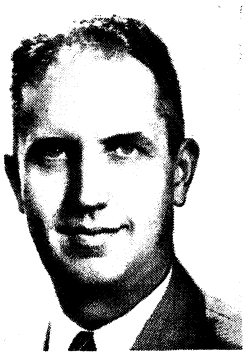

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Infiltration Measurements In Two Research Houses

During the winters of 1959-60 and 1960-61, investigations were made into the energy sources and requirements for residential heating on two residences constructed and instrumented for this purpose. The details of these houses and much of the test results have been presented in several earlier articles.[1,2,3,4]

These research houses were located on adjacent 120 x 135-ft North-South oriented lots in Stillwater, Minnesota, approximately 18 miles east of St. Paul. Except for differences in type and thickness of the wood fiber blanket insulation used, the houses were constructed identically in size, shape, and orientation. A family of four, consisting of two adult males, one adult female and one child, was postulated and the total heat supplied by these occupants simulated through electrical cone heating elements with a portion of the heat translated into a moisture load by the operation of humidifying units. The operation of the refrigerator, range, freezer, television, lights, and miscellaneous electrical appliances were simulated also through the operation of electrical heaters. The electric dishwasher, water heater, clothes washer, and clothes dryer actually were operated, with cycling controlled by a programmer.

The heating requirements for each room of the structures were independently monitored with separate electric resistance heaters, zoned and metered to define the heating demands for each area. Thus, an attempt was made to provide a complete picture of the interplay of the various heating demands and heating losses to which a structure is subjected when placed in the transient environment in which it actually exists.

Quite early, however, it was recognized that although all heat supplied to the residence was carefully recorded for each zone, that both the internal and external environment were carefully and continuously defined, and that the transmission losses for the structure could be accurately determined, one of the least well-defined variables was that of infiltration. Indeed, most of the crackage values reported for various types of windows in the 1961 ASHRAE Guide And Data Book are still based upon measurements and work conducted in the early 1930's. The air change recommendations for use in the simplified method of calculating heating loads are the same today as they were three decades ago. If a designer is to calculate infiltration by crackage computations, it is soon discovered that there are no data reported for new designs of window construction. As a result, the infiltration calculations remain a judicious estimate, at best.

Nevertheless, excellent new research tools have been developed by Dick,[5] Coblentz and Achenbach[6] and limited field studies re-

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despite construction changes which have evolved during the last thirty years since these coefficients were determined. If it is assumed that the awning type window used in the research houses would perform approximately the same as a weatherstripped double-hung wood sash window with storm sash, then, at a wind velocity of ten miles per hr, the crackage coefficient would be 21 cu ft/lin ft of crack per hr. The door coefficient may be taken as 35 cu ft/hr/lin ft of crack. There are 117 ft of window crackage and 40 ft of door crackage on the first floor. If infiltration is assumed through one-half of the total cracks and exfiltration through the other half, then the resulting infiltration is 1928 cu ft/hr, or approximately 0.23 air changes per hr. This compares favorably with the experimented determinations.

The most striking and meaningful tests made were those which showed the effect of operating the shower fan, clothes dryer, and the shower fan and range fan together. One test made on the entire house with the shower fan in operation indicated an air change per hr, corrected to standard condition of 0.53. When the clothes dryer was in operation, the infiltration value, also with the stair doors closed, was 0.58 and with the stair doors open, 0.61. A single test made on House B with both the shower and range fans in operation showed an infiltration rate of 1.41 air changes per hr.

These values may be compared with the actual ventilation fan capacities. In order to determine the air discharge rates of the fans used in these residences, calibrated hot wire anemometer traverses were made. Although the kitchen fan was rated at 450 cfm of air free delivery, the actual discharge under the operating conditions of a closed house and a short connecting duct reduced this capacity to 220 cfm.

The shower fan was rated at 100 cfm free discharge, and under test actually produced 103 cfm discharge. Several traverses were made at different times and the variations in discharge capacity proved to be less than 5% from these figures. The total volume of the first floor and basement of either house was 13,435 cu ft. Thus, operation of the shower fan should produce 0.47 air changes per hr and operation of both shower fan and kitchen fan should produce 1.01 air changes per hr. It would be expected that operation of the fans would dominate the infiltration determinations from the houses, especially when both shower and range fan were in operation. The only infiltration test made under these conditions was Test No. 14 in which the actual air change per hr for the total house was 1.34 and the air change corrected to 10 mph at 40 F temperature differential was 1.41 air changes per hr.

From a practical standpoint, it is evident that with houses as well constructed and tightly weatherstripped as these, and under conditions of no occupancy, the actual air changes per hr ranged well under ½ and can safely be taken as ⅓ under almost all conditions of wind velocity and temperature difference encountered. However, the actual infiltration increased greatly when clothes dryer, shower or range fan was in operation and under these circumstances, a value of ⅓ or even ½ would be too low.

During periods of short duration, with several fans or air discharging appliances in operation at the same time, the rate of infiltration may jump as high or higher than 1½ air changes per hr. With the limited evidence here presented, it would appear that for houses as tightly constructed as these, an air change per hr of ¾ could be safely assumed for design purposes. Additional tests, however, should be made under a wider variety of simulated living conditions and further infiltration studies, such as those currently in progress by the National Bureau of Standards, should be pursued.

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AMERICAN PETROLEUM INSTITUTE SCHEDULES RESEARCH CONFERENCE

New research findings will be presented at the third API Research Conference on Distillate Fuel Combustion, to be held in Chicago, Ill., June 18-19. An activity of the API Oil-Burner Development Committee, the Conference will feature results from the API oil-burner research program plus other research of interest to equipment designers. Engineers representing equipment manufacturers are especially invited to attend and take part in the technical discussions.

Papers scheduled for presentation are as follows: A Practical Ultrasonic Oil Burner, R. R. Perron, J. R. Swanton (Member ASHRAE) and E. E. Shanley, A. D. Little, Inc. Optimization Studies on the Ultrasonic Burner, R. J. Lang, Esso Research & Engineering Co. Some Results from the Study of Ultrasonic and Electrostatic Atomization, R. L. Peskin and R. Raco, Rutgers University. Feasibility of a Vaporizing Burner for No. 2 Heating Oil, G. M. Hein and A. E. Weller, Battelle Memorial Institute. Pre-Combustion Deposits, F. W. Rakowsky and G. H. Meguerian, American Oil Co. The Ignition and Combustion of Drops in Sprays of No. 2 Heating Oil, B. J. Wood, W. A. Rosser, Jr. and H. Wise, Stanford Research Institute. Air-Fuel Mixing and Recirculation as Combustor Design Parameters, R. Kamo, P. W. Cooper and C. W. Solbrig, Armour Research Foundation. Aspiration in Fuel-Oil Combustion, B. R. Walsh, Gulf Research & Development Co. The Application of Available Research Results to the Design of Practical Oil Burners, speaker to be announced, Shell International Petroleum Company, Ltd. (London). NOFI-Sponsored ASA Standards for Equipment Performance, a panel discussion.

sulting from the use of this equipment is already reported in the literature. The gap which exists between the availability of this research tool and the development of an accurate procedure for estimating infiltration requirements in modern-day residences remains to be filled.

In recognition of this gap which existed in attempting to make a complete and comprehensive study of all of the variables affecting demands on these two research residences, it was decided that the only way in which a true measurement of the actual infiltration to the test residences could be determined would be through the helium tracer gas method for determining the air changes. Through the cooperation of P. R. Achenbach and C. W. Coblentz of the National Bureau of Standards, the portable infiltration meter developed by them was lent to the project, and a series of 25 tests was made through the months of January through May 1961 under varying conditions of weather and mechanical operation.

DESCRIPTION OF TEST HOUSES

A detailed description of the test houses has been provided in the earlier articles and only those factors pertinent to the present tests will be related here. The floor plan shown in Fig. 1 presents the location and relative size of the individual rooms. The first floor contains approximately 1100 sq ft of living area and the basement rooms approximately 650 sq ft directly below the bedroom-bath section of the house. The remaining ⅓ of the floor area below the living-dining room area is crawl space. Considerable care was exercised in the application of the insulating materials to the walls, ceilings, and floors to fully utilize the air sealing characteristics of the insulating blanket. All wood windows are welded, double-glass units with a weatherstripped awning type opening sash. North and south-facing windows have a fixed upper sash and a movable lower sash. Two windows located in the west wall are operating awning types. The east wall has no windows. A removable third pane was installed in the sash exterior with clips in all windows as shown in Fig. 2.

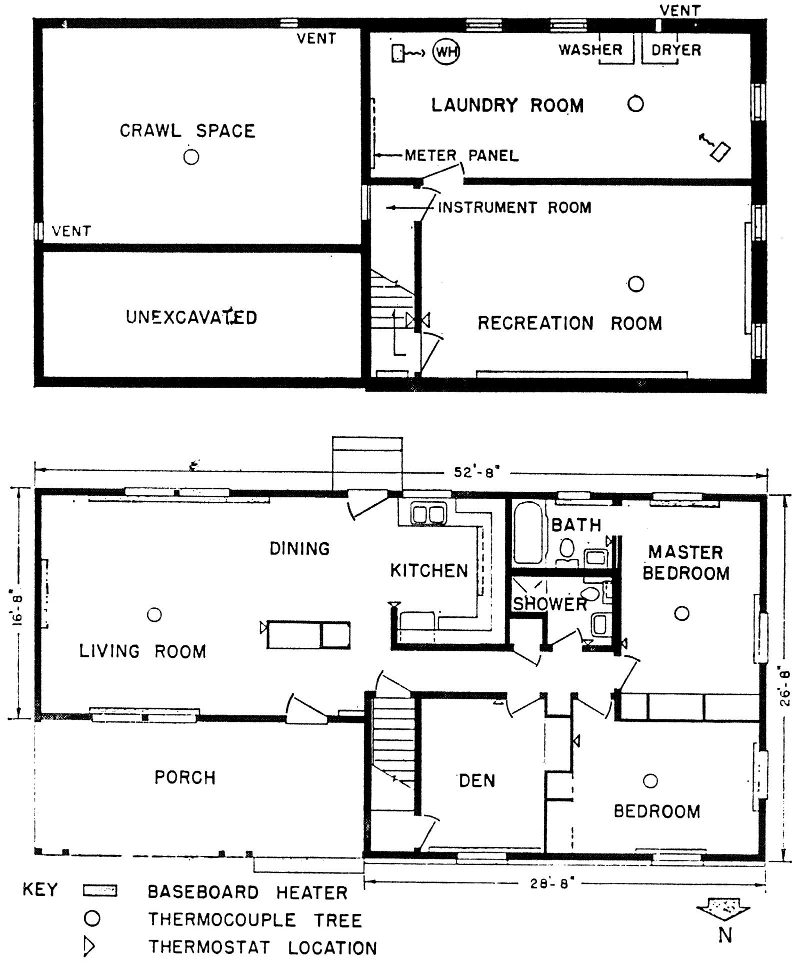

Fig. 1—Plan of first floor and basement

The total window and door areas occupy approximately 15% of the gross wall area. The area, volume, and window and door crack lengths of each room and the volume distribution of the various areas of the house are shown in Table I. Table II provides a summary of the test house construction data indicating the wall, ceiling and floor constructions, as well as thicknesses of wood fiber blanket insulation.

DESCRIPTION OF TEST EQUIPMENT AND PROCEDURE

The National Bureau of Standards portable infiltration meter measures the relative concentration of helium tracer gas injected into the rooms under test, and permits determination of the infiltration-exfiltration air movement by measuring the rate at which this helium concentration decayed. The meter measures the change in concentration of the tracer gas by determining the change in thermal conductivity of the tracer gas-air mixture sampled. Good mixing of the leakage air with the room air is essential to the validity of the tracer gas technique.

Fig. 3 shows the equipment, consisting of the measuring console connected by a 3-conductor cable to 10 sensing probes. Probes were placed in the centers of the main rooms, 3 ft above floor level as shown at the left side of Fig. 3. Helium was introduced into the areas of the house to be tested in an amount sufficient to provide a helium concentration of ½% of the total volume.

The helium was thoroughly mixed with the air by several desk fans located throughout the house. Closets and cupboard doors were opened in order to permit the same rate of gas decay in these places as in the living space. Interior doors leading to the individual rooms were also opened during the majority of the tests, except where

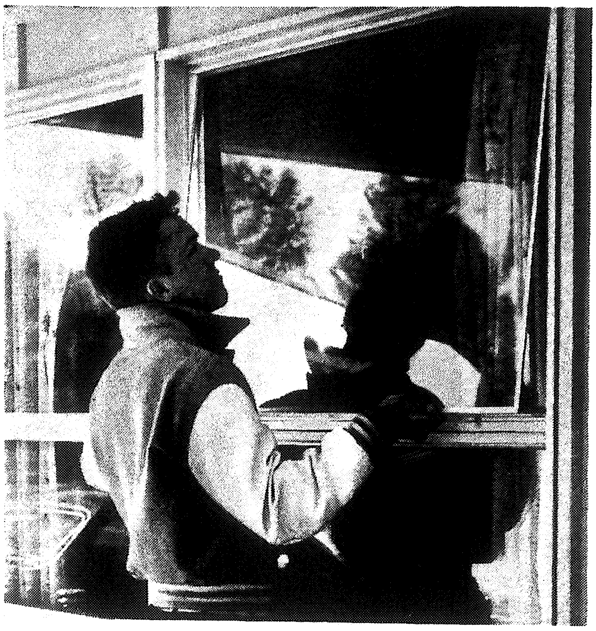

Fig. 2 Installation of third pane of glass

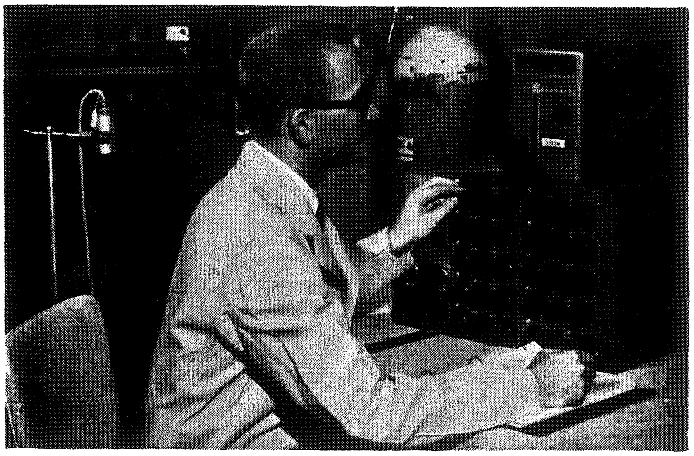

Fig. 3 Portable air infiltration meter console. Sensing probe is shown at left

indicated. Both interior and exterior air temperatures, wind velocity and direction, and solar radiation were recorded continuously during all tests, since a constant thermal environment is preferable during the measuring periods. The total house infiltration rate or air change per hour was determined by the equation:

$$\frac{Kt}{V} = \log_e \left(\frac{c_o}{c} \right) \qquad (1)$$

where

V = volume of the space
c = concentration of tracer gas at time t
K = average volume of air infiltration per unit time for the time interval

TEST RESULTS

Results of these infiltration tests performed on the research houses are recorded in Table III. In total, 18 tests were made in House B and seven in House A under a wide range of outside temperatures, wind velocity and wind direction conditions, and inside operating conditions. The 3rd column of this table presents the average temperature difference between outdoor and inside air, the 4th column the average outdoor wind velocity during the test, and the 5th column the wind direction. The 6th, 7th, 8th and 9th columns of this table define the conditions under which the tests were made.

In some cases, as has been indicated, both stairwell doors leading to the basement were closed and helium was injected only into the first floor rooms. In other cases, the stairwell doors were open and helium was injected into both the first floor area and the basement area. Most of the tests were made under static conditions, that is, with no ventilation from the house by opening or closing of doors or through use of appliances or fans. However, since such conditions are not completely indicative of the dynamic conditions under which a house is operated when people are living in the houses, tests 9, 11, 12 and 14 were made with some ventilation provided through the operation of appliances or ventilation fans.

The 10th, 11th and 12th columns of Table III show the actual test results uncorrected to any standard or common conditions of

Table I Area Volume and Window and Door Crackage of Rooms Used in Infiltration Studies

Room	Area (Sq Ft)	Volume (Cu Ft)	% of Total House Volume	% of First Floor Volume	Window (movable sash) and Door Crack Length (Ft)
Living room ..... Dining room	380	3040	22.6	35.0	(W) 40.8 (D) 20.0
Kitchen	106	848	6.3	9.8	(W) 12.7 (D) 20.0
Hall .... Shower	104	832	6.2	9.6	
SW bedroom .... Bath	202	1616	12.0	18.7	(W) 30.9
NW bedroom	150	1200	8.9	13.8	(W) 21.9
Den	142	1136	8.4	13.1	(W) 10.5
Total First Floor* .	1084	8672		100.00	(W) 116.8 (D) 40.0
Stair well	40	290			
Recreation room .	329	2385	17.8		(W) 14.4
Laundry room ...	288	2088	15.6		(W) 14.4
Total Basement ..	657	4763			(W) 28.8
Total House	1741	13,435	100.0		(W) 145.6 (D) 40.0

* Area based on inside dimensions to outside walls. Volume based on inside dimensions of each room; closets and cabinets not deducted.

temperature or wind velocity. The last of these three columns show the test results for the first floor only for those tests made with the total house under test. These data were calculated by considering only those readings taken in the first floor rooms and disregarding those made in the basement areas.

It is quite difficult to make a valid comparison of the results taken under a variety of temperature difference and wind velocity conditions. Research conducted at the University of Illinois[7] on infiltration into a two-story residence and a one-story residence, both over basements, indicated that the infiltration rate is a function of the temperature difference between the inside and outside air and the wind velocity. Work done at the National Bureau of Standards[8] has suggested the relationship.

$$I = A + BW + CT \qquad (2)$$

where

I = hourly air change rate
W = wind velocity, mph
T = inside-outside temperature difference, F
A = air change rate with no wind and no temperature difference hr^{-1}
B, C = the changes in infiltration rate per unit change in wind velocity and temperature difference, respectively

that an accurate evaluation of these constants requires a more extensive series of tests than is usually possible or than was conducted at the Stillwater project.

However, with the Stillwater residences it is conservative to assume that with the type construction involved the basic infiltration rate, with no wind or no indoor-outdoor temperature difference, was 0.1 air change per hr. Based upon the limited evidence available, the values for the constants B and C have been arbitrarily selected as 0.03 and 0.01, respectively. The observed air change rates have then been corrected to a standard condition defined as 10 mph wind velocity and 40 F temperature difference. The last three columns of Table I present these converted values. It must be emphasized, however, that while these values are more nearly comparable than are the observed values, they must be regarded as approximate only since no accurate determinations have been made of the constants A, B and C.

Table II Test House Construction Data

One-story frame house over ⅔ basement, ⅓ crawl space
Heated first floor area — 1084 sq ft

Walls:
- Wood Shingles with Shingle Backer
- 25/32 in. Insulating Sheathing
- 2 in. x 4 in. Studs
- ½ in. Gypsum Board
- Latex Base Paint

Ceiling:
- ⅜ in. Gypsum Board
- ¾ in. Cross Stripping
- 2 in. x 6 in. Joists

Floor:
- ¾ in. Oak Flooring
- ⅝ in. Plywood
- 2 in. x 10 in. Joists
- ¾ in. Stripping*
- ½ in. Tile*

Insulation: All types shown are Balsam-Wool blankets completely enclosed in liners.

	House A		House B	
	Thickness	Liners	Thickness	Liners
Walls	3⅝ in.	Regular	2 in.	Reflective
Ceiling	5 in.	Reflective	3⅝ in.	Reflective
Floor	2 in.	Regular	1 in.	Reflective

Pitch — 5/12
Ventilation — Two gable vents plus 14 soffit openings
Total area = 521 sq in.

Crawl Space:
Ventilation — Two screen openings
Total area = 111 sq in.

* Only in recreation room.

Basement:
- Full basement under bedroom-kitchen area—650 sq ft
- Crawl space under living-dining room—350 sq ft
- Recreation room walls insulated with ⅝ in. wood fiber insulation applied to 2 in x 2 in. stripping with ½ in. insulating plank interior finish.
- Laundry room has no wall insulation or ceiling tile.
- Exterior walls are 12 in. concrete blocks.

Windows:
Factory manufactured units with weatherstripped awning type wood sash. Double welded glass is mounted in the sash with a third pane attached to the exterior of the sash by means of clips.

Doors:
Wood with storm door (wood and glass).

Heating System:
All first floor and recreation rooms are heated with convection type baseboard electric heating elements. First floor thermostats are low voltage relay type with line voltage control in the recreation room. Two 2000 watt units with individual thermostats were used in the laundry rooms.

DISCUSSION

These tests were planned as an adjunct to the larger project concerned with the integrated effect of temperature, wind conditions, rainfall, snowfall, solar radiation, extraneous internal heat loads, and internal occupancy and habits upon the actual heating demands made upon heating systems. In planning the test program, it was recognized that single variables could be explored with high accuracy but that the expense of constructing multiple buildings, each identical but operated under a single variable, and, further, the need for extensive field information, dictated the programming of a combination of variables despite the more approximate results to be expected. In keeping with this intent of the program, no detailed or extensive infiltration test program could be involved.

Therefore, only a limited number of tests was conducted in

Table III Infiltration Test Data and Calculations

Test No.	House	Temp Difference Indoor to Outdoor	Avg Wind Velocity mph	Wind Direction	Test Conditions: Test on First Floor	Test Conditions: Test on Total House	Test Conditions: Fan Ventilation	Test Conditions: Stair-door Position	Air Changes per Hr: Test Determination: First Floor	Air Changes per Hr: Test Determination: Total House	Air Changes per Hr: Calculated: First Floor	Air Changes per Hr Corrected to 10 mph and 40 F Diff: Test Determination: First Floor	Air Changes per Hr Corrected to 10 mph and 40 F Diff: Test Determination: Total House	Air Changes per Hr Corrected to 10 mph and 40 F Diff: Calculated: First Floor
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	B	40	3	S		X	None	Open		0.13	0.12		0.18	0.16
2	B	30	7	S		X	None	Open		0.23	0.26		0.30	0.34
3	B	27	5	S		X	None	Open		0.14	0.10		0.22	0.15
4	B	31	10	NW		X	None	Open		0.25	0.26		0.28	0.29
5	B	43	9	ENE		X	None	Open		0.18	0.11		0.18	0.11
6	B	64	10	WSW	X		None	Closed	0.34			0.26		
7	B	76	9	S	X		None	Closed	0.51			0.36		
8	B	60	15	ENE	X		None	All doors closed	0.38			0.26		
9	B	37	6	W		X	Shower	Open		0.43			0.53	
10	B	42	12	S		X	None	Closed		0.31	0.27		0.28	0.25
11	B	43	12	S		X	Clothes dryer	Closed		0.65			0.58	
12	B	35	6	S		X	Clothes dryer	Open		0.45			0.61	
13	B	36	11	SE		X	None	Closed		0.39	0.31		0.39	0.31
14	B	30	12	N		X	Shower & range	Closed		1.34			1.41	
15A	A	34	14	NW		X	None	Closed		0.12	0.14		0.11	0.13
16A	A	38	18	NW		X	None	Closed		0.13	0.13		0.10	0.10
17A	A	25	12	S		X	None	Closed		0.20	0.13		0.23	0.15
18A	A	30	14	WNW		X	None	Closed		0.15	0.16		0.15	0.16
19	B	30	14	NNW	X		None	Closed	0.28			0.27		
20	B	5	15	E	X		None	Closed	0.61			0.68		
21	B	14	19	ESE	X		None	Closed	0.34			0.34		
22	B	24	12	W	X		None	Closed	0.15			0.17		
23A	A	22	15	NNW	X		None	Closed	0.16			0.17		
24A	A	18	16	NNW	X		None	Closed	0.22			0.23		
25A	A	16	12	NW	X		None	Closed	0.17			0.22		

order to determine the range of infiltration conditions which might be expected and to determine the significance of this factor in relation to calculation of the entire heating load and analysis of the heating demand. Although it is possible to group the results obtained into a variety of categories and discuss the differences between the average infiltration coefficients so determined, such results would not be statistically significant. For this reason, discussion is limited to broad comparisons.

From an inspection of the air changes per hr, approximately corrected to 10 mph wind velocity and 40 F temperature difference, and under conditions of no ventilation, the infiltration air changes per hr ranged from a minimum of 0.1 to a maximum of 0.4, with but a single exception. This exception occurs in test No. 20 made on House B and shows a corrected air change test value of 0.68. However, it should be noted that the actual temperature difference between the inside and outdoor air for this test was only 5 F, by far the lowest for any test made. Since there are several possible reasons for this single discrepancy in the results, this value is disregarded in the discussions on the basis of its improbability.

As shown in Table III, a number of tests was made with the basement stair doors open and with helium injected throughout the house, including the basement. Under these conditions, it might be expected that any stack effect tending to carry the helium injected into the basement up to the first floor area would be magnified. It would also be expected that infiltration from the first floor would be greater than from the basement as a result of the greater window and door crackage of the first floor.

However, in most cases, the rate of infiltration for the total house was not greatly different than that for the first floor alone. In any event, an insufficient number of tests was made to provide any statistically accurate estimate of magnitude of this effect if it exists. Further, from a practical standpoint, it is seen that it is relatively unimportant whether the corrected air changes varied as much as 0.1 air change per hour.

A similar investigation of the differences between House A and House B was equally indecisive, and although it is probable that slight differences in the tightness of the houses did exist, an insufficient number of tests was available to determine such differences. For example, all tests run on House A on the first floor only, with the stair doors closed and with no fan ventilation, showed only slight differences from similar tests run on House B. The six tests run on House B showed an average air change per hr, corrected to standard conditions of 0.27, while on House A, the three tests showed an average value of 0.21 and the probable error is greater than the differences.

It is possible to make an approximate check on these infiltration determinations by assuming the window and door crackage coefficients as tabulated in the ASHRAE Guide And Data Book. To do so, however, involves an arbitrary selection of coefficients from the values available and the assumption that they are still valid