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Average Infiltration Rates in Residences: Comparison of Electric and Combustion Heating Systems

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ABSTRACT: Research and test results presenting measurements of air infiltration rates in residences are reviewed. In particular, comparison of electric and combustion heating shows (on the average) infiltration rates to be 0.1 to 0.25 higher for residences with combustion heating.

KEY WORDS: infiltration, air exchange, electric heating, combustion heating, energy use

Infiltration is that air which enters a residence from the outside environment via cracks, pores, or whatever openings connect the living area with the outdoor environment. Some infiltration always may be desired as it can provide fresh air for the comfort and health of the occupants. However, in most cases a comparison of the required fresh air for health (in accordance with appropriate standards and in the absence of major sources of pollution) and that naturally infiltrating will show the latter to be more than necessary.

Infiltration beyond that required for providing fresh air is not desirable as it imposes an additional load on the heating or cooling equipment. This is because that outside air has to be either heated or cooled from the outdoor to the indoor conditions. Normally (at design conditions), that additional load is estimated at about 25% of the load attributed to temperature difference (and hence conduction through the walls, roofs, etc.), and for the case of cooling is due also to internal heat gains and solar effects. In the case of well

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insulated residences, the load due to infiltration will be a much higher percentage—in some cases well above 40%.

Infiltration is caused by three phenomena, which are generally coupled together.

The first is the wind. As the wind blows on the outside surface of a building, it causes a pressure difference between the inside and outside and hence a driving pressure gradient across any cracks or pores on the walls, ceilings, or whatever. Generally, the stagnating face (facing upstream) will cause an increase of the outside pressure and hence a pressure difference between the outside and the inside, driving air into the residence. The downstream side, with the predominant wake effects and separation, generally will have a pressure which is lower than the atmospheric pressure and hence a tendency to have air from inside the residence driven to the outside. This is also the case over the roof, where the wind again causes a pressure difference which would drive air from the inside ambient to the outside environment. The pressure distribution across the face of one given surface (that is, roof, wall facing upstream, wall facing downstream, etc.) is essentially uniform due to the bluff geometry of most buildings. This means that the actual distribution of the cracks and openings on a given surface (that is, whether they are all bunched near the edges or all in the midplane) will not affect much the wind-driven infiltration. It is for this reason that fan pressurization or "blower tests" sometimes are used to obtain the "leakage area" of a residence in order to estimate infiltration rates.

A parenthetical comment is in order. Air will not only infiltrate a residence but will also exfiltrate. In the just-cited example, air infiltrates through the windward-facing wall and exfiltrates through the backward-facing wall and roof. The infiltration and exfiltration are such that over time the same mass of air that enters has to leave. Traditionally, volume flow rates have been used as the reference, although strictly speaking mass flow rates should be used. Furthermore, in a purist sense, a more proper expression would be "air exchange rate" (which clearly accounts for both infiltrating and exfiltrating air) rather than simply "infiltration rate."

The second phenomenon driving infiltration is the temperature difference between the inside and outside. It is important, when analyzing this component, to recognize that air is not incompressible. Its density, pressure, and temperature will vary with elevation not only due to "hydrostatic" effects but also due to a "polytropic" process or some similar relationship governing the properties of the air. Different mean temperatures indoors and outdoors then will lead to different pressure distributions with height on the indoor and outdoor faces of the walls (irrespective of the wind effects). These differences can in turn impose a pressure difference across cracks, pores, or whatever openings connect the indoor and outdoor environments. The distribution of these openings along the surface of the wall will obviously affect the infiltration driven by these differences in temperature. The phenomenon is sometimes called the "stack" effect, or the "buoyancy" driven component. The fact that it is so dependent on the location of the openings (not only on the total leakage area) means that it is impossible to quantify the "stack effect" from only a "blower test."

The third phenomenon is an internal-induced phenomenon. Two types are common: the first is induced by a blower with part of its ductwork outside of the living area; the second is a combustion process. Normally, the infiltration rates due to these induced phenomena are treated as additive to the infiltration rates driven by the wind and temperature difference between the indoors and outdoors. A single package heat pump would be a clear example of the first case. Due to cracks in the outside section of the ductwork (as well as in the unit itself), outside air will infiltrate and cause an increase in the inside pressure and hence a balancing increase in the exfiltration—with a net increase in the air changes per hour (ACH). Another example of blower induced infiltration would be systems with a return or supply ductwork in spaces not directly connected with the living quarters. There, the net effect of unavoidable duct leakage would be a similar change in the indoor pressur and a related increase in the infiltration rate. The second effect would be du to any combustion process whatsoever requiring inside air and having th products of combustion exhausted to the outside. This effect can be substan tial. For example, White et al [1] determined that a 23.4-kW (80 000-Btu/h gas furnace [in a mobile home with an inside volume of about 141 m^3 (500 ft^3)] required about 12 L/s (1500 ft^3/h) of combustion air while the furnac was on. Had this air been provided from the inside environment, it woul have led to a substantial increase of 0.3 ACH to the otherwise natural infiltra tion rate.

Infiltration is understood to be that uncontrolled exchange of air between the indoors and the outdoors. The controlled exchange (via kitchen and bathroom exhaust fans, make-up air inlets, open windows, etc.) is considered as a ventilation rate and can be called upon as needed to provide health and comfort. As infiltration is reduced, ventilation rate can be increased and hence controlled. Provision of fresh air by controlled ventilation air through controlled inlets (rather than by infiltration through uncontrolled and multiple openings) permits the use of energy-saving devices such as heat recovery exchangers. These devices are not common yet in residential applications, but their availability to homeowners is coming.

It is obvious, then, that any economical and practical scheme to reduce infiltration rates in residences should be considered. Of first and primary concern is defining the actual levels of infiltration for residences of different types. The U.S. Department of Energy in one of its draft documents simply characterizes infiltration rates as 1.0 for "average" construction, 0.7 for "tight" construction, and 0.4 for "very tight" construction. The Department does this with limited backup data and without differentiating between types of heating systems.

The use of a conventional fossil-fuel-fired system, when compared with an electric system will lead to increases in infiltration rates. This will be due to two factors: (1) the increased leakage paths due to the presence of a chimney protruding generally through the roof; (2) the call for combustion air. Any generalization or analysis on the comparative consumption of residences will have to account for these increases.

The use of sealed combustion furnaces is almost universal in mobile homes (and rare in stick-built homes). In the case of sealed combustion systems, the combustion air would not add to the infiltration. However, the stack itself generally will add measurably to the leakage paths.

In some special installations, the furnace might be located completely outside of the living area. When that is done, the benefits of eliminating the leakage paths through the chimney-roof and the lack of effects of combustion air on infiltration are apparent. However, in this case there will be detrimental effects in that the blower and inherent duct leakages will cause an additional infiltration (as well as the leakage paths for the ductwork-wall), while at the same time none of the furnace jacket losses of thermal energy will be gained by the living area (which is not the case with a furnace at least partially in the living area).

There is a considerable shortage of dependable field data on the comparative infiltration rate of residences heated with either electric or fossil-fuel-fired systems. The essential differences between these systems are obvious from the previous discussion. The need for dependable field data is crucial in any estimate of energy consumption, especially when recalling that the load due to infiltration can be in the order of 25% or more of the total load. (Caffey [*2*] estimates that to be up to 40%; Blomsterberg[2] about 33%, even for tight Swedish homes; Shaw and Tamura [*3*] estimate 20% for electric-heated homes; Warren [*4*], 20 to 40%; Lipschutz et al [*5*] quote a study where infiltration is 25 to 40% of the heating load; Collins [*6*] refers to a study where well-insulated homes showed 35 to 36% of the energy loss through air infiltration under both heating and cooling and 19 and 27% for heating and cooling modes, respectively, in uninsulated houses; Diamond et al [*7*], 28%; and Veenhuizen and Lin [*8*] estimate that 46% of the total heat is lost through infiltration.)

Methods of Measurement

There are two basic test methods employed in the field. One is the blower test, and the other is the tracer gas test.

[2]Blomsterberg, A., "Air Tightness vs Air Infiltration for Swedish Homes—Measurements and Modelling," private communication of a manuscript draft, 1983.

Blower Test

The blower test simply consists of pressurizing or depressurizing the residence with a blower introduced through a sealed opening (such as a window or door) until a predetermined pressure difference between the inside and the outside is reached (in the order of 50 Pa). The blower flow rate necessary to maintain that pressure difference then is measured. With that measurement, one of two things is done: either it is related to an expected infiltration rate (via some calibrating coefficient), or an effective leakage area is determined and then used to estimate infiltration rate. Both methods have major and fundamental shortcomings. First, the measurement with the blower test is never done in the complete absence of wind or temperature differences, hence "smearing" the blower test data. Second, the blower test (in principle) induces a uniform pressure difference through all the external surfaces of the building, while the wind always induces positive differences in some surfaces and negative differences in others and is hence dependent on the geometry of the building (which the blower test is not). Third, and most important, the blower test cannot by itself account for the temperature-driven ("stack") effects as these effects depend not only on leakage areas but very strongly on the distribution of the leakage paths. Fourth, the blower test is not capable of directly determining the induced infiltration rates (that is, due to combustion processes, external ducts, etc.).

The blower test has become popular as it is simple and rapid. A number of authors address themselves to its use, and some acknowledge its shortcomings. The major advantage of the blower test is that it is straightforward and readily permits comparison of "leakage areas" for different buildings. In spite of that, its relationship to actual infiltration rates leaves a lot to question—both in practical aspects as well as physical principles. (The limitations of the blower test, or fan pressurization test, while clearly stated in ASTM standards, sometimes are ignored in published literature.)

Gas Decay Rate (Tracer Gas Test)

The basic principle of the decay gas technique is straightforward: to inject a tracer gas, mix it well in the residence, and measure its decay of concentration with time. (A convenient alternative is to continuously measure tracer added in order to maintain a constant concentration.) That decay will be due to the inlet of fresh air (that is, infiltration). The faster the decay, the higher the infiltration. Without recourse to the simple mathematics governing gradient mass transport, it suffices to state that the slope of the natural log of the average concentration of the tracer in the building when plotted against time gives a measure of the infiltration rate in changes per unit of time.

The complications with the decay gas technique are many. First, inasmuch as the infiltration rate is generally a strong function of wind and temperature, its measure requires simultaneous recording of the weather and the indoor temperatures. Furthermore, a single value of infiltration is not what is required but rather a set of values under different weather conditions. At best, a table or expected functional relationship is obtained, but only after considerable test data are taken to average out test uncertainties. A third complication lies in the need for multiple point sampling of concentration in order to obtain an average concentration. It does not suffice to "bag" samples at some arbitrary location in the building at fixed times after injection of the tracer and to hope from that alone to determine infiltration rates. [An ASTM standard, ASTM Method for Determining Air Leakage Rate by Tracer Dilution Test (E 741-83), recommends procedures to follow while conducting tracer gas tests.]

The most applicable field data, then, are those that result from decay gas measurements: (*a*) taken over sufficiently long time periods, (*b*) with essentially constant wind and temperatures and (*c*) with multiple sampling within the residence (or, at least, in the return duct for forced air systems). These data should be looked upon with the highest credibility in the review of the literature.

Field Data

Some of the current and salient publications providing field data on infiltration rates are listed in the bibliography. Of interest are those references that at least (*a*) compare the effects of different heating systems, (*b*) present effects of retrofitting or (*c*) give representative values.

In quoting published literature, the units reported therein are used. For conversion to SI, mph $\times$ 0.447 = m/s, and temperature difference (DT)(°F)/1.8 = DT(°C) and (°F − 32)/1.8 = °C.

Different Heating Systems

Of primary interest is the comparison of electric and fossil-fuel-fired heating systems. Among the field data permitting that comparison are the following:

Battelle [9]—Part of this report addresses itself to infiltration data. In particular, it refers to Institute of Gas Technology (IGT) data suggesting an excess infiltration rate, ϕ, due to the fossil-fuel-fired furnace, given by ϕ as about 0.5 and equal to

$$\phi = (I \text{ stack open} - I \text{ stack closed})/\text{Chimney flow rate} \qquad (1)$$

The report also reviews some of the models available for infiltration. The Ohio State University (OSU) model fails to effectively account for the location of the furnace; the linear modified Coblentz-Achenbach equation fails to

match quite a bit of the field data; the Lawrence Berkeley Laboratory (LB
model is suggested as an improvement—it is based on an effective leaka
area; the IGT model requires permeability coefficients for each wall type; t
National Research Council (NRC) model does include an effect adding 0.
to 0.40 ACH due to furnace operation (for an extremely limited sample of tv
homes). Finally, Peterson [10] suggests that simply

$$I = A + B(\mathrm{DT}) + C(\mathrm{W}) \quad ($$

where $A = 0.10$, $B = 0.006$ to 0.012, and $C = 0.015$ to 0.030; where DT is
°F and wind (W) in mph. In the case of furnaces, A should increase to at lea
0.20. For instance, at a 15 mph wind and a DT of 40°F, the value of I th
would be between 0.57 and 1.03 for homes without furnaces and 0.67 to 1.
otherwise.

Cole et al [11]—The report refers to data taken at Canton, Ohio, Princ
ton, New Jersey, Columbus, Ohio, and Canada (published in other ref
ences), as well as intensive data taken in a gas-heated, ranch-style home,
well as in other homes tested by IGT. The data for the ranch test home i
cluded a number of runs, some with the furnace on, others with the furna
off (apparently all with the blower on). Comparisons also were made with t
stack closed or open. Averaging some of these data:

Wind, mph	DT, °F	Stack Closed	Stack Open	Furnace On
2 to 3	4 to 18	0.17	0.24	0.34
2 to 3	33 to 55	0.33	0.39	0.53
4 to 7	0 to 14	0.20	0.29	0.41
4 to 7	29 to 56	0.31	0.43	0.53
8 to 11	25 to 37	0.30	0.50	0.57
SIMILAR DATA FOR A TEST HOME AND INDOOR FURNACE				
4	58	0.72	0.77	0.86
8 to 9	48 to 52	0.94	0.70	0.92
15	64	1.03	0.97	1.17
FOR A HOME WITH A FURNACE IN THE GARAGE				
7 to 8	34 to 41	0.50	0.45	...
13 to 15	28 to 37	0.48	0.56	...
FOR ANOTHER FOUR HOMES				
8	21	0.29	0.31	0.35
8	58	0.49	0.81	1.0
13	55	0.45	0.66	0.46
15	55	0.59	...	0.72

Cole et al [12]—This is a rather comprehensive report, with reference
considerable field data. In particular, the study presents decay gas data

three "intensive homes" (one ranch and two 2-story homes) and 20 "extensive" homes. The data for the ranch included infiltration under the condition of open doors, as well as the simulation of an "electric" home when the chimney was closed. (The home was actually heated with a gas furnace.) The following data resulted with the door closed:

DT, °F	W, mph	Blower	Burner	Chimney	Infiltration
50	14	on	on	open	0.51
50	14	on	off	open	0.53
50	14	off	off	open	0.42
50	14	on	off	closed	0.31
50	14	off	off	closed	0.21
38	7	on	on	open	0.47
46	8	on	off	open	0.36
45	5	on	off	open	0.44
44	8	off	off	open	0.39

An additional table compares various readings under different modes. Their averages give:

Blower	Burner	Chimney	Infiltration
Off	off	closed	0.26
Off	off	open	0.45
On	off	open	0.46
On	on	open	0.51

Data also are given for a "northern home," a rather modern home with an aerodynamic design roof, passive solar heating, and a pulse-combustion boiler/fan-coil unit. The following were noted:

Wind, mph	DT(°F)	Infiltration	Conditions
21	26	0.81	solarium closed
15	60	0.66	solarium closed
15	59	0.73	solarium open
15	30	0.51	solarium closed
13	62	0.70	solarium closed
13	28	0.81	solarium open
10	40	0.44	solarium closed
9	29	0.31	solarium open
8	34	0.38	solarium closed

A comparison also was made to find the effect of the fireplace being on. For that case, the infiltration increased from 0.31 to 0.48. Data also are given for the MEDII home, a home with a solar collector for hot water, high levels of insulation, and a balanced-flue, direct-vent, hydronic boiler/fan coil unit for space heating. The unit also had an economizer with a damper with substan tial leakage. The measured values (with the blower off to not include th damper leakage effects) gave:

Wind, mph	DT(°F)	Infiltration
11.8	14	0.27
8.0	13	0.27
6.9	14	0.32
5.8	15	0.35
5.8	1	0.22

Based on what appears as a pretty good model average heating season, in filtration rates are estimated for five different homes in both Washington D.C. and Madison, Wisconsin. Four of these homes (two IGT, one OSU, an one Tamura) were gas heated. One, OSU, has electric heat. The averages fo these simulated homes are:

	Washington, D.C.	Madison, Wisconsin
Four gas	0.46	0.51
One electric	0.39	0.45

Dale et al [13]—Preliminary data in six uninhabited wood-frame, single story modules are presented. Although electrically heated, they simulated "gas-furnace" by venting appropriately (but without including combus tion . . .). The six modules modelled different construction possibilities; th "conservation" one included a vapor barrier as well. At an outdoor tempera ture of −10 to −20°C and winds from 3 to 6 m/s, the following resulted:

Home	Infiltration	Infiltration Flue Blocked
Standard	0.51	...
Short Term	0.52	0.22
Conservation	...	0.08
Passive Solar	0.33	0.12
Solar Liquid	0.42	...
Solar Air	0.42	...

Dickinson et al [14]—The results of metering pre- and postretrofit of 20 houses by Pacific Gas and Electric (PG&E) and 18 houses by the Bonneville Power Administration (BPA) are reported. The only check for infiltration was by the blower test. Little relationship was found between the retrofit action and the change in infiltration rate. The 18 houses tested by BPA were all electric and built between 1945 and 1968; the homes tested by PG&E were all heated with forced-air-natural-gas and were built between 1956 and 1969. A heating season infiltration rate was determined following the LBL model based on the blower data and on a total annual energy use estimated, giving the following averages:

Heating	Energy Use, Pre	kW/year, Post	Expected Seasonal Infiltration	
			Pre Retrofit	Post Retrofit
Electric	18 830	14 980	0.38	0.34
Gas	38 614	34 459	0.49	0.40

Dumont et al [15]—Pressure tests on 176 houses of different types, ages, and contractors are reported. A comparison of the data for different heating systems leads to the following:

Type of Homes	Q/V at 50 Pa
Pre-1945, all gas heat	10.35 (19 home average)
1946 to 1960, all gas heat	4.55 (20 home average)
Post-1960, all gas heat	3.58 (95 home average)
Post-1960, all electric	3.16 (2 home average)
"Low energy," gas heat	1.28 (22 home average)
"Low energy," electric	1.67 (17 home average)
"Low energy," oil	1.88 (1 home average)

NOTE: Q/V = ACH at 50 Pa.

Dumont et al [16]—Measurements on 27 low-energy houses, all equipped with a continuous vapor barrier, are reported. These data include blower tests of airtightness. The pressure test results (in ACH at 50 Pa) gave values as follows:

Heating Type	Range	Average
Electric furnace	1.3 to 4.0	2.2
Electric bunsen burner	0.8 to 3.2	1.9
Gas furnace	0.6 to 3.2	1.9

Two words of caution are in order when comparing the just-cited averages. First, they are not based on actual decay gas data, only on pressurization tests. Second, of the five electric furnace homes tested, all but one had an air-to-air heat exchanger, whereas, of the seven gas-heated homes, five did not have an air-to-air heat exchanger installed. (The average for the two gas homes with an exchanger was 2.0; the average for the five without was 1.8.)

Elkins and Wensman [17]—The infiltration rates in two identical homes, one with electric heat and the other with gas heating, are reported. The data suggest strong dependence on the wind speed and considerably lower val of infiltration rate for the all-electric home. The following table tabula some of the data:

	Temperature, °F	Wind, mph	Infiltration Rate
Home Gas	71	4.2	0.26
	36	6.9	0.62
	43	7.7	0.52
	30	6.8	0.54
	47	9.8	0.67
	5	12.2	0.83
	4	8.2	0.50
	20	8.7	0.44
	38	6.8	0.62
	70	4.5	0.24
	76	6.0	0.44
	35	6.5	0.52
Electric	73	4.8	0.21
	49	5.2	0.36
	86	8.6	0.36
	96	3.2	0.13
	34	5.6	0.31
	24	6.2	0.41
	76	6.1	0.35
	38	6.8	0.42
	28	10.0	0.33
	28	9.0	0.33

The paper suggests a constancy of the ratio of the infiltration to the wind Based on such, the infiltration rate for the gas home is, on the average, abou 1.5 times larger than that for the electric home.

Janssen et al [18]—The measure of infiltration in two homes located i Minneapolis is reported as well as that for five Denver and Kansas Ci homes, all with combustion heating systems. A comparison is made of th levels of infiltration with the furnaces on and with the furnaces off. The da in the table at the top of Page 81 suggest that on the average the infiltrati rate is about 1.25 times higher when the furnace is on. The infiltration ra when the furnace is off with the stack plugged might be about 15% less th when the furnace is off but the stack is not plugged.

Laschober and Healy [19]—Data for the Institute for Building Resear (IBR) hydronic and the warm air-heated test homes (reported in part Bahnfleth et al [*20*]) are thoroughly analyzed proposing governing models. particular, the warm air home is heated in one instance with electric res tance heat (and all flues sealed) and in the other with a gas furnace. Compa son of these data leads to the following values of infiltration measured by

Type of Home[a]	Wind, m/s	Temperature, °C	Infiltration Rate	
			Furnace On	Furnace Off
Tri-level, MN	4 to 6	−6	0.49	0.46[b]
Tri-level, MN	9 to 13	−1	1.07	0.95
Rambler, MN	8 to 14	−8	...	0.30
Rambler, MN	3	6	...	0.24
Two story, Denver	0.7	0	0.95	0.97
Ranch, Denver	1.3	4	0.41	0.44
Tri-level, Denver	1.0	4	0.69	0.58
Tri-level, Denver	0	1	1.19	0.67
Tri-level, Denver	0	5	0.96	0.41
Two story, KC	9 to 13	21	0.48	0.42
Tri-level, KC	1	4	0.47	0.52
Split, KC	0	2	0.74	0.57
Tri-level, KC	0.7	−3	0.75	0.57
Rambler, KC	0.5	1	0.65	0.57

[a] MN = Minnesota; KC = Kansas City.
[b] 0.40 with the stack plugged.

decay gas technique at winds between 10 and 17 mph and at outside temperatures between 13 and 38°F:

1. Electric: 0.61, 0.61, 0.47, 0.70, 0.45, 0.54, 0.64 and 0.67.
2. Gas: 1.01, 0.71, 0.53, 0.78, 0.50, 1.44 and 0.47.

The average values are: for electric—0.59 and for gas—0.78 (1.32 times larger).

Peterson [10]—Based on a partial review of the literature, a rather simplistic approach to determine infiltration rates is given. Values from 0.36 (for tight) to 0.86 (for loose) are suggested as representative (at 20°F and 5 mph). The article also recommends adding 0.10 ACH (or 21% more) to the infiltration rate in gas-heated homes when comparing to equivalent electric-heated homes.

Reeves et al [21]—The Ohio State Electric Power Research Institute (EPRI) data included nine homes and the possibility to compare the effects of gas or electric heating in forced air systems. Even with infiltration rates measured only in the living space (somewhat erroneously excluding the basements where the furnaces were located), an additional 12.5% of infiltration was noted as due to combustion heating.

Shaw and Brown [22]—Results are reported of an experimental evaluation of the effect of a chimney on the infiltration of an unoccupied two-story detached house with a forced air system heated by either gas or resistance heat. Data for the gas-fired system were taken with the burner on, off, and cycling. The chimney was capped while data were taken with the electric heating system. The conclusions, based on the decay gas data alone, are that: the infiltration with the burner on continuously is 10% greater, on the average, than with the burner cycling; switching from an electric furnace to a gas furnace results in a 50% increase in air infiltration (for the test house and with calm winds); the infiltration for the gas furnace showed a dominant stack action (even with winds up to 7 m/s). (The infiltration rates measured ranged from 0.17 to 0.4 ACH.)

Tamura [23]—The earlier air leakage measurements (1960–1962) on two single-story houses are recalled. The houses were both five-room, wood-frame homes with a forced air, oil-fired furnace system. The following table presents some of the data, permitting an estimate of the effect of the furnace operating:

House No.	Infiltration	Furnace	Temperature Difference (°C)	Wind, m/s
1	0.22	off	29.4	1.4
	0.24	off	17.8	3.4
	0.25	off	25.0	4.3
	0.38	off-on	41.7	0.2
	0.41	off-on	35.5	3.8
	0.23	on	21.1	1.7
	0.25	on-off	23.3	3.7
	0.16	damper sealed	19.4	3.2
2	0.42	off	14.4	1.2
	0.39	off	22.8	1.1
	0.50	off	16.6	2.6
	0.39	off	18.3	2.7
	0.45	off	21.6	4.1
	0.25	off	3.3	1.9
	0.63	on-off	25.0	4.6
	0.49	on-off	26.6	3.2
	0.55	on-off-on	33.3	4.6
	0.40	off-on-off	17.8	1.9
	0.24	damper sealed	13.9	0.0
	0.59	off—fireplace damper open	10.0	2.5

The values in this table suggest, for House 1, an average infiltration of 0.24 with the furnace off and 0.32 with the furnace on. Sealing the damper lowers that to 0.16 or so. Similarly, for House 2, the furnace operation changes the average from 0.40 to 0.52, while sealing the barometric damper reduced that to 0.24. These values are extremely crude due to the limited data. But they do suggest an increase in infiltration in the order of 30% due to furnace operation and a substantial decrease when the barometric damper is sealed.

Among related studies, adding some insight into the possible effects of ductwork location, chimneys, dampers, furnace operation, etc. are the following:

Bahnfleth et al [20]—Measurements of infiltration rates in two test homes (the IBR and the warm air homes) are reported. Both homes were gas heated, the first by hydronic means and the second by forced air. The homes were not otherwise identical. Some of the representative data gave:

Home	Tout (°F)[a]	Wind, mph	Infiltration
Hydronic	28	4	0.32
	24	8.5	0.38
	25	13	0.35
Warm air	31.4	5	0.52
	32	9	0.56
	32	12	0.60

[a]Tout means outside temperature.

Blomsterberg [24]—Three comparisons of measured infiltration rates are given for a one-story, three-bedroom Swedish home built in 1977. At an outside temperature of 3.0°C and a light wind, the natural infiltration was noted to be 0.11. With an exhaust fan turned on, that value increased to 0.23, while with the addition of opening slightly a few windows that value increased further to 0.41.

Dickerhoff et al [25]—Thirty-four houses were tested (primarily through a blower test) in Atlanta, Reno, and San Francisco in order to estimate the paths of the leakage. The Atlanta homes also had decay gas tests. Fireplaces with dampers accounted for about 13% of the leakage (37% when the damper was left open), while the ductwork in forced air distribution systems accounted for about 9% of the total. The infiltration measured with the decay gas technique was extremely limited in that the winds were all measured as very low (under 1.5 m/s), and the outside temperatures were generally slightly above the indoor values. Under these conditions, the infiltration rates for six homes with the distribution fan on ranged from 0.29 to 0.92. In particular, the values for three homes with the fan on or sealed gave the following:

Home	Fan On	Fan Sealed
6	0.60	0.23
7	0.92	<0.02
8	0.64	0.41

Etheridge and Phillips [26]—Limited data are presented for a two-story home with a fossil-fuel-fired hydronic system. Data for overall infiltration gave:

Wind, m/s	Temperature (°C)	Infiltration	Comments
2.2	1.7	1.15	furnace on
3.05	4.4	0.90	furnace on
3.86	8.6	0.69	furnace on
4.00	11.1	0.75	furnace off

The dependence on wind is quite erratic. However, a simple average of t data gives infiltration rates of about 0.9 with the furnace on (compared w the single value of 0.75 with the furnace off).

Grimsrud et al [27]—Infiltration data for a Walnut Creek natural g forced-air-heated house are presented. Interestingly, data with the ductw(sealed exhibit an average infiltration rate about 0.7 times smaller than th with the ductwork unsealed. This suggests considerable leakage through t distribution system. Although not suggested by the authors, this leakage expected to be mostly up the stack or through the duct in the attic space.

Guillaume et al [28]—Measurements in six houses built in Belgium in 19 are reported. The homes were apparently designed to be heated with h dronic-gas-fired systems; however, during the tests the homes were heat(with electric space heaters, and the openings to the flues were sealed. A though complete data are not given for all the houses, the conclusions are th the natural infiltration of a 4-m/s wind is about 0.4 to 0.5, while the infiltr tion when the exhaust system was operational gave values considerably in e cess of the flow rate through the fan. (The difference corresponded to tl natural infiltration rate.)

Hartmann and Muhlebach [29]—Data for the EMPA single-family te home are presented. The infiltration rate is shown to satisfy a relationship the form:

$$I = a + b\mathrm{DT} + c\ (\text{wind squared})$$

When the temperatures are in °C and the wind in m/s, the coefficients are a follows:

Condition	a	b	c
Chimney sealed	0.1070	0.0090	0.0059
Chimney flap closed	0.0244	0.0264	0.0056

For the case with the chimney always completely sealed, the typical winter da infiltration rates with winds between 1 and 3 m/s are 0.25 to 0.3 ACH.

Hartmann and Muhlebach [30]—This report presents extensive decay ga and pressurization data in a Swiss residence heated with a hydronic oil-fire(system. Extensive measurements were taken with and without a chimney be ing blocked off. At about a 5-m/s wind and a temperature difference betwee1 10 and 15°C, infiltration rates of about 0.23 were measured with the chimne blocked off, and 0.4 otherwise. In general, the data were found to satisfy a relationship of the form:

$$I = a + b(\Delta \mathrm{T})^{0.8} + c(\mathrm{W})^{1.7}$$

with the coefficients unique to the reference home and its configuration.

Lipschutz et al [5]—Pressurization and decay gas data are presented for twelve energy-efficient homes. None had ducts located outside the heated space, nor did any employ fossil-fuel-fired heating systems. All twelve homes had either woodburning stoves or fireplaces with glass doors. All were equipped with external combustion air inlets. Some of the homes used forced air, some resistance heat, others heat pumps, others radiant resistance heat, and others solar. The "heating season" infiltration rates were estimated to be an average of 0.34 (with a lowest of 0.17 and a highest of 0.49, unrelated to type of heating system). The decay gas measurements were limited to one run per home. All houses except for House H were at wind speeds under 2.6 m/s and with DT under 7°C and gave measurements of 0.09 to 0.27 L/h. House H was tested at 3 m/s and with a DT of 8°C and gave 0.21 ACH. The study also includes the effect of furnace fan operation, estimating the effect of the fan as 0.05 to 0.14 ACH.

Lipschutz et al [31]—Primarily pressurization data for a number of homes are given. In particular, some 59 homes in Rochester, New York, with heating systems identified are compared. For the set of post-1976 homes, the average predicted heating season infiltration rates become: 0.28 for two with electric baseboard heat; 0.37 for eight with electric forced air; 0.47 for five with (central?) heat pump systems, and 0.59 for eleven with gas-fired systems. It must be underscored that the just-mentioned statistics were not based on decay gas data.

Macriss et al [32]—A rather thorough model is presented and verified against a sample of 23 homes. Of interest is the conclusion that on the average the existence of a chimney and furnace burner operation in a home increases infiltration rate losses by almost 20%. The average seasonal air infiltration rates were found to be:

Conditions	Infiltration, Average Seasonal		
	Mean	Min	Max
Burner on	0.67	0.3	1.7
Chimney closed	0.55	0.25	1.25

Sepsy et al [33]—The report is a summary of a long research project. Infiltration models based on data taken in nine different homes are summarized. These models permitted changing the heating systems in two residences from forced-air, gas-heated to electric heating. The changes also were done in the field. The conclusions are that the infiltration rates of the residences were between 12 and 14% higher for gas than for electric heating. These values were obtained without considering the basements in the analysis. In reality, the difference is expected to be more (see also Reeves et al [*21*]).

Shaw [34]—Fan pressurization and decay gas data are correlated. The data used for the comparison are those reported in Shaw and Tamura [*3*], as well as data by Tamura and Wilson [*35*], Kronvall [*36*], and Dumont [*15*]. F(wind speeds of 3.5 to 10 m/s and temperature differences of 20 to 40°C, th spread in the data suggests: for oil-fired furnaces, means of 0.3 to 0.5, rang ing from 0.25 to 0.65; for natural gas heating, means around 0.23; for a electric, values from 0.18 to 0.4; for gas hydronic (but all sealed), values fro 0.2 to 0.3.

Treado et al [37]—Air infiltration and blower tests on a three-bedroo townhouse with a forced air, gas-fired furnace are presented. The house wa an end unit, two-story house built in 1970. With the burner off, average wi ter infiltration rates are estimated to be 0.56. Accounting for the burner, th value becomes 0.717. The data suggest that combustion and draft-diverter a accounts for 21.9% of the air leakage and the blower operation for 7.7%.

Warner [38]—Considerable data in (obviously) prewar dwellings are pr sented. Of relevance might be the comparison between sealed and unseale flues for gas heaters in two flats. The infiltration rates increased from 0.8 and 0.72 to 1.17 to 2.06 ACH.

Effects of Age, Retrofit, or Other Changes

Various studies have attempted to compare the relationship of building ag on infiltration as well as of benefits of retrofit on reduction of infiltration rat

Bassett [*39*] presents pressurization studies on 40 different homes. Th comparison of air change at 50 Pa is made to building age. In Blomsterberg pre-1975 Swedish homes are noted to have natural infiltration rates in th order of 0.23; post-1975, 0.16. Conventional U.S. homes are noted to b about three times leakier. Three test homes were analyzed in more detail an their expected natural infiltration rates at summer conditions (16.6°C, 4. m/s wind) found to be 0.09, 0.12, and 0.14, whereas at winter conditio (−0.6°C, 5.5-m/s wind) the values were 0.13, 0.15, and 0.18 ACH. Blom sterberg and Harrje [*40*] give pressurization and tracer gas data for a numb of houses. The tracer gas data is limited to four townhouses two stories hig all supposedly exposed to a wind of 4 m/s and a DT of 17°C. The measure infiltration rates were 0.38, 0.31, 0.36, and 0.42. On the other hand, an old detached dwelling heated with "warm air" and under the same wind and ter perature is quoted as having a measured infiltration rate of 0.82 (compa with Blomsterberg et al [*41*]). Coblentz and Achenbach [*42*] present data f ten houses, five new (as of 1963) and five 20 to 40 years old, which led to t following decay gas data (adjusted to 10-mph wind and a temperature diffe ence of 40°F):

1. New houses: 0.37, 0.48, 0.48, 0.50, and 0.66.
2. Old houses: 0.62, 0.71, 0.75, 0.86, and 0.99.

Collins [*6*] shows results of 59 metered homes, with supersucker (pressu ization) measurements in 29 of these pre- and postretrofit homes. Two hous also included tracer gas testing before and after retrofit. The comparisons for these two homes gave the following data (the I levels are estimated for 10-mph wind and 40°F difference).

House No.	Infiltration L/h		Induced Infiltration at 25 Pa	
	Pre	Post	Pre	Post
R-15	0.70	0.50	6.7	3.6
R-10	0.45	0.29	6.7	<2.6
R-15 ducts closed	0.33	0.20	...	...

The experiment with the R-15 ductwork sealed shows the effect of isolating the crawl space from the living quarters. The lack of a constant ratio between the measured and "induced" infiltration rates shows the uncertainty of the blower-type test. The major part of the retrofit consisted of caulk and tape. Diamond and Grimsrud [*43*] make reference to measurements (with the blower test) on 50 homes in Rochester, New York (Ryan homes). The average heating season air change was 0.73 for the pre-1976 homes and 0.52 for the post-1976 homes. In Dickinson et al [*44*], a study is reported based on 18 all-electric homes built between 1943 and 1968. The retrofitting consisted of adding insulation, caulking, and in some cases storm doors and windows. The only infiltration-related testing was through a blower test. The retrofitting was done in two phases, with homes in different "cells" according to the type of retrofit. The following heating season air changes (based on blower tests) were noted:

Cell	Prephase I	Postphase I	Prephase II	Postphase II
1	0.42	0.43	0.44	0.32
2	0.35	0.33	...	...
3	0.36	0.33	0.35	0.28

Infiltration rates were measured by E+ Energy Consultants [*45*] in two houses following the decay gas technique, one (A) caulked and the other (B) not. The "bag technique" was used for sampling and analysis. It appears as if both homes were heated with fossil-fuel-fired furnaces. They both had fireplaces—the one in House B was closed 50 min into the test. The average wind during the test was 15 mph with an average ambient of 33°F. The corresponding data for infiltration are quite approximate, in the order of 0.7 for House A and 1.0 to 1.6 for House B. Goldschmidt et al [*46*] and Goldschmidt et al [*47*] present measurements for two mobile homes, both with electric resistance heat but one with sheathing and the other not. At the design winter conditions of −16°C and 6.7 m/s, values of 0.83 and 1.53 ACH are found, whereas the design summer conditions of 32.8°C and 6.7 m/s, values of 0.46 and 0.' ACH are noted. The infiltration at a gas-heated townhouse when the wi was intercepted by an evergreen windbreak was noted by Mattingly et al [4 to be reduced from 1.13 to 0.66 (for a wind of 12.5 mph and a temperatu difference of 32.5°F). The discussion acknowledges that the infiltration ra for electric heating should have been lower.

In Shaw and Tamura [3] data for four detached two-story homes are pr sented. These data include the measure of infiltration rate for two of t homes, one forced air resistance heat, the other forced air, heat-pump he ing. Comparison of blower tests and decay gas tests suggests that these da may be correlated. The monthly averaged infiltration rates for the "standa house" were around 0.25, whereas the "heat pump" house had averag around 0.18 ACH. The "heat pump" house was an upgraded wood fran with additional insulation as well as a vapor barrier. Data taken for the Ci of Seattle Department of Lighting are presented. These data include blow test and decay gas tests on five pre- and postretrofitting homes. The infiltr tion data result in a correlation of coefficients as given in the Sepsy et al rel tionship. For comparison purposes, the values at a 10-mph wind and a ze temperature difference would be about:

Home	Type	Year	Expected Infiltration at 10 mph	
			Pre	Post
1	el. air	49	2.19	1.83
2	baseboard	50	3.03	2.16
3	baseboard	99	1.33	1.14
4	el. air	79	1.25	. . .
5	el. air	23	0.89	0.67

NOTE: El. air = electric forced air.

Representative Values

In addition to the data already summarized in the preceding sections, da also are presented by the following:

Biggs[3]—Measurements in the Australia Commonwealth Scientific and I dustries Research Organization (CSIRO) "Low Energy House" (that is, ful. solar) show infiltration rates in the order of 1.0 for winds of about 6 m/s an in the order of 0.5 for winds of 2 m/s. On a separate and ongoing stud infiltration data for two houses and pressurization data for a total of 1

[3]Biggs, K. L., private communication, 1983.

houses, some solar and others supposedly gas heated, are compared. The infiltration data for two homes, both solar, suggest levels in the order of 0.4 for calm winds and 0.8 to 1.0 for winds around 3 m/s.

Blomsterberg et al [41]—The paper refers to earlier infiltration rate measurements taken at Princeton and in California. These values were as follows:

House	Average I	Wind, m/s	DT (°C)	Comments
NJ	0.37	4	17	two-story townhouse basement
NJ	0.4 to 0.6	4	17	detached, 1.5 to 2 stories
Ca-Da1	0.31	2.1	6	one-story, detached taped vents
Ca-Da2	0.64	4.5	9	one-story, detached taped vents
Ca-Ha1	0.18	2.8	13	one-story, detached taped vents
Ca-Ha2	0.17	2.8	9	fireplace and kitchen vents open
Ca-Ha3	0.21	2.0	9	all vents open

Caffey [2]—The "supersucker" is described, and the results of its use in measuring the leakage in some 50 homes are reported. Infiltration rates were estimated as one fourth of the value measured with the blower test. For tighter homes, values in the order of 0.35 to 0.5 are suggested as adequate.

Etheridge et al [49]—Data presented include a measure of the natural infiltration rates in a four-bedroom, 1967 test home. The home has a hydronic heating system with a gas-fired, room-sealed boiler. The natural infiltration rate was measured with and without sealing the doors and windows and found to be essentially unchanged. At wind speeds of 5 m/s, the infiltration rates were about 1.5, whereas at 3 m/s they were closer to 0.8 ACH.

De Gids [50]—The report includes data for three homes; two were two-story dwellings and the third was a flat. The data include the air change rate with windows closed (and for one house with open windows as well) as well as pressure differences and blower test data. The homes were occupied and undetached, and apparently all had flues and were heated with gas-fired boilers. The decay gas data for the single-family houses are similar: infiltration rates in the order of 0.8 to 1.0 at calm winds, in the order of 0.8 to 1.3 at 5 m/s, and 1.0 to 1.8 at 10 m/s. Surprisingly, the flat exhibited little dependence on wind velocity, with an infiltration rate in the order of 0.3.

Goldschmidt and Wilhelm [51]—Measurements in a mobile home are recalled. The home had electric resistance heat and caulking. The measured infiltration (over a 16-month period) is seen to satisfy a relationship of the type

$$I = 0.034 + 599\ \mathrm{DT}/(T_i T_o) + 2.9\ \mathrm{W}/T_o,$$

where the wind is in m/s and the temperatures are in degrees Kelvin. (T_i is the indoor temperature, T_o outdoor, and $\mathrm{DT} = |T_i - T_o|$.)

Graham and Sulatisky [52]—Pressurization tests on 24 houses are reported. Four of the houses had electric baseboard heat; all the others h: electric forced air. The homes were all bungalows with an average floor ar of 100 m^2. The effective leakage areas were seen to vary from 440 to 750 cr for houses built by one contractor and from 690 to 1110 cm^2 for houses bu by the other contractors. There was no notable difference between forced : and baseboard heating (when comparing effective leakage areas). It is of i terest that a plot of consumption (in terms of kW/DD) showed no correlati to the effective leakage area [even though consumptions varied from 2.1 to 4 kW/degree day (DD)].

Grimsrud et al [53]—A survey is made for over 300 houses, determining : average heating season air change based on blower data or on decay gas dat The histogram of the air change results shows a mean of 0.63 and a median 0.50.

Grot and Clark [54]—Measurements for 266 homes are given, which i clude both tracer gas (using bag samples) and pressurization tests. There little correlation between the two types of tests.

Although the sample included 62% natural gas heating, 20% oil, 14% pr pane, 3% electricity, and 1% kerosene, no comparison is made between tho types of systems. The data for infiltration rate do not permit a correlatic with weather (it appears as if weather was not measured); however, for th entire data set, it has 19% measurements of infiltration rate to under 0.: 40% between 0.5 and 1.0, 20% between 1.0 and 1.5, and 20% above 2.0. (direct quote from the conclusions; there must be a typo in the last numbe 1.5 instead of 2.0.)

Hartmann et al [55]—Measurement of infiltration with tracer gas tecl niques in apartment buildings with different window openings is reported. A apartments were nonair-conditioned. Even small window openings greatly ir creased the infiltration rate. All the units tested were apartments withi larger buildings. The following data were the results (with windows closed,

Building	Wind, m/s	DT, °C	Infiltration, L/h
A	1.2	17	0.09
	3.5	20.5	0.17
	5.5	14.5	0.2
C	1.3	19.5	0.06
	2.0	11.5	0.07
D	2.2	12.5	0.33
	8.5	17.0	0.97
	8.5	14.0	1.12
E	2.0	3.0	0.63
	2.5	1.5	0.68
	4.5	17.5	0.67
F	1.0	16.5	0.42
	0.7	15.5	0.49
	1.5	18.0	0.72

(continued)

Building	Wind, m/s	DT, °C	Infiltration, L/h
G	2.2	3.5	0.23
	0.6	14.0	0.26
H	1.1	4.0	0.13
	1.2	9.0	0.55
	3.4	12.5	0.86
I	2.4	7.0	0.42
	2.8	8.5	0.52
	4.0	8.0	0.6
K	1.2	13.0	0.35
	0.8	17.0	0.44

Jordan et al [56]—Data for two test homes, both heated with baseboard electric heating units, are presented. For the total house, infiltration rates in the order of 0.18 to 0.30 were estimated at 40°F and 10 mph wind with the stair door to the basement open in House B, and 0.10 to 0.23 with the stair door closed in Test House A.

Kronvall [36]—Data on pressure tests for 29 homes are given. From these data, (doubtful) infiltration levels ranging from 0.06 to 0.41 are obtained.

Nusgens and Guillaume [57]—Measurements in three single-family houses are given. Two were parts of a duplex; the third was a detached building. The measurements in the duplex (its heating system is not described) were primarily room by room. The global infiltration rate for one of these houses is given as 0.47 at a wind velocity of 2 m/s. The following data are given:

Wind velocity, m/s	1.0	1.6	1.7	1.9	2.5
Infiltration rate	0.32	0.50	0.36	0.46	0.68

The third house definitively had a forced air, heat-pump-driven system. The heat pump was in the basement, connected to the garage with a poorly sealed door. The following data are given for the total infiltration rates:

Wind, m/s	2.3	3.5	4.4	4.8	4.0	7.3
Infiltration	0.14[a]	0.05[a]	0.19[a]	0.17[a]	1.20	0.61

[a]Corresponds to data with the air vents covered.

Potter [58]—Data based on decay gas measurements are given for a three-story home with a gas-fired, hydronic heating system. Unfortunately, the operating temperatures are not noted. However, it appears as if for calm winds the infiltration rate would be around 0.37 ACH, whereas at 6 m/s it could be as high as 1.5 and at 4 m/s between 0.5 and 1.1 ACH.

Sherman and Grimsrud [59]—Data for 15 different homes are quoted, an the results from pressurization tests and tracer gas tests compared. Diffe ences in the order of 40% are noted. The decay gas data do not explicit include the operating temperatures and wind velocities, however, the data c include a description of the homes. The following results (leakage areas are square centimetres):

Home Reference	Infiltration	Leakage Area	Comments
Ivanhoe	0.1 to 0.12	100	solar sealed wood stove
Nogal	0.22	960	solar, forced air
Telemark	0.08 to 0.13	140	radiant oil space heating and wood stove
Torey Pines	0.31 to 0.42	200	solar water greenhouse
R-10	0.45	330	baseboard electric resistance
T-1	0.16 to 0.23	330	fireplace, forced air
T-2	0.11 to 0.46	680	fireplace, forced air
Haven	0.21 to 0.37	770	fireplace, forced air
Purdue	0.50 to 0.69	855	fireplace, forced air
Neilson	0.64 to 1.36	1275	fireplace (undampered), furnace
V1	0.31 to 0.33	560	solar, wood stove
V2	0.29 to 0.64	630	solar, wood stove
Fels	0.68 to 0.76	1480	forced air
San Carlos	0.62 to 1.02	845	fireplace (undampered), furnace
Southampton	0.19 to 0.31	1640	fireplace, forced air

In order to properly interpret the just-cited values, it is necessary to go to th original references. The fact that undampered fireplaces are so noted implie that the others were dampered. The data also suggest that the heating system were most likely not operating during the testing.

Stewart et al [60]—Data, including decay gas data, are presented for thre unoccupied test houses. All houses were heated with a forced air resistanc heating system and were identical except for levels of insulation (and equip ment sizing). The data are summarized via a fit to the modified Reeve McBride, and Sepsy [*21*] model where:

$$I = A + B \text{ (square root of } P)$$

where P is the sum of the theoretical wind and stack pressures in Pascals. Th values in the table on the top of Page 93 are found. Although not indicated i the report, it appears as if the infiltration rate (as measured by the decay ga technique) is slightly higher for the noninsulated home. (Pressurization test also confirmed this.) On the average, at a pressure of 50 Pa, the infiltratio rate would be about 0.5.

	Most Insulated	Some Insulation	No Insulation
		SUMMER 1978	
A	0.282	. . .	0.195
B	0.037	. . .	0.055
		WINTER 1978–1979	
A	. . .	0.195	0.263
B	. . .	0.041	0.094
		SUMMER 1979	
A	0.129	0.151	0.157
B	0.038	0.035	0.045

Warren [4]—Preliminary results of natural ventilation in six houses are given at what is called "mean speed." Homes with flues (H and J) had these sealed. The following is found:

House Type	Year Built	Infiltration at Mean Speed
C—3-bedroom end terr	1972	1.25
D—3-bedroom semidetached	1971	0.55
F—3-bedroom end terr	1975	1.35
G—4-bedroom end terr	1975	0.80
H—3-bedroom semidetached	1957	0.30
J—3-bedroom semidetached	1957	0.50

Incidentally, direct comparison of blower test data and decay gas data is made in a few of the references. Among them: Warren and Webb [*68*] (not cited), Collins [*6*] (who suggests an uncertainty in the blower type test), Hartmann and Muhlebach [*30*], Lipschutz et al [*5*], Shaw [*34*], and Shaw and Tamura [*3*]. (For a description of the blower test itself, see Diamond et al [*7*].)

A few of the references in the bibliography include the same data. For instance, Bilsborrow [*61*] used Tamura and Wilson's [*35*] data, which in turn is reported in Tamura [*23*]. Dickinson et al [*14*] present essentially the same data as Grimsrud et al [*62*] presented earlier in Krinkel et al [*63*]. The base data of Sherman [*64*] is also in Sherman and Grimsrud [*59*] and Sherman and Grimsrud [*65*], which Sherman et al [*66*] and Modera et al [*67*] report.

Conclusions

The implications of the literature review are the following:

1. The infiltration rates are dependent on wind and temperature.
2. Seasonal average values, in the order of 0.4 to 1.0, might be descriptive and adequate for estimates of energy consumption, but these are not the same

as the design values, which should be used for sizing of heating, ventilating and air-conditioning (HVAC) equipment.

3. There is a notable increase in the infiltration rate when combustio heating is used instead of electric resistance heating.

4. There is some increase in the infiltration rate when air distribution sys tems have the blowers on compared with the blowers off.

5. The pressurization data by themselves are limited; they do not readil lead to an estimate of infiltration rate, nor do they directly give a measure o the stack effects.

6. Many researchers fail to provide sufficient field data to permit genera izations. In many instances, the governing weather parameters are not wel defined.

7. There is some lack of consistency in the models proposed by the variou investigators.

Of particular interest is the estimate of the expected increase in the infiltr tion rate attributed to the use of combustion heating instead of electric resi tance heating. A few studies permit that estimate by either (*a*) using compar ble homes with different heating systems, (*b*) using one home in whic different systems are compared, or (*c*) testing with the burner off and th stack sealed in a home with combustion heating. The following can be o tained:

Reference	Increase in Infiltration Air Changes	Increase, %	Comments
Battelle [*9*]	0.10	...	...
Cole et al [*12*]	0.25	100	measured
Cole et al [*11*]	0.21	80	averages, ranch home
	0.09	10	averages, test home
	0.23	51	three-home averages
Dale et al [*13*]	0.25	60	simulated flue
Dickinson [*14*]	0.11	29	large sample averages, preretro
Dickinson [*14*]	0.06	18	large sample averages, postretr
Elkins and Wensman [*17*]	0.20	62	averages, two homes
Janssen et al [*18*]	0.09	22	same home, one data
Laschober and Healy [*19*]	0.19	27	same home, averages
Macriss et al [*32*]	0.12	22	...
Peterson [*10*]	0.10	21	...
Reeves et al [*21*]	...	12.5	living area only
Shaw and Brown [*22*]	0.10	50	same home
Tamura [*23*]	0.16	100	same house

The increase in infiltration rate ranges from 0.1 to 0.25 ACH. This can explained well (in most part) by the additional requirement of combusti air. The estimates of 0.1 to 0.25 additional changes per hour generally account for the fact that the furnace will not be running continuously but will cycle on and off according to the load.

Recommendations

The data available suggest that the type of ducts and the type of heating system (and its location) will affect the infiltration rate. Any estimates at that increase are exactly that—estimates. Further field data are needed to compare the infiltration performance of different HVAC systems.

When using heating systems that are expected to cause different infiltration levels in otherwise similar homes, such differences should be accounted for. If seasonal design ACH 0.4, 0.7, and 1.0 are used for "very tight," "tight," and "average" construction homes without a combustion process, and hence without a chimney, then the representative infiltration rates for combustion heating with a chimney should be increased to no less than 0.5, 0.9, and 1.2 for "very tight," "tight," and "average-type" construction, respectively. Presently computer programs, such as DOE2, do not properly account for these changes in the infiltration load with type of heating system. These changes should be incorporated into any analysis of expected building performance.

Acknowledgments

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