6	61.8	80.6	99.0	117.6	135.7	104.7	174.8	218.2	10.0	20.9	34.9	50.3	66.5	84.6	102.0	118.9	136.0	170.0
	Ave. H & I	3/32	3/32	4	4	6	1	28.7	50.3	72.8	95.0	117.1	139.4	161.3	182.5	204.4	248.2	18.7	33.3	48.2	63.6	78.1	92.3	105.6	118.4	131.6	157.8
	Ave. M & N	3/32	3/32	5	1	4	1	23.9	43.0	63.2	83.7	104.4	124.5	145.0	165.0	186.7	232.5	10.6	22.0	36.2	52.0	68.9	87.0	105.2	123.5	142.3	180.2
	Ave. D,H,I,M,N	3/32	3/32	5	3	5	1	28.3	50.4	74.0	97.7	121.5	145.3	168.5	191.4	215.3	263.8	14.4	28.1	44.1	61.4	79.3	98.1	116.6	135.2	154.2	189.4
6 Mo. Later	D	3/32	7/64	5	2	6	0	44.0	74.3	107.8	137.2	168.8	203.7	235.8	268.3	302.8	375.2	28.0	52.3	80.3	103.4	129.4	157.5	187.2	219.0	254.3	332.0
	H	3/32	3/32	4	3	6	0	35.6	62.0	88.2	113.9	139.4	164.4	190.4	213.5	244.0	304.4	16.6	33.2	52.6	68.6	86.0	103.7	122.3	141.2	161.2	205.0
	I	3/32	3/32	8	10	10	2	23.3	42.4	62.2	82.0	102.0	122.8	144.3	166.6	189.4	240.5	17.4	32.0	49.2	65.4	81.7	98.8	116.8	135.4	155.7	200.9
	M	3/32	3/32	5	2	4	2	21.4	42.9	64.9	87.1	108.3	129.7	149.7	170.0	191.2	235.5	15.7	32.6	50.8	70.3	89.2	107.4	124.2	140.6	157.1	191.1
	N	3/32	3/32	4	4	5	1	30.3	49.4	68.9	86.9	104.3	121.2	138.0	156.0	174.3	214.7	16.3	33.2	52.6	72.0	91.7	111.2	129.8	148.3	166.9	210.8
	Ave. H & I	3/32	3/32	6	6	8	1	29.5	52.2	75.2	98.0	120.7	143.6	167.4	189.9	216.7	272.5	17.0	32.6	50.9	67.0	83.9	101.3	119.6	138.3	158.5	203.0
	Ave. M & N	3/32	3/32	4	3	4	1	25.9	46.2	66.9	87.0	106.3	125.5	143.9	163.0	182.6	225.2	16.0	32.9	51.7	71.2	90.5	109.3	127.0	144.5	162.0	201.0
	Ave. D,H,I,M,N	3/32	3/32	5	4	6	1	30.9	54.2	78.5	101.4	124.5	148.3	171.6	194.9	220.3	274.1	18.8	36.7	57.1	75.9	95.6	115.7	136.1	156.9	179.0	228.0
Weatherstripped	D			14	11	11	6	5.4	11.4	19.2	27.9	37.0	46.7	56.2	66.0	75.7	96.6	5.1	11.1	18.9	27.4	36.6	46.0	55.2	64.8	74.0	93.4
	H			12	9	14	6	5.7	12.7	18.0	25.0	30.6	37.7	45.2	53.6	63.1	83.4	5.7	12.7	18.0	25.0	30.6	37.7	45.2	53.6	63.1	83.4
	I			30	24	14	14	4.0	8.6	14.3	20.9	27.1	34.6	41.7	48.9	56.3	71.4	4.0	8.6	14.3	20.9	27.1	34.6	41.7	48.9	56.3	71.4
	M	As	Above	24	24	18	15	4.3	8.9	14.0	19.5	24.7	30.4	36.1	42.2	48.3	62.0	4.0	8.3	13.4	18.6	24.0	29.4	34.9	40.9	46.9	60.6
	N			19	20	15	8	4.0	8.6	14.0	20.0	25.9	32.2	38.9	46.1	53.6	69.5	3.7	8.3	13.4	19.2	25.2	31.2	37.4	44.0	51.4	66.0
	Ave. H & I			21	16	14	10	4.9	10.7	16.2	23.0	28.9	36.2	43.5	51.3	59.7	77.4	4.9	10.7	16.2	23.0	28.9	36.2	43.5	51.3	59.7	77.4
	Ave. M & N			22	22	17	11	4.2	8.7	14.0	19.7	25.3	31.3	37.5	44.1	51.0	65.5	3.9	8.3	13.4	18.9	24.6	30.3	36.2	42.5	49.2	63.3
	Ave. D,H,I,M,N			20	17	15	10	4.7	10.0	15.9	22.7	29.1	36.3	43.6	51.4	59.4	76.5	4.5	9.8	15.6	22.2	28.7	35.8	42.9	50.5	58.4	75.0

a 300-mile radius of Madison. On an average, 16 were taken on each building, 4 on each side. The readings were taken in December and January and therefore should represent cracks and clearances existing in the heating season. Eight of the men were assistants in the infiltration testing work and received personal instruction, and every observer received a complete and carefully worded description of the requirements and the method to be followed so that all values would be comparable. A blue-print defining crack and clearance, as does Fig. 5, accompanied the instructions as did mimeographed blanks to be used for the recording of data. Each observer was given a set of thickness gages for determining the clearance. The instructions emphasized the need for watching the warping of sash in measuring clearance and that the lack of clearance at the end of the meeting rails against the parting stops must be compensated for to obtain the full value of the crack. Particular emphasis was placed on the fact that the crack exists on both sides of the sash at the same time as shown in Fig. 5. The average values obtained were 1/16 in. crack and 3/64 in. clearance. The values obtained were slightly less than this for the upper sash and slightly greater for the lower sash. Table 2 shows a summary of the cracks and clearances obtained. The crack and clearance on the series of nine windows were accordingly adjusted to these values of 1/16 in. and 3/64 in. before the final plain and weatherstripped tests were made.

Weatherstripping

After the crack and clearance had been set to the final values and the leakage of the plain windows determined, the windows were weatherstripped by local mechanics representing the weatherstrips they installed. The 3 mechanics for the 3 strips were men that had been at such work for many years and had had at least several years' experience with the strip they installed. Two interlocking and one rib type of strip were represented. The mechanics were instructed to install the strips just as they would in actual building construction and it is believed that they did this. The average time to install one strip was 1½ hr and the deviation from this was little. It was not necessary to increase the crack or clearance at the sides of the sash except in a few cases in order to square up the sash.

Presentation of Results

The results of the tests on the 14 windows are shown in Tables 3 and 4 and in curve form in Figs. 6 to 13 inclusive. Table 1 explains the system of designating the windows and weatherstrips in the tables and on the curves. The tables in addition to giving the leakages at pressures corresponding to wind velocities up to 30 mph also give the pull in pounds necessary to open and close each sash in every test. These pulls give some indication of how tight a plain window has been fitted and the increase in sash pulls upon weatherstripping gives an indication of how closely a strip has been fitted. In some cases, a strip might be made very effective but at an undue loss of ease in opening and closing.

The tables present the values for individual windows and also averages for all of the windows of the two series termed as of good grade and poor grade to which each type of weatherstrip was applied and also the average of the entire groups of 5 and 9 of the two series. Although two not-locked runs,

TABLE 4. RESULTS OF TESTS ON NINE WINDOWS WITH 1/64 IN. CRACK AND 1/32 IN. CLEARANCE AND WITH 1/16 IN. CRACK AND 3/64 IN. CLEARANCE, PLAIN AND WEATHERSTRIPPED, IN CUBIC FEET PER HOUR, PER FOOT OF SASH PERIMETER

	WINDOW	CRACK	CLEARANCE	SASH PULLS (POUNDS) UPPER		LOWER		AVERAGE FOR 1ST AND 2ND CLOSURES — WIND VELOCITY - MILES PER HOUR										LOCKED — WIND VELOCITY - MILES PER HOUR									
				UP	DN.	UP	DN.	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	30.0	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	30.0
SEPT. TESTS - ORIG. FIT.	A	1/64	1/32	8	9	7	6	2.8	5.8	9.4	13.4	17.8	22.3	26.9	31.6	36.5	46.2	2.6	5.4	8.9	12.9	17.2	21.6	26.0	30.6	35.3	45.2
	B	1/32-	1/32+	7	8	2	3	2.0	4.6	8.0	11.9	16.0	23.6	25.7	31.1	36.9	49.4	2.2	5.2	8.9	13.2	17.9	23.0	28.5	34.3	40.5	53.5
	C	1/64	1/32+	15	11	7	8	2.1	4.5	7.7	11.3	15.4	19.8	24.4	28.6	33.6	43.3	1.9	4.3	7.4	11.0	15.1	19.5	24.0	28.6	33.2	42.8
	E	1/64+	1/32	5	3	3	4	3.3	6.8	10.8	15.5	20.4	25.8	31.5	37.6	44.0	56.9	3.3	6.8	10.8	15.5	20.4	25.8	31.4	37.3	43.5	56.2
	F	1/64	1/32	7	6	5	2	4.2	8.9	14.4	20.5	27.1	34.3	42.2	50.4	59.2	73.3	4.4	9.2	14.8	21.0	27.7	34.9	42.0	48.8	55.8	67.3
	G	1/64	1/32	16	20	4	6	1.6	3.6	6.2	9.2	12.7	16.6	20.5	24.8	29.3	38.7	1.0	2.6	4.6	7.1	9.7	12.9	16.3	20.0	23.8	32.0
	J	1/64-	1/32	24	24	11	10	2.0	4.5	7.7	11.5	15.5	19.9	24.4	29.1	34.0	44.0	1.7	3.9	6.8	10.3	14.1	18.2	22.5	26.9	31.5	41.1
	K	1/64-	1/32	5	7	8	8	4.2	8.4	13.1	18.3	23.8	29.4	35.1	40.9	47.0	60.1	4.2	8.4	13.1	18.3	23.8	29.4	35.1	40.9	47.0	60.1
	L	1/64	1/32	14	15	36	34	3.1	6.3	10.2	14.7	19.5	24.6	28.8	35.2	40.8	53.1	3.3	6.6	10.6	15.2	20.2	25.3	30.6	36.1	41.8	54.3
	AVE. A,B,C	1/64+	1/32+	10	9	5	6	2.3	5.0	8.4	12.2	16.4	21.9	25.7	30.4	35.7	46.3	2.2	5.0	8.4	12.3	16.7	21.4	26.2	31.2	36.3	47.2
	AVE. E,F,G	1/64+	1/32-	9	10	4	4	3.0	6.4	10.5	15.1	20.1	25.6	31.4	37.6	44.2	56.3	2.9	6.3	10.1	14.5	19.4	24.5	29.9	35.3	41.0	51.8
	AVE. J,K,L	1/64-	1/32	14	15	19	17	3.1	6.4	10.3	14.8	19.6	24.6	29.8	35.1	40.6	52.4	3.1	6.3	10.2	14.6	19.4	24.3	29.4	34.6	40.1	51.8
	AVE. C,G,L	1/64	1/32+	15	15	16	16	2.2	4.8	8.0	11.7	15.9	20.3	24.9	29.5	34.5	45.0	2.1	4.5	7.5	11.1	15.0	19.2	23.6	28.2	32.9	43.0
	AVE. A,B,C,E,F,G,J,K,L	1/64	1/32	11	11	9	9	2.8	5.8	9.6	14.0	18.7	24.0	29.0	34.4	40.2	51.7	2.7	5.9	9.6	13.8	18.5	23.4	28.5	33.7	39.1	50.2
6 Mo. LATER	C	1/32	3/64	22	20	12	10	4.6	9.8	15.4	21.4	27.4	34.0	42.0	49.7	58.0	76.3	3.4	7.6	12.9	18.0	24.6	30.6	38.6	46.3	54.0	72.3
	G	1/16	1/16	4	4	4	6	3.7	7.9	13.8	21.0	28.9	36.2	45.7	55.2	65.0	85.9	2.3	6.0	10.9	17.2	23.7	30.3	38.9	47.5	56.6	75.7
	L	5/64	3/64	7	7	16	16	5.0	11.3	18.5	26.0	33.0	40.9	49.5	57.8	66.6	85.6	5.1	11.7	18.9	26.6	33.7	41.4	50.0	58.3	67.2	86.6
	AVE. C,G,L	1/16-	3/64+	11	10	11	11	4.4	9.6	15.9	22.8	29.8	37.0	45.7	54.2	63.2	82.6	3.6	8.4	14.2	20.6	27.3	34.1	42.5	50.7	59.3	78.2
FINAL FIT	A	1/16	3/64	5	6	2	4	6.9	14.6	23.4	33.2	43.2	53.7	63.7	73.7	84.0	104.3	8.0	16.3	25.1	35.4	45.4	56.0	66.3	76.6	86.6	106.6
	B	1/16	3/64	4	5	2	4	5.0	10.3	16.8	23.5	31.1	38.2	47.6	56.3	65.6	87.2	5.0	10.6	17.2	23.7	31.5	38.9	48.3	57.2	66.6	87.4
	C	1/16	3/64	16	16	8	10	6.6	13.2	20.5	27.9	35.6	43.6	52.1	60.5	69.3	88.2	6.3	12.3	19.3	26.4	34.0	41.9	50.2	58.3	67.1	85.7
	E	1/16	3/64	4	2	3	3	5.1	11.9	19.6	28.5	38.0	47.3	57.2	67.1	77.3	99.6	5.6	12.3	20.3	30.0	40.6	51.5	62.3	73.1	84.9	108.9
	F	1/16	3/64	6	4	6	5	7.4	14.9	24.0	33.7	44.0	53.4	65.2	75.7	86.6	108.3	8.6	16.9	26.6	36.6	46.9	56.3	68.0	78.3	88.6	109.1
	G	1/16	3/64	4	5	2	3	3.7	7.7	12.7	18.5	24.7	31.4	38.4	45.4	53.0	69.2	3.2	7.4	11.8	17.0	22.7	28.8	35.2	42.0	49.2	64.6
	J	1/16	3/64	10	12	8	10	6.2	12.5	20.5	29.1	38.6	48.8	58.5	69.0	79.6	101.6	4.0	8.3	14.7	21.2	29.2	37.7	46.3	55.4	65.2	86.0
	K	1/16	3/64	4	5	3	6	4.6	9.2	16.3	24.0	32.1	39.5	48.9	57.7	66.3	84.5	4.3	8.9	16.0	23.4	31.5	38.6	47.7	56.0	64.0	81.2
	L	1/16	3/64	8	8	28	28	4.6	11.0	18.3	25.6	33.2	40.9	48.6	56.9	65.4	84.0	4.6	11.0	18.3	25.6	33.2	40.9	48.6	56.9	65.4	84.0
	AVE. A,B,C	1/16	3/64	8	9	4	6	6.2	12.7	20.2	28.2	36.6	45.2	54.5	63.5	73.0	92.9	6.4	13.1	20.5	28.5	37.0	45.6	54.9	64.0	73.4	93.2
	" E,F,G	1/16	3/64	5	4	4	4	5.4	11.5	18.8	26.9	35.6	44.0	53.6	62.7	72.3	92.4	5.8	12.2	19.6	27.9	36.7	45.5	55.2	64.5	74.2	94.2
	" J,K,L	1/16	3/64	7	8	13	15	5.1	10.9	18.4	26.2	34.6	43.1	52.0	61.2	70.4	90.0	4.3	9.4	16.3	23.4	31.3	39.1	47.5	56.1	64.9	83.7
	AVE. A,B,C,E,F,G,J,K,L	1/16	3/64	7	7	7	8	5.6	11.7	19.1	27.1	35.6	44.1	53.4	62.5	71.9	91.8	5.5	11.6	18.8	26.6	35.0	43.4	52.5	61.5	70.8	90.4

TABLE 4 (Concluded)

	WINDOW	CRACK	CLEARANCE	UPPER UP	UPPER DN.	LOWER UP	LOWER DN.	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	30.0	LOCKED 5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	30.0
WEATHERSTRIPPED	A	1/16	3/64	33	32	10	10	2.2	3.9	6.4	9.1	12.0	14.9	18.0	21.3	25.0	32.7	1.6	3.4	5.5	7.9	10.2	12.7	15.5	18.3	21.4	28.1
	B	1/16	3/64	16	18	16	15	1.8	3.8	6.4	9.3	12.4	15.7	19.1	22.7	26.5	34.5	1.5	3.2	5.5	8.0	10.6	13.6	16.5	19.5	22.7	29.4
	C	1/16	3/64	22	22	13	12	2.1	4.4	7.2	10.3	13.8	17.2	20.7	24.1	27.8	35.5	1.7	3.5	5.7	8.4	11.3	14.2	17.2	20.2	23.5	30.4
	E	1/16	3/64	14	14	9	7	3.4	6.9	10.5	14.9	19.2	23.6	28.2	32.5	37.4	47.9	3.1	6.3	9.9	14.0	18.3	22.7	27.1	31.3	35.9	45.4
	F	1/16	3/64	18	16	12	9	4.1	8.3	13.0	17.7	22.5	27.4	32.8	37.9	43.8	56.8	3.6	7.6	12.1	17.2	21.7	26.0	30.7	35.4	40.6	51.6
	G	1/16	3/64	16	16	9	12	3.0	6.3	10.1	14.0	18.3	22.3	26.6	31.2	35.5	45.6	3.6	7.1	11.1	15.2	19.7	24.0	28.3	32.9	37.2	47.7
	J	1/16	3/64	22	24	16	15	2.8	5.7	8.7	12.7	16.6	18.9	24.2	28.3	32.4	40.7	2.6	5.4	8.3	12.3	16.0	19.2	23.4	27.4	31.4	39.7
	K	1/16	3/64	18	20	11	10	2.7	5.3	8.5	11.7	15.1	18.0	21.8	25.5	29.4	38.4	2.4	4.7	8.2	11.5	14.7	17.8	21.6	25.4	29.5	38.9
	L	1/16	3/64	17	15	22	20	1.9	4.0	6.7	10.3	13.9	17.9	22.0	26.0	30.5	35.2	1.7	3.4	6.0	9.1	12.6	16.3	20.0	23.7	28.3	37.4
	AVE. A,B,C	1/16	3/64	24	24	13	13	2.0	4.0	6.6	9.6	12.7	15.9	19.3	22.7	26.4	34.2	1.6	3.4	5.6	8.1	10.7	13.5	16.4	19.3	22.5	29.3
	" E,F,G	1/16	3/64	16	15	10	9	3.5	7.2	11.2	15.5	20.0	24.4	29.1	33.9	38.9	50.1	3.4	7.0	11.0	15.5	19.9	24.2	28.7	33.2	37.9	48.2
	" J,K,L	1/16	3/64	19	20	16	15	2.5	5.0	8.0	11.6	15.2	18.6	22.7	26.6	30.8	39.8	2.2	4.5	7.5	11.0	14.4	17.8	21.7	25.5	29.7	38.7
	AVE. A,B,C,E,F,G,J,K,L	1/16	3/64	20	20	13	12	2.7	5.4	8.6	12.2	16.0	19.6	23.7	27.7	32.0	41.4	2.4	5.0	8.1	11.5	15.0	18.5	22.3	26.0	30.1	38.7

TABLE 5. FRAME LEAKAGE IN FRAME AND MASONRY WALLS IN CUBIC FEET PER HOUR PER FOOT OF SASH PERIMETER

PRESSURE DROP ACROSS WINDOW IN INCHES OF WATER	WIND VELOCITY MI/HR.	WOOD FRAME WALLS — NARROW PLASTER GROUND WALL "A"	WALL "B"	WIDE PLASTER GROUND WALL "A"	WALL "B"	AVE. OF FOUR TESTS	MASONRY WALLS — NOT CALKED WALL "A"	WALL "B"	AVE.	CALKED WALL "A"	WALL "B"	AVE.
0.012	5.0	3.2	2.6	2.5	2.3	2.7	6.2	1.9	4.1	0.8	0.4	0.6
0.027	7.5	5.9	5.0	4.5	4.5	5.0	10.2	3.8	7.0	1.5	0.9	1.2
0.048	10.0	9.0	8.0	6.6	7.0	7.7	14.3	6.3	10.3	2.3	1.5	1.9
0.075	12.5	12.3	11.0	8.8	9.7	10.5	18.4	9.2	13.8	2.9	2.2	2.6
0.108	15.0	16.0	14.4	11.0	12.7	13.5	22.7	12.3	17.5	3.6	2.9	3.3
0.147	17.5	20.3	18.2	13.7	16.0	17.1	27.0	15.6	21.3	4.3	3.7	4.0
0.192	20.0	24.9	22.2	16.3	19.5	20.7	31.5	19.1	25.3	5.0	4.4	4.7
0.243	22.5	29.7	26.3	19.1	23.1	24.6	36.3	22.7	29.5	5.7	5.0	5.4
0.300	25.0	34.9	30.8	22.2	27.0	28.7	41.6	26.3	34.0	6.4	5.6	6.0
0.431	30.0	46.4	40.5	28.9	35.5	37.8	53.1	33.5	43.3	8.0	6.4	7.2

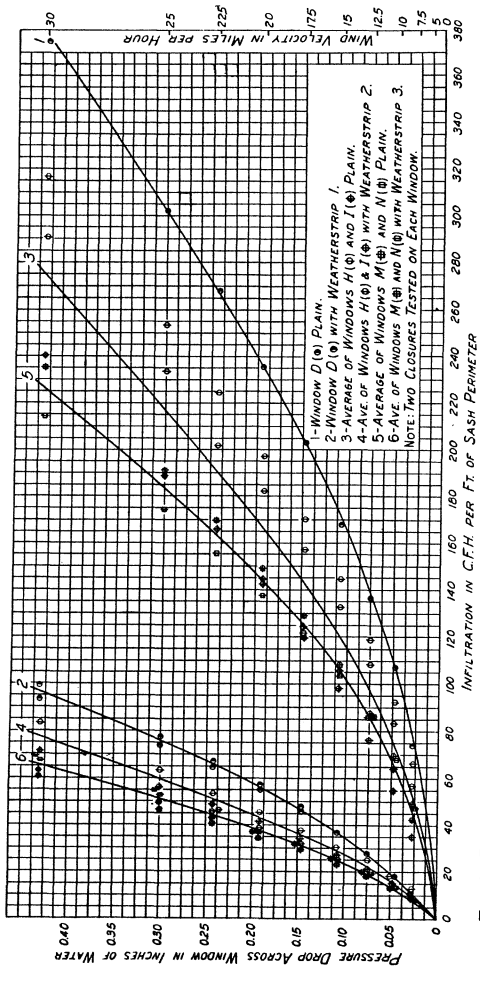

FIG. 6. RESULTS FOR 5 PLAIN AND WEATHERSTRIPPED WINDOWS WITH 3/32 IN. CRACK AND CLEARANCE—NOT LOCKED

termed first and second closures, were made in each case, the tables show only the average of the two. The curve sheets that show the points for individual windows and the averages of groups as curves show points for both the first and second closures except where they were identical. However, in getting values for average curves all test values, whether identical or not, were given equal weight. This explanation is considered necessary because some of the curves do not appear to be the average of the points they represent because some runs are represented by 1 point and others by 2 points at each pressure reading.

Table 3 shows the results of the tests on 5 windows of a poor grade with 3/32 in. crack and clearance, both plain and stripped. Table 4 shows the results for the 9 windows termed as of a good grade both plain with the original 1/64 in. crack and 1/32 in. clearance and plain and weatherstripped with the final 1/16 in. crack and 3/64 in. clearance that were established as representing the average crack and clearance by field measurements on a large number of windows.

Fig. 6 presents the results for the five windows plain and weatherstripped with 3/32 in. crack and clearance, not locked. Fig. 7 is the same for the locked runs. Figs. 8 and 9 show the corresponding results for the nine windows with 1/16 in. crack and 3/64 in. clearance. These 4 figures show the points by individual windows and the average curves by weatherstrips.

Fig. 10 shows the variation in infiltration over the standing period of 6 months between the original and the check tests without the making of a manual alteration in the crack and clearance. Fig. 11 shows the average curves for the series of 5 windows using 3/32 in. crack and clearance under locked and not-locked, plain and weatherstripped conditions. Fig. 12 shows the average curves for the series of nine windows with the original 1/64 in. crack and 1/32 in. clearance and with the final 1/16 in. crack and 3/64 in. clearance, both plain and weatherstripped.

DISCUSSION OF RESULTS

The average leakage found for the 5 plain, not-locked windows with 3/32 in. crack and clearance, was 124.5 cfh per foot of sash perimeter at 15 mph. This is the result of the tests made directly before weatherstripping and compares with 29.1 cfh for the same windows weatherstripped with the same crack and clearance. The points on Fig. 6 show that there was considerable variation in leakage between the 5 plain windows. This is considered to be due largely to the poor workmanship and material of this group. It was difficult to set an even crack and clearance on these 5 windows.

Window *D* showed a very high leakage as a plain window due to a combination of an upper sash that was warped and not square so that the head and meeting rail leakages were high and a larger than average clearance. Plain window *H* was also higher in leakage than the average when not locked. Locking reduced the leakage through this window so that windows *H, I, M,* and *N* had very nearly the same air leakage when locked as shown in Fig. 7. Locking window *D* reduced the leakage somewhat but left its position relative to the average about the same. Although window *D* deviates from the average considerably, it appeared to be an entirely possible window to be in any group of 5 windows of this type; consequently, it was used in the averaging of the group. The average leakage at 15 mph for this window when plain, for both

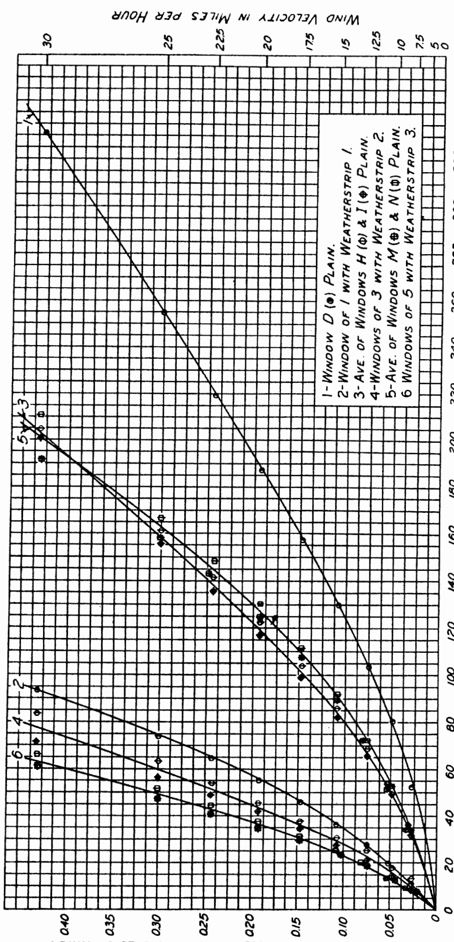

FIG. 7. RESULTS FOR 5 PLAIN AND WEATHERSTRIPPED WINDOWS WITH 3/32 IN. CRACK AND CLEARANCE—LOCKED

locked and not locked runs, was 35 per cent above the average of the group. It was 28 per cent above the average of the group when weatherstripped. Windows *H* and *I* were 8 per cent lower than the average of the group as plain

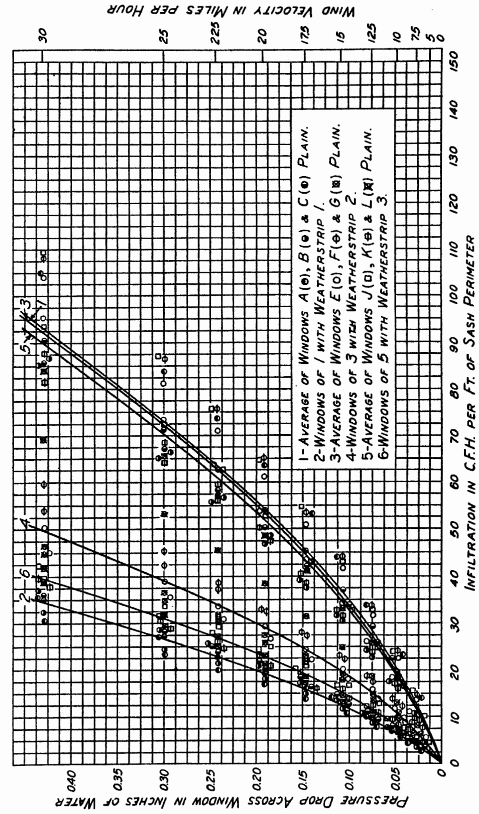

FIG. 8. RESULTS FOR 9 PLAIN AND WEATHERSTRIPPED WINDOWS WITH 1/16 IN. CRACK AND 3/64 IN. CLEARANCE—NOT LOCKED

windows and were equal to the average as weatherstripped windows. Windows *M* and *N* were 10 per cent lower than the average when plain and were 14 per cent lower when weatherstripped, considering both locked and not-locked results. This seems to indicate that the leakage through the weatherstripped window for this class and fit of window depends largely on the leakage of the original plain window. The curves in Figs. 6 and 7 indicate this relation between the leakage of the plain and weatherstripped windows. Weatherstrip (1) applied to window *D* did not prove relatively as effective as when applied to windows *A*, *B*, and *C* as shown in Fig. 8. It would seem that the high leakage of the poorest of the five windows was caused by factors that the weatherstrip could not overcome to the same extent as on the better windows *A*, *B*, and *C*.

An examination of individual points shows that there is a considerable variation between windows *H* and *I*, plain and not locked, to which weatherstrip *2* was applied. Locking reduced the leakage through window *H* to a value very close to that of *I* when locked. Applying weatherstrips to *H* and *I* brought the leakage of these two windows very close together. The points for each weatherstripped window lie very close to the average for the windows to which that strip was applied.

The curves for the three groups of windows, *D* and *H I*, and *M N* in Figs. 6 and 7 show that much more variation exists between the averages for the plain windows than for the weatherstripped windows. At 15 mph the variation is 62 cu ft for the plain windows and 12 cu ft for the weatherstripped windows.

Fig. 11 shows a considerable reduction in the results for the locking of the plain windows. When weatherstripped, locking resulted in very little reduction on these 5 windows.

The average leakage for the 9 plain, not-locked windows with $\frac{1}{16}$ in. crack and $\frac{3}{64}$ in. clearance is shown in curve *3* of Fig. 12 and was 35.6 cu ft per hour per foot of sash perimeter at 15 mph. The greatest variation from this for the groups of 3 windows was only 3 per cent. The variation for individual windows in the group as shown in Fig. 8 was considerably more. Window *G* had an especially low leakage as a plain window. When weatherstripped, the leakage of this window was one of the highest. Window *A*, plain, was the highest in leakage of the entire nine, but when weatherstripped was the lowest. The same strip (1) was applied to a window (*C*) which as a plain window had about the average leakage of the entire 9 and to one with next to the lowest leakage (*B*). When weatherstripped, these 3 windows with widely varying leakages as plain windows were very uniform in leakage. The same variation is noticed with windows *E*, *F* and *G* to which weatherstrip (2) was applied. As plain windows, the results for the 3 windows of the group varied widely, yet when weatherstripped, the results group themselves quite closely to the average curve (*4* of Fig. 8). The variations in the 3 groups as plain windows are about the same except that *G* had considerably lower leakage than *B*, the lowest in the other two groups. When weatherstripped, group *E*, *F*, *G* was highest in leakage and group *A*, *B*, *C* the lowest in leakage. The results of the tests of these weatherstripped windows were closely grouped about their own average group curve (*2*, *6*, and *4*). This close grouping of the weatherstrips about the average curve for each group regardless of the variation of the individual windows in the group as plain windows, seems to indicate that each strip as applied to a window of this average crack and clearance has certain characteristics that determine the weatherstripped window leakage. Had

considerable variation been found among the weatherstripped windows of each group, it would have been due likely to a non-uniformity of the strip, to the influence of the plain window fit and leakage, or to the variation in workman-

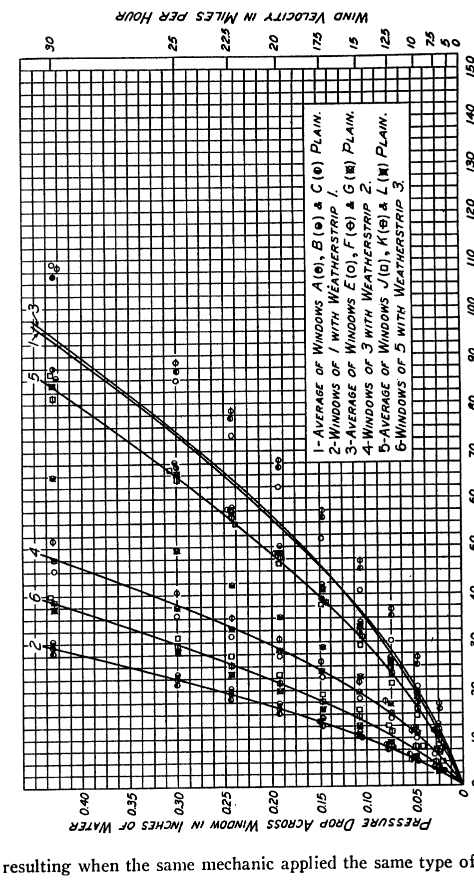

FIG. 9. RESULTS FOR 9 PLAIN AND WEATHERSTRIPPED WINDOWS WITH $\frac{1}{16}$ IN. CRACK AND $\frac{3}{64}$ IN. CLEARANCE—LOCKED

ship resulting when the same mechanic applied the same type of strip to several windows.

The grouping of the points for the individual weatherstripped windows *D*, *H*, *I*, *M*, and *N* with $\frac{3}{32}$ in. crack and clearance as shown on Fig. 6 is very

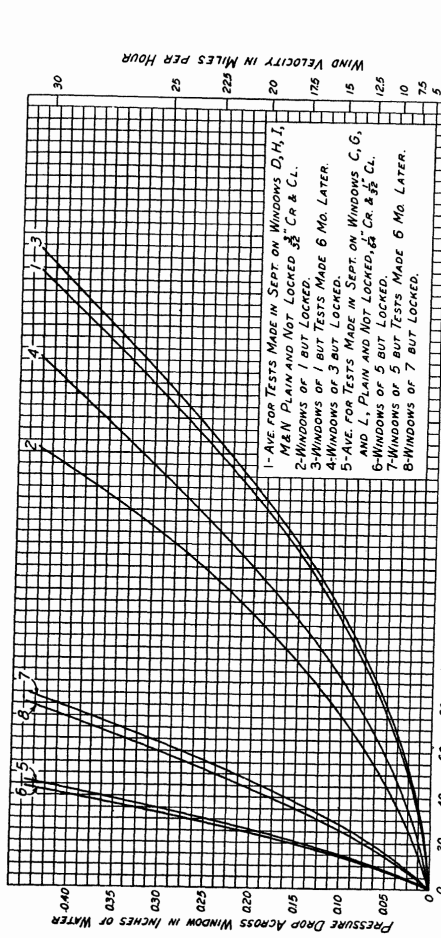

FIG. 10. VARIATION IN INFILTRATION OVER A STANDING PERIOD OF 6 MONTHS, CRACK AND CLEARANCE NOT ALTERED MANUALLY

close to the average curves for *D* and *H I* and *M N*, although the plain windows *H* and *I* varied widely. One difference noted between the application of strips to the two groups of 5 and 9 windows was the relative positions occupied

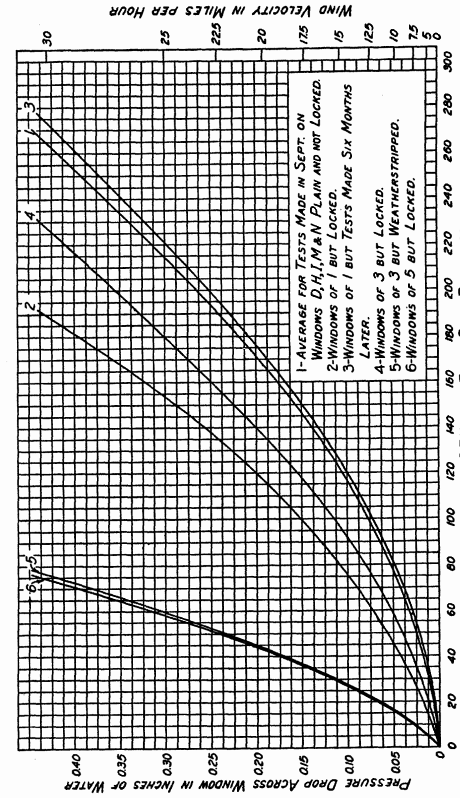

FIG. 11. SUMMARY CURVES FOR 5 WINDOWS WITH 3/32 IN. CRACK AND CLEARANCE

by the plain and stripped results of the windows *A*, *B*, *C* and *D* to which strip (1) was applied. *A*, *B*, and *C* as a group had the highest plain-leakage of the nine and as weatherstripped the lowest leakage. Window *D*, plain, had considerably the highest leakage of the 5 in the series, and when weatherstripped, it still had the highest leakage. It, however, was about 8 per cent nearer the average of the group when weatherstripped than when plain.

The average leakage for the nine weatherstripped windows not locked as

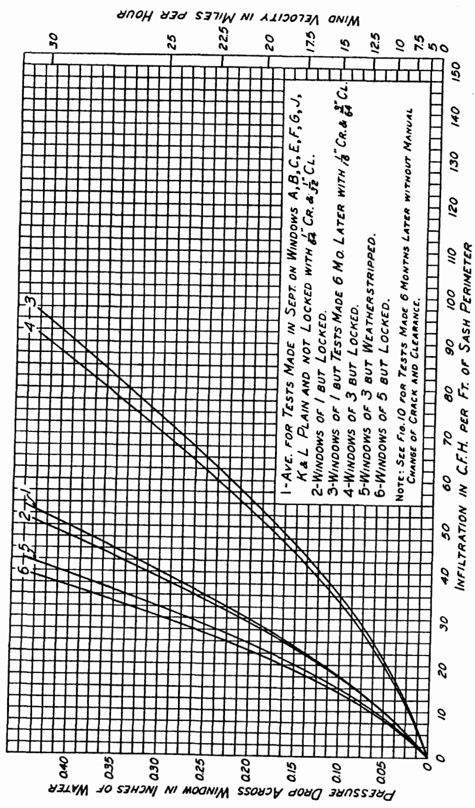

Fig. 12. Summary Curves for 9 Windows with 1/64 in. Crack and 1/32 in. Clearance and with 1/16 in. Crack and 3/64 in. Clearance

shown in Fig. 12, curve *5* was 16.0 cu ft per hour per foot of sash perimeter at 15 mph. The deviation of the average of each of the 3 groups from the general average of the 9 windows when weatherstripped is considerably more than the maximum deviation of 3 per cent when plain. Group *A, B, C* was about 20 per cent lower than the average, group *E, F, G* was 25 per cent higher, and group *J, K, L* 5 per cent lower than the average. This indicates that there is more variation between the 3 groups when weatherstripped than when plain for these windows fitted to a 1/16 in. crack and 3/64 in. clearance.

The average leakage of the nine plain windows as originally fitted with 1/64 in. crack and 1/32 in. clearance was 18.7 cu ft as compared to 16.0 cu ft for the weatherstripped window with a crack of 1/16 in. and a clearance of 3/64 in. This is shown in Fig. 12. A plain window then can be made with a small crack and clearance and yet will open and close easily, and will have a leakage almost as low as a weatherstripped window fitted with an average crack and clearance. It is not known what the comparison would be if the weatherstrips had been applied to the windows retaining the small crack and clearance. It also must be borne in mind that the plain windows were fitted too closely to permit working under all conditions encountered in actual building constructions.

Locking the 9 plain and weatherstripped windows resulted only in a 1 cu ft reduction in leakage. The reduction due to locking was also slight in the case of the 5 windows when weatherstripped. The only case where locking resulted in a substantial reduction in leakage was that of these 5 plain windows which were fitted to a 3/32 in. crack and clearance. All locked runs were made with the locks just as they were originally fitted at the mill. Locking comparisons are shown on Figs. 11 and 12 for the two series of windows.

Fig. 10 shows the variation in results between the original tests made in September and 6 months later without manually changing the crack and clearance. On the 5 windows of a poor grade, the crack and clearance remained practically constant. The 6 months later tests on the plain, not-locked windows showed an increase in leakage of less than 3 per cent. Comparing the locked runs, the leakage of the same windows increased about 20 per cent. The reason for this larger increase for the locked as compared to the not-locked runs is not known. It would seem that a shrinking or warping of the window members would have less effect on the leakage when locked than when not locked.

Curve *5* of Fig. 10 shows the average leakage through 3 plain windows, *C, G,* and *L* with a 1/64 in. crack and 1/32 in. clearance. After a 6 months' standing period, the windows had become much looser. The average crack became slightly less than 1/16 in. and the average clearance slightly over 1/32 in. The average leakage for the plain, not-locked windows in the original tests was 15.9 cu ft per hour per foot of sash perimeter at 15 mph. The leakage after the standing period of 6 months was 29.8 cu ft. This is an increase in leakage of 87 per cent. A large part of the increase in clearance was due to the warping and shrinking of the wood pulling loose the finishing nails with which the frames were held together. The driving in of larger nails restored the clearances to somewhere near their original values. The crack and clearance were then adjusted to the final values of 1/16 in. crack and 3/64 in. clearance by planing. The leakage then obtained for the plain, not-locked window was 31.2 cu ft per hour per foot of sash perimeter at 15 mph. Locking resulted in a very small reduction in leakage in these 3 sets of tests on windows *C, G,* and *L*.

Locking resulted in no change in leakage in 20 per cent of all the runs made in these tests of the 14 windows. In another 20 per cent of the runs, locking

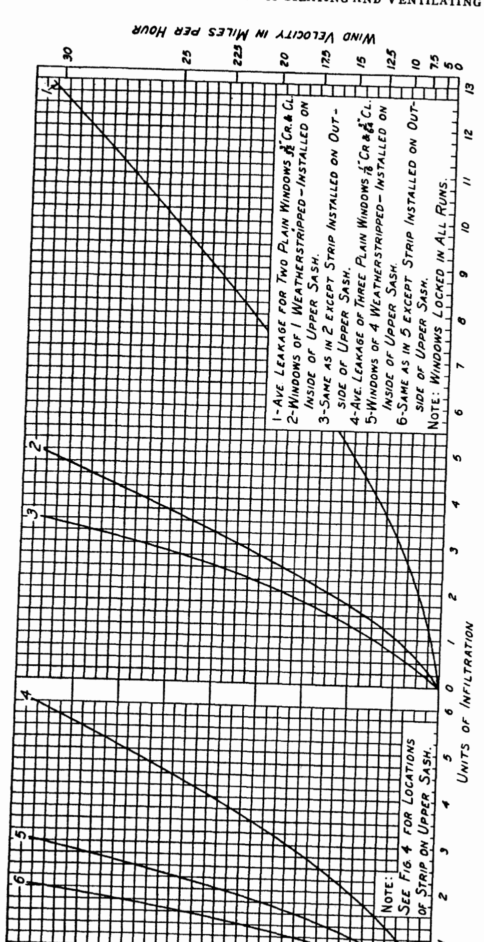

Fig. 13. Effect on Infiltration of Strip Location

increased the leakage and in 60 per cent of the runs, it decreased the leakage. The greatest decrease in leakage was 38 per cent and the greatest increase was 13 per cent. The average of all changes was an 8 per cent reduction.

Comparing the results of the first and second closures, it was found that in 31 per cent of the runs the leakage was the same for both closures. The average variation between the two closures was 5 per cent. The greatest variation was 21 per cent; the variation was greater than 10 per cent in 12 per cent of the runs.

Fig. 13 shows the influence on the infiltration of the location of the weatherstrip on the upper sash. Fig. 4 at *c* shows the strip located on the inside of the upper sash and *d* shows the strip located on the outside of the upper sash. When located as at *c*, it is possible for air entering the sash perimeter to gain entrance to the room through the pulley holes. The only reduction weatherstripping in this position could make in this leakage through the pulley holes would be in decreasing the clearance at the outside joint between the sash and the runway by exerting a force in that direction. The strip represented in Fig. 13 is regularly applied to the inside of the upper sash. The results of the tests of two windows with large crack and clearance weatherstripped in this manner are shown by curve *2* and as applied to 3 windows of average crack and clearance are shown in curve *5*. After the completion of these tests, the strips were removed from the upper sash and similar strips installed on the outside of this sash. The change in location resulted in a reduced leakage in every case. Curves *3* and *6* show the results for this relocation of the strips. The reduction was 26 per cent for the 2 windows with large crack and clearance and 37 per cent for the 3 windows with small crack and clearance. This reduction is due to the reduction of sash perimeter leakage that enters the room through the pulley holes.

Frame Leakage

The results of the tests on the 14 windows as given in Tables 3 and 4 and Figs. 6 to 13 inclusive are for sash perimeter leakage only. To this leakage must be added any air leakage that occurs through the frame of the window. In a plain plastered wall whether of masonry or frame construction, the leakage on a plain wall area the size of a window opening is negligible. Any leakage over this negligible amount when a window opening is placed in the wall is rightfully chargeable to the window. This leakage in a wood frame wall is mainly due to air entering at the edges of the building paper at the frame opening. A certain amount also enters at the corners of buildings and after getting under the paper travels in the joints of the sheathing from one studding space to another until a window opening, door opening or baseboard is reached that allows entrance to the room.

In a masonry wall, the leakage originates mainly at the joint between the window frame and the masonry wall, known as the frame joint. This leakage can be practically eliminated by the proper use of calking compound. A smaller amount of the frame leakage originates in the wall itself and travels horizontally in the voids to the window frame. Calking, of course, does not reduce this leakage. The use of solid masonry, that is, completely slushed joints, rather than the use of incompletely slushed joints that leave voids in the interior of the wall, would reduce this leakage. A portion of the frame leakage enters the room around the interior window trim, and some enters the sash weight boxes from where for the most part it enters the room through the lower sash pulley holes. The total pulley hole leakage is composed of this part of the frame leakage and the part of the sash perimeter leakage that entered the weight boxes mainly through the upper sash pulley holes. Pulley hole covers are at times applied to reduce this leakage. They reduce the very evident leakage at the pulley holes but the net reduction is not likely to be a large percentage.

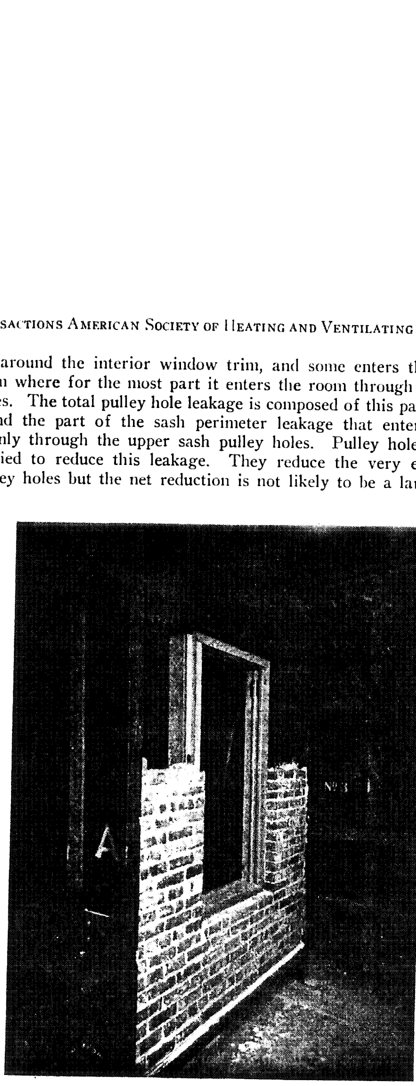

FIG. 14. BOX FRAME IN MASONRY WALL TESTED FOR FRAME LEAKAGE

Their application likely builds up the pressure slightly in the weight spaces and the leakage for the most part finds its way into the room through smaller and less noticeable openings between the window trim and plaster or at the baseboard. The proper place to stop the air leakage in good building construction would be at the points of entrance near the exterior surface of the wall.

Two 13-in. brick masonry wall sections and two wood frame wall sections were built to investigate frame leakages. Fig. 14 shows one of the masonry walls in the course of construction. Incompletely slushed walls were built in

each case but mortar was slushed completely against the window frames. The room sides of the walls were plastered. Fig. 15 shows one of the two frame wall sections completely built and in position ready to close the machine for testing. The construction from outside to inside was bevel siding, building paper, sheathing, 2 x 4 studding, wood lath and plaster. Two variations were tested on each of these two walls. In one, the plaster ground stopped at the 2 x 4 framing for the window opening; this was termed *narrow plaster ground* test. In the other, the plaster ground bridged across from the 2 x 4 window framing to the window frame so as to offer greater resistance to air passage

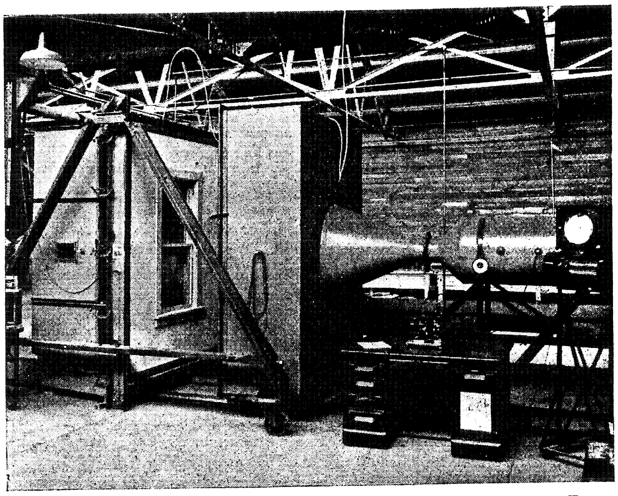

FIG. 15. WINDOW INSTALLED IN A WOOD FRAME WALL AND TESTED FOR FRAME LEAKAGE

from the studding and weight spaces and was termed *wide plaster ground* test. The wall sections were built by average building mechanics to represent average building construction.

Table 5 shows the results of these tests for frame leakage for both types of wall. The average leakage obtained at 15 mph for the wood frame walls was 13.5 cu ft per hour referred to per foot sash perimeter. The infiltration through the five plain, not-locked windows with 3/32 in. crack and clearance was 124.5 cu ft and for these windows weatherstripped was 29.1 cu ft per hour per foot of sash perimeter at 15 mph. The average value for the 9 plain, not-locked windows with 1/16 in. cracks and 3/64 in. clearance which are considered to represent the fit of an average window was 35.6 cu ft and for the weatherstripped condition was 16.0 cu ft per hour per foot of sash perimeter at 15 mph. To these sash perimeter leakages should be added the 13.5 cu ft of frame leakage when applied to wood frame construction.

The average leakage through the frame in a masonry wall was found to be 17.5 cu ft per hour per foot of sash perimeter at 15 mph. Calking the frame joint resulted in reducing this leakage to 3.3 cu ft. When a perfect job of calking, which is easy to approach, is done, the frame leakage consists of air that enters into the brick work and travels to the window frame. This amounts to about 20 per cent of the uncalked frame leakage with the usual not completely slushed brick wall construction.

The particular frame leakage applying to the masonry wall, with the frame joint calked or not calked, should be added to the values of sash perimeter leakages to obtain the total leakage for the window opening.

Table 6 shows in the first line the average results for the plain and weatherstripped windows *D*, *H*, *I*, *M*, and *N* that were fitted to 3/32 in. crack and clearance. In addition, Table 6 shows the results of tests of seven windows termed *miscellaneous* of somewhat the same crack and clearance. These were tested as plain windows over the past several years and then weatherstripped. Only one test of each type is included in the miscellaneous tests although two different types of the same make are included in some cases. The thickness of the sash was 1⅜ in. in every case. The results shown in this table are those from the original tests for the plain windows. The results shown as for weatherstripped windows are from tests made during 1931. The cracks and clearances are the measured values taken in the past at the time of the original plain window tests. Since the cracks and clearances are only approximately the same as those used on the present series of five, and because the method of sealing is in question on a few of the plain window tests and because of the cracks and clearances when tested as weatherstripped windows had probably changed from the original plain window values, it is considered best not to use an average obtainable from the inclusion of these so-called miscellaneous windows in Table 6. The average, allowing each window equal weight, however is given in this table for comparison to the average as determined in the present program on 5 windows of 3/32 in. crack and clearance. The average of the entire 12 is lower than the average of the 5 for both plain and weatherstripped conditions.

GENERAL CONCLUSIONS

Table 7 shows a summary of the frame leakages, the sash perimeter leakages and the sum of the two or the total window opening leakages for wood frame and for masonry wall constructions. In the case of masonry walls, only the total with the frame joint calked is given, since the benefit from calking is so obvious.

The Infiltration sections of A. S. H. V. E. GUIDES of 1930 and 1931 quote a leakage of 155.0 cu ft per hour per foot of sash perimeter at 15 mph. The crack is 1/16 in. and the clearance is 3/64 in. and the window not locked. The value for the weatherstripped window is given as 28.6 cu ft. A note states that these figures include the elsewhere leakage but not the frame leakage. These figures were arrived at by tests on windows with the seal made on the inside of the upper sash. The elsewhere leakage referred to as added is

TABLE 6. SUMMARY TABLE FOR INFILTRATION IN CUBIC FEET PER HOUR PER FOOT OF SASH PERIMETER THROUGH MISCELLANEOUS DOUBLE-HUNG WOOD WINDOWS WITH APPROXIMATELY 3/32 IN. CRACK AND CLEARANCE—NOT LOCKED

WINDOW	CRACK	CLEARANCE	PLAIN (6 MO. LATER)										WEATHERSTRIPPED									
			SASH PULLS POUNDS				MILES PER HOUR						SASH PULLS POUNDS				MILES PER HOUR					
			UPPER		LOWER								UPPER		LOWER							
			UP	DN.	UP	DN.	5	10	15	20	25	30	UP	DN.	UP	DN	5	10	15	20	25	30
AVE. FOR WINDOWS D, M, H, N, I	3/32	3/32	5	4	6	1	30.9	78.5	124.5	171.6	220.0	274.1	20	17	15	10	4.7	15.9	29.1	43.6	59.4	76.5
WINDOW O, WEATHERSTRIP 4	3/32	3/32	3	5	3	5	20.5	49.5	80.0	113.0	150.0	190.0	22	22	24	26	2.1	7.8	16.1	25.5	34.6	43.5
" P, " 5	1/8	3/32	7	4	4	2	27.5	74.8	126.0	175.5	223.0	266.0	18	16	10	4	2.4	10.0	20.5	32.5	45.0	57.0
" Q, " 6	1/8	3/32	–	–	–	–	14.5	50.0	81.0	116.0	147.0	175.0	8	6	10	7	5.1	18.0	34.4	52.0	68.6	85.3
" R, " 7	1/8	3/32	–	–	–	–	18.0	55.5	91.5	131.0	169.0	202.0	11	10	8	9	4.1	14.2	24.9	35.9	47.3	60.7
" S, " 8	7/64	3/32	2	1	9	2	25.0	58.0	91.5	122.5	152.9	181.0	15	11	25	20	5.0	14.8	25.2	36.0	48.2	62.0
" T, " 9	5/64	3/32	5	3	5	0	10.5	33.0	58.0	84.0	111.3	141.0	30	24	20	16	3.5	12.8	23.0	33.2	43.3	53.5
" U, " 10	5/64	3/32	5	5	8	0	8.7	27.3	49.3	72.5	97.3	123.5	34	34	40	28	2.6	9.7	19.7	31.2	42.8	54.0
WEIGHTED AVERAGE	3/32+	3/32	4	3	5	1	23.3	61.7	100.4	139.4	179.2	220.8	20	17	18	13	4.0	13.9	25.8	38.7	52.2	66.5

TABLE 7. SUMMARY TABLE OF INFILTRATION IN CUBIC FEET PER HOUR PER FOOT OF SASH PERIMETER THROUGH DOUBLE-HUNG WOOD WINDOWS—NOT LOCKED

PRESSURE DROP ACROSS WINDOW IN INCHES OF WATER	WIND VELOCITY MI./HR.	FRAME LEAKAGE			SASH PERIMETER LEAKAGE				FRAME LEAKAGE PLUS SASH PERIMETER LEAKAGE							
		WOOD FRAME WALL	MASONRY WALL		1/16" CR. & 3/64" CL.		3/32" CR. & 3/32" CL.		WITH WOOD FRAME WALL				WITH MASONRY WALL—CALKED			
									1/16" CR. & 3/64" CL.		3/32" CR. & 3/32" CL.		1/16" CR. & 3/64" CL.		3/32" CR. & 3/32" CL.	
			NOT CALKED	CALKED	PLAIN	WEATHER-STRIPPED	PLAIN	WEATHER-STRIPPED	PLAIN	WEATHER-STRIPPED	PLAIN	WEATHER-STRIPPED	PLAIN	WEATHER-STRIPPED	PLAIN	WEATHER-STRIPPED
0.012	5.0	2.7	4.1	0.6	5.6	2.7	30.9	4.7	8.3	5.4	33.6	7.4	6.2	3.3	31.5	5.3
0.027	7.5	5.0	7.0	1.2	11.7	5.4	54.2	10.0	16.7	10.9	59.2	15.0	12.9	6.6	55.4	11.2
0.048	10.0	7.7	10.3	1.9	19.1	8.6	78.5	15.9	26.8	19.3	86.2	23.6	21.0	10.5	80.4	17.8
0.075	12.5	10.5	13.8	2.6	27.1	12.2	101.4	22.7	37.6	22.7	111.9	33.2	29.7	14.8	104.0	25.3
0.108	15.0	13.5	17.5	3.3	35.6	16.0	124.5	29.1	49.1	29.5	138.0	42.6	38.9	19.3	127.8	32.4
0.147	17.5	17.1	21.3	4.0	44.1	19.6	148.3	36.3	61.2	36.7	165.4	53.4	48.1	23.6	152.3	40.3
0.192	20.0	20.7	25.3	4.7	53.4	23.7	171.6	43.6	74.1	44.4	192.3	64.3	58.1	28.4	176.3	48.3
0.243	22.5	24.6	29.5	5.4	62.5	27.7	194.9	51.4	87.1	52.3	219.5	76.0	67.9	33.1	200.3	56.8
0.300	25.0	28.7	34.0	6.0	71.9	32.0	220.3	59.4	100.6	60.7	249.0	88.1	77.9	38.0	226.3	65.4
0.431	30.0	37.8	43.3	7.2	91.8	41.4	274.1	76.5	129.6	79.2	311.9	114.3	99.0	48.6	281.3	83.7

leakage that originated at the sash perimeter and entered the room through the pulley holes. These figures, then, are to be compared to the sash perimeter results of the tests on the five windows with a 3/32-in. crack and clearance of the present program. The average sash perimeter leakage of these windows, plain, was 124.5 cu ft and 29.1 cu ft for the weatherstripped window per foot of sash perimeter per hour at 15 mph.

The measurement of a large number of windows in actual buildings at this time indicates that the crack and clearance of the average window is considerably less than the foregoing GUIDE values of 1/16 in. crack and 7/64 in. clearance or the 3/32-in. crack and clearance of the series of 5 windows of the present program. According to these measurements and the tests on the nine windows of this program, the average window would have a 1/16-in. crack and a 3/64-in. clearance and as a plain not-locked window would have a leakage of 35.6 cu ft per foot of sash perimeter per hour at 15 mph. When weatherstripped, its leakage on the average would be 16.0 cu ft. To these values should be added, when applied to wood frame construction, 13.5 cu ft of frame leakage, making a total of 29.5 cu ft per foot of sash perimeter per hour at 15 mph for the weatherstripped window. When applied to a calked masonry construction, the sash perimeter leakages should be increased by a 3.3 cu ft leakage making a total window opening leakage of 19.3 cu ft for the weatherstripped window. The plain window figures would be 49.1 cu ft for wood frame construction and 38.9 cu ft for masonry construction.

It is realized that the program reported in this paper is a laboratory program and that somewhat more representative figures might be obtained if a much larger number of windows were included in the tests. Furthermore, the effect of wear and weathering such as takes place in actual building constructions has not been considered. A valuable addition to the program as presented at this time might be made by the subjecting of the fourteen windows to wear and weathering. To accomplish this, they could be built into an enclosure that would be heated and on the outside subjected to weather conditions. The windows could be opened and closed a certain large number of times during a period of exposure of a year or more. The ease of opening and closing as measured by sash pulls under various weather conditions would check the belief of the authors that the weatherstrip installations on these fourteen windows represent average installation workmanship. The windows when removed from the exposure would be re-tested by the method followed in the tests of this paper to arrive at the leakage for a window as found in actual buildings.

DISCUSSION

W. C. RANDALL (WRITTEN): In view of the statement made in the next to last paragraph of the paper, do you feel that THE GUIDE should be revised to incorporate the infiltration secured from the good grade of window having 1/16 in. crack and 3/64 in. clearance as typical of general conditions? Since you were able to secure, from the mills, windows of such varying qualities, it is evident that all types are being used and it would seem rather risky to use a figure secured by testing good windows without knowing that this was the type being used in the particular building.

The tests from which data for THE GUIDE were secured showed very little difference in infiltration for crack widths from 1/16 in. up to 1/4 in. Since your tests found the leakage for the good windows with 1/16 in. crack to be only about 1/8 of that for the poor ones with 3/32 in. crack (Table 7), would not this difference appear to be due to the type and construction of the window rather than the size of the crack?

Two major factors in weatherstripping are given in this paper. It has also been stated that windows are to admit light and to allow the entrance of air when it is wanted. Would not ease of operation, therefore, be a third important factor? It was somewhat disappointing to find, from Table 4, that the weatherstripping increased the pull required to open the windows to about five times that required originally. Could it not be said then that the most practical weatherstrip would be one that was efficient for preventing infiltration, without destroying the original ease of operation?

E. W. CONOVER (WRITTEN): Table 2, showing field measurements, lists the buildings mostly as university, high school and fraternity. Is it not thought that these represent buildings in which good windows had been installed rather than the average of buildings throughout the country? It appears doubtful that the five poor windows are typical of the average. Likewise, does it not seem reasonable that the nine good ones are above the average since it was stated that they were considered tighter than would be permissible in actual building construction?

The paper states that a plain window can be made that will have a leakage almost as low as a weatherstripped window fitted with an average crack for clearance. In view of the fact that this statement is based upon tests of the good windows and that these were considered tighter than permissible, also that six months later these same windows had a leakage about 80 per cent more than originally, is this considered a practical statement to make?

In regard to the frame leakage given in Table 5, I would like to ask whether or not the basis of per foot of sash perimeter is correctly stated. Ordinarily, sash perimeter includes the meeting rail which is not a factor in frame leakage. Should it not be per foot of frame perimeter?

When testing for frame leakage in different walls, it would be interesting to know how much time elapsed between building and testing, what grade of windows were installed, and what painting was done.

Is a continuation of this program, as outlined in the last paragraph, contemplated? If such is the case, would it not more nearly represent typical installation conditions if new windows are installed in a building and subjected to weather rather than the original 14 windows? New windows which have not been subjected to the seasoning that these original ones have might exhibit a greater tendency to shrink and warp as they weathered than would those that have been well seasoned in the laboratory.

AUTHORS' CLOSURE (WRITTEN): The original data for THE GUIDE were determined for crack widths of 1/16 in. to 1/4 in. The clearance was 7/64 in. Under such conditions, the crack makes very little difference as the clearance path is the narrower and therefore limits the flow of air. This clearance allows a 7/128 in. width of path on the sides of the sash as compared to a path 1/16 in. or more in width between the sash and the bottom of the runways.

In the present tests, the clearance was again the limiting factor rather than the crack. In the case of the average fit of windows the clearance path is 3/128 in. wide and in the case of the poor fit of windows, it was 3/64 in. Based on a direct comparison of these areas for air travel, it would be expected that the leakage would be double with the loosely fitted than with the average fit of windows. But doubling the width of the passageway more than doubles the effectiveness to air travel because of reduced skin friction due to a larger ratio of cross-sectional area to boundary surface.

Since this holds true, little of the difference in leakage of the so-called *good* and *poor* windows can be attributed to a difference in materials or workmanship. The difference in the two types of windows was largely in the fit of the sash at the time of testing. The sash in each type were of the same material and grade. The frame material was poorer in the so-called poor windows in that poorer lumber was used. The parting stops also were of poorer material. But the two types of windows were probably made in the same types of mill work machines so that when adjusted to the same crack and clearance, the difference in material could affect the sash perimeter leakage very little. Unfortunately, no tests were made at the same crack and clearance. The windows were all ordered before the average crack and clearance were established by field measurements and the five poorly fitted windows were ordered loosely fitted as that was considered to go along with poor workmanship and materials. The nine closely-fitted windows were ordered to be as closely fitted as smooth working would allow because tests on a few such closely-fitted windows were desired and because naturally careful workmanship on the crack and clearance would demand the same grade of workmanship in other ways and the use of good material.

The paper has stated that there are two major factors in weatherstripping; one is the location of the strip and the other is the effectiveness of the strip to stop leakage that reaches it. Windows are to admit light and allow the entrance of air when it is wanted. This latter statement might be revised to say, to open easily to allow the entrance of air when it is wanted and to close easily when air is not wanted. It seems obvious that in improving the air resistance qualities of a window the weatherstrip should not affect adversely some other quality of the original plain leakage such as ease of opening.

Weatherstripping the nine windows of average fit resulted in an increase in sash pulls from about 7 lb to 16 lb, or a little over a doubling of the pull required to open and close. It seems natural that the installation of metal strips to definitely make close contact to reduce air leakage would increase the friction of sash movement. The only case where it would not increase the sash pull when properly fitted weatherstrips are applied would be with badly warped sash. Warping causes a drag on the plain window that is to a large extent corrected by the weatherstrip mechanic by truing with a plane at the time of strip installation. From this, it should not be understood that a moderate degree of warping is entirely a loss as it prevents rattling of sash in many plain windows.

The average sash pull of 16 lb when weatherstripped did not seem excessive and a period of operation would likely decrease this figure.

In obtaining the field measurements, an effort was made to secure windows in the average type of building using the double-hung wood type. Twelve of the 32 buildings were residences so that it seems doubtful that too much prominence has been given to university, high school and fraternity buildings. Further, some of the five fraternity buildings were at one time residences.

At no time were the five *poor* windows considered as typical of the average. They have been considered as representing the average of poorly fitted windows with a large crack and clearance. It probably is possible to find windows fitted more poorly; in fact, some may be so loose that the sash will not stay in the run-ways. But the five as fitted are in our judgment representative of the poorest fit that would be tolerated in a building to be heated to 70 F.

The nine windows termed *good* windows when fitted to the average crack and clearance as determined by field measurements were considered to represent the average window in a building at least five years old. When received as ordered, they were not average, since the crack and clearance were smaller than could be tolerated in a building exposure. These windows when tested plain with the final fit and when weatherstripped are taken to represent as closely as possible the average installed window. The only way of securing a closer figure to the average would be by the testing of a large number of windows installed in buildings for a period of years.

The statement "that a plain window can be made that will have a leakage almost as low as a weatherstripped window fitted with an average crack and clearance" is a correct and practical statement to make when not divorced from the two succeeding statements, one of which states that "it should be borne in mind that the plain windows (when received) were fitted too closely to permit working under all conditions encountered in actual building constructions." The fact that the leakage increased by 80 per cent over a standing period of six months shows the original fit was not a practical fit. This increase in leakage was due to the letting go of the small finishing nails holding the frames together.

The results of tests for frame leakage as given in Tables 5 and 7 are correctly stated as per foot of sash perimeter. Sash perimeter has no direct relation or at least does not cause frame leakage, but the latter was tabulated on this basis for convenience in comparing with sash perimeter leakage and for direct addition in Table 7 to get total leakage per unit of sash perimeter chargeable against the window opening.

The brick walls were allowed to stand 2½ months and the frame walls one month between the time of building and testing. An average grade of window was used and the installations were made by average building mechanics to represent average building conditions. A prime coat was given all exposed wood on these walls.

The additional program suggested in the last paragraph of the paper of exposing windows to wear and weathering over a period of years was considered in connection with the 14 windows of the present program and now in the state of average weatherstripped windows. The additional exposure and retesting would prove our contention that these weatherstrip installations represent the average strip installation in buildings. Nine of these represent the installations on the average fit of windows and five on poorly fitted windows. It is the contention of some that a poor weatherstrip may be made *tight* on a laboratory installation but on exposure to weather the strips would not stand up nor would they retain their original freeness of movement. Exposure and wear tests would prove or disprove the author's belief that the strip installations are average workable installations.

Valuable additional data on double-hung wood windows might be secured by installing new plain windows in a building and subjecting them to wear and weather for a period of years before removing to a laboratory for test. This procedure was not contemplated in the writing of the last paragraph of the paper. One difficulty would be in setting the crack and clearance to such values that at the end of the period of exposure they will have assumed the values found for the average installed windows; that is, how much of the final crack and clearance as found on the average installed window is due to the original fit set by the building carpenter and how much to the wear and weathering of the following years. Another difficulty would be in the length of time needed to make exposure tests on the window plain and later weatherstripped. Likely the final leakage result is somewhat different, depending upon whether a weatherstrip is applied when the building is new or when it has aged for several years.

There is no end to the variations that might be studied. The present paper is considered to have determined a reasonably close value for the leakage through the average plain and weatherstripped window. The clearance of the average window was found to be 3/64 in. and the crack 1/16 in. It is considered that the figures obtained for these windows should be used in THE GUIDE to represent the average window of this type. In addition, the leakage was determined through poorly fitted windows having a 3/32 in. crack and clearance. The results of these tests might also well be incorporated in THE GUIDE. It would be up to the designer to establish whether the windows he is concerned with are average in fit or typical of poorly fitted windows. An average fit of windows is easy to obtain by specification and inspection just as is an average good brick wall. There would seem to be no reason for saddling an average window installation with excess radiation just because it is possible to make and install windows of poorer than average fit.