PREDICTION AND MEASUREMENT OF INFILTRATION IN RESIDENTIAL BUILDINGS:
In Application to a Construction Quality Standard

D.T. Grimsrud, M.H. Sherman, R.C. Sonderegger

Lawrence Berkeley Laboratory
University of California
Berkeley, Ca., 94720
U.S.A.

SUMMARY

An acceptable ventilation rate for residential structures must satisfy the competing demands of minimizing energy loads while assuring adequate indoor air quality. Even if an optimal ventilation rate were established, there currently exists no well-defined procedure that allows a designer or builder to predetermine a target ventilation rate for a house, nor to verify that a house meets a particular ventilation standard. This paper describes the application of a model that relates infiltration to a quantity called the effective leakage area. This quantity scales the infiltration to local weather conditions and major design features of the house. We have used this model to calculate the ratio of infiltration to leakage area averaged over the heating season, for a large number of sites in the United States. We believe this model provides, among others things, an effective tool for builders and designers who need a rational basis for assessing compliance with construction quality standards.

RESUME

Un taux de ventilation acceptable pour des structures residentielles doit repondre aussi bien au critere de minimisation des charges energetiques ainsi qu'au critere rival concernant une qualite adequate de l'air interieur. Meme dans l'hypothese ou un taux optimal de ventilation serait defini, il n'existe pas actuellement de procedure bien definie qui permette aux constucteurs

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de predeterminer un objectif relatif au taux de ventilation pour une maison donnee, ainsi que de verifier que la maison repond a telle ou telle norme de ventilation. Ce papier decrit l'application d'un modele qui relie l'infiltration a une quantite appelee surface de fuite effective. Cette quantite represente l' infiltration en tenant en compte des conditions climatiques et des principales caracteristiques propres a la maison consideree. Nous avons utilise ce modele pour calculer le rapport d'infiltration sur la surface de fuite moyennee pour la duree de la periode de chauffage, pour un nombre eleve de villes des Etats-Unis. Nous pensons que ce modele constitue, entre autres, un outil effectif pour les bureaux d'etudes et les constructeurs en vue de leur fournir une base rationnelle pour une estimation conforme aux normes de qualite de construction.

1 INTRODUCTION

Construction quality is becoming an increasingly important concept in the building industry in North America. As materials, time and energy become more scarce, steps are being taken to use each more efficiently. This paper focuses on energy efficiency improvements associated with construction quality and reducing air leakage in buildings. In particular we concentrate on small buildings whose energy use is dominated by the thermal performance of its external envelope.

As we move toward a more energy-efficient economy throughout North America, construction practices and construction quality are being increasingly scrutinized. In the building sector, particularly in residential buildings, the potential for energy savings is great, and can be largely realized through the relatively simple practice of reducing the amount of air leakage or infiltration in the structures. Reducing air leakage carries with it several benefits: in addition to reducing energy use, it increases thermal comfort, improves control of moisture migration that results from the convective flow of vapor through openings in the building shell, and it reduces noise transmission from the exterior into the occupied portions of the building. On the other hand, there are potential problems attendant to increasing building tightness that must be addressed. Reducing air leakage reduces infiltration the most common source of ventilation air that normally serves to dilute undesirable airborne contaminants found within the living/working space; that is, while infiltration itself cannot cause an indoor air quality problem, decreasing the total ventilation rate can aggrievate an existing one.

To assure that changes in building practice or construction quality in the interests of energy-efficiency are not obtained at the expense of human health and safety, it is important that ventilation standards be based on reliable data verifying that reduced infiltration deos not seriously compromise indoor air quality. At present, the only recognized ventilation standard available in North America is ASHRAE Standard 62-81[1]. This prescribes ventilation values in single-family residences of 5 l/s per room [10 cfm per room] independent of room size. In addition, 50 l/s [100 cfm] spot ventilation is required for kitchens for intermittent use (as required) while 25 l/s [50 cfm] ventilation capacity is required for bath and toilet rooms.

For a standard reference house having a floor area of 140 m^2 [1500 ft^2] and seven rooms, Standard 62-81 prescribes a nominal ventilation rate of 125 m^3/hr [70 cfm] without the use of task ventilation fans. If the house has a standard 2.5 m [8 ft] ceiling, this translates into an air change rate of 0.37 air changes per hour (ach). Occupancy effects may add 0.10 to 0.15 ach, yielding a total ventilation rate of 0.47 to 0.52 ach for this particular house.

We have now compiled sufficient field data demonstrating that infiltration can be reduced without adversely affecting indoor air quality, very high ventilation rates do not always assure adequate indoor air quality in buildings where indoor pollution sources are unusually high. The range of infiltration rates in U.S. housing span an order of magnitude (i.e. from a minimum of 0.1 to 0.2 to a maximum of 1.0 to 2.0 ach); on the other hand the range of relative pollutant source strengths may span three orders of magnitude[2]. In some areas infiltration rates have been high while indoor air quality has been poor [3] and in some areas infiltration rates have been quite low without any indication of indoor air quality problems [4]. In other words, the issue of pollutant source strength may well dominate any assessment of indoor air quality. In any case, measurements are essential if doubts about air quality exists.

Despite this, the authors feel that the source strength problem should not delay the introduction of a construction quality standard for air leakage in buildings. Recent research in infiltration and air leakage has produced a simplified test procedure for the measurement of air leakage characteristics of a structure, and its relation to the average infiltration. It is critical that a compliance test for a construction quality standard be simple; it is equally essential that its results can be interpreted in terms of naturally occuring air infiltration. The importance of this interpretation is illustrated below by several procedures that designers and builders can use to interpret air leakage measurements. The degree of cooperation and understanding can be achieved if all parties are satisfied that the standard is consistent with existing good building practice, that it adequately addresses issues of human safety and comfort, and that it contains adequate procedures for verification and interpretation.

2 CONSTRUCTION QUALITY AND EXISTING BUILDING PRACTICE

We have collected measurements of average infiltration rates for the heating season in more than 300 houses in the United States and Canada in an effort to assess average infiltration rates. The median value of the infiltration rate averaged over the entire heating season was 0.52 ach; fifty percent of the houses in the sample had average values between 0.41 and 0.72 ach. These values are calculations based upon fan pressurization measurements of the air leakage of the houses. In this technique, no

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allowance is made for the impact an occupant has on the total ventilation rate of the house. We estimate this to be approximately 0.10 to 0.15 ach. Therefore, the median value of the total ventilation rate of these houses will have a median value of approximately 0.67 ach.

In small, envelope-dominated buildings the major ventilation source is infiltration. If these buildings are tightened to meet a construction quality standard, either additional mechanical ventilation must be provided or else measurements must be made to show that the infiltration remaining is adequate to supply the necessary ventilation.

3 VERIFICATION TECHNIQUES

The fan pressurization technique, recently incorporated into ASTM Standard E 779-81[5], provides a measurement of air tightness that can be used, along with climate and siting data, to predict the infiltration.

The fan pressurization technique is fairly common and requires but a brief description. A fan mounted on an adjustable wooden plate is sealed into a doorway of the house to be tested. The fan speed, which can be adjusted using a DC motor and controller, is varied to produce a pressure drop, ΔP, across the building envelope. The flow through the fan is measured and the process repeated for fixed pressure increments to produce a curve relating the pressure drop across the envelope to the flow required to produce it. With fan direction reversed, a corresponding curve of depressurization versus flow can be obtained in the same manner.

While pressurization measurements are common, the manner in which the data is reported differs widely. One procedure used for reporting total leakage of a building stem from the observation that the leakage characteristic of a building can usually be represented by a power law:

$$Q = C\,\Delta P^{n} \qquad (1)$$

where: Q is the volume flow rate of the fan [m^3/s],
C is a constant,
ΔP is the absolute value of the pressure drop across the building envelope [Pa], and
n is an exponent in the range $0.5 < n < 1.0$.

The constant C may also be interpreted as the flow at 1 Pa pressure, a practice followed in the Netherlands and in Japan.

Another technique seeks to determine the effective leakage area of the structure from fan pressurization. It is this technique that is the basis of a model we have developed for predicting natural infiltration from air leakage and weather data [6]. In this approach the flow characteristics of the building are measured and the results are expressed using Eq (1), above. The flow at 4 pascals, Q(4), is then computed. A particular flow model is now invoked to compute the effective leakage area of the structure. An assumption is made that in the low pressure regime of

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approximately 4 pascals (a pressure typical of the pressures that drive natural infiltration) the pressure-flow relationship has the form of inviscid flow through large openings, i.e.

$$Q = L\sqrt{\frac{2}{\rho}\Delta P} \qquad \text{for } \Delta P \simeq 4 \text{ Pa} \tag{2}$$

where: L is the effective leakage area [m^2], and
ρ is the density of air [kg/m^3].
ΔP is the absolute value of the pressure drop across the building envelope [Pa] , and
n is an exponent in the range $0.5 < n < 1.0$.

This model, which has been extensively validated at the Lawrence Berkeley Laboratory[7], is the key element that allows the inclusion of fan pressurization measurements in an energy audit to predict infiltration values. Briefly, the model combines the effective leakage area, L, with parameters associated with the house and the local weather conditions to predict the infiltration, Q.

$$Q = \sqrt{Q^2_{stack} + Q^2_{wind} + Q^2_{mech}} \tag{3}$$

where: Q is the total infiltration [m^3/s],
Q_{stack} is the stack induced infiltration,
Q_{wind} is the wind induced infiltration and
Q_{mech} is the infiltration induced by mechanical systems.

Both weather induced infiltration terms (i.e. wind and stack) are linearly proportional to the measured leakage area. For a detailed explanation of the model see the references 6 and 7.

4 APPLICATION OF INFILTRATION MODEL — THE REFERENCE HOUSE

We have developed a procedure, based on this infiltration model, that is simple enough to be used by persons with relatively little technical training. Here we will show its application to a reference house in reference surroundings. Our reference house is a single-story building (height = 2.5 m) with average leakage distribution (i.e., ceiling and floor leakage areas together are equal to the wall leakage area). By reference surroundings we mean rural or open sub-urban areas with low buildings and trees and some obstructions within two house heights.

It is useful at this point to introduce the term specific infiltration, which is the infiltration divided by the effective leakage area. To obtain numerical values of convenient size, the units used for infiltration are m^3/hr while those for effective leakage area are cm^2. (A strict SI formalism would require the infiltration to be in m^3/s the leakage area to be in square meters and the specific infiltration to be in meters per second; to obtain specific infiltration in SI units, divide our specific infiltration by .36.)

If auditors know the value of the specific infiltration for a reference house for that location, they need only multiply the specific infiltration by the measured effective leakage area to find the predicted infiltration. We have calculated monthly values of specific infiltration for the reference house in reference surroundings for 59 cities, using weather tapes for Test Reference Years (TRY-tapes). Table 1 shows seasonal averages (November through March) of wind and stack components as well as total specific infiltration.

TABLE 1: HEATING SEASON SPECIFIC INFILTRATION IN 59 U.S. CITIES ($m^3/hr/cm^2$)

City	$\frac{Q_{stack}}{L}$	$\frac{Q_{wind}}{L}$	$\frac{Q}{L}$	City	$\frac{Q_{stack}}{L}$	$\frac{Q_{wind}}{L}$	$\frac{Q}{L}$
Albany	.21	.23	.31	Medford	.18	.10	.21
Albuquerque	.18	.17	.24	Memphis	.15	.21	.26
Amarillo	.17	.30	.35	Miami	.00	.20	.20
Atlanta	.15	.22	.26	Minneapolis	.23	.23	.32
Bismarck	.24	.23	.33	Nashville	.16	.22	.27
Boise	.19	.20	.27	New Orleans	.12	.22	.25
Boston	.19	.32	.37	New York	.17	.27	.32
Brownsville	.05	.26	.27	Norfolk	.15	.26	.31
Buffalo	.20	.29	.35	Oklahoma Ci.	.17	.32	.36
Burlington	.21	.22	.31	Omaha	.20	.23	.31
Charleston	.13	.21	.25	Philadelphia	.18	.26	.32
Cheyenne	.20	.29	.35	Phoenix	.12	.10	.16
Chicago	.19	.22	.29	Pittsburgh	.19	.19	.27
Cincinnati	.18	.20	.27	Raleigh	.16	.21	.26
Cleveland	.20	.25	.32	Richmond	.18	.19	.26
Columbia	.18	.22	.29	Sacramento	.16	.14	.21
Detroit	.20	.26	.33	Salt Lake C.	.20	.18	.27
Dodge City	.19	.29	.35	San Antonio	.12	.21	.25
El Paso	.15	.19	.24	San Diego	.11	.15	.19
Fort Worth	.14	.25	.29	S. Francisco	.14	.19	.24
Fresno	.14	.12	.19	Seattle	.17	.22	.28
Great Falls	.21	.36	.42	St. Louis	.19	.24	.30
Houston	.12	.25	.27	Tampa	.06	.21	.21
Indianapol	.19	.24	.31	Tulsa	.16	.24	.29
Kansas City	.19	.23	.30	Washing. DC	.17	.17	.24
Lake Charles	.12	.21	.24	Jacksonville	.10	.20	.23
Los Angeles	.11	.17	.20	Jackson MS	.14	.22	.26
Louisville	.18	.23	.29	Portland ME	.21	.19	.28
Lubbock	.16	.30	.34	Portland OR	.17	.23	.29
Madison	.21	.21	.30				

It is interesting to note that the variation in infiltration per-unit-leakage area across the U.S. is relatively small for this reference case. Fifty percent of the specific infiltration values for the stack and wind components are within ± 15% [0.025] of the median values of 0.17 and 0.22 [$m^3/hr/cm^2$], respectively. The total specific infiltration displays a similar stability across the U.S. Fifty percent of the values are within ±

11% [0.03] of the median value of 0.28 [$m^3/hr/cm^2$]. See Figure 1 for a plot of the total specific infiltration for the reference house.

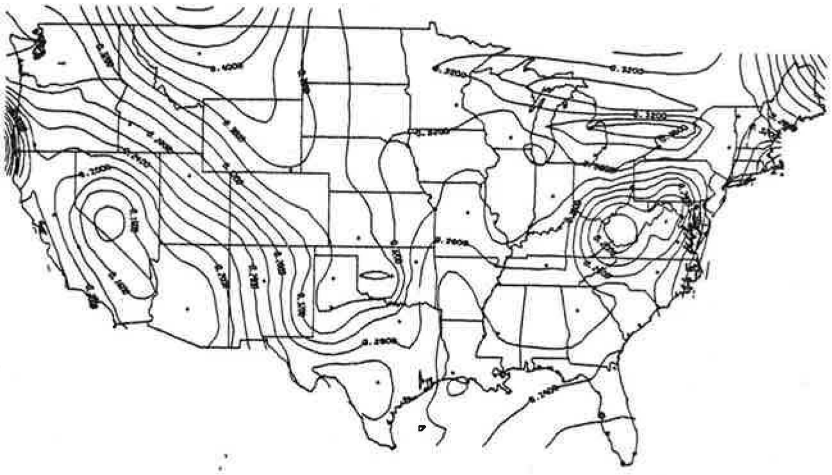

Figure 1. Contours of specific infiltration for the reference house during the heating season from 59 U.S. cities. ($m^3/hr/cm^2$)

Although field measurements of infiltration rates show significant variation from one house to another and one day to another, Table 1 shows comparatively little variation of average specific infiltration across the country. The apparent contradiction is resolved when we consider that all of our infiltration figures are expressed per-unit-leakage area, actual houses have leakage areas varying by a factor of three or more; we used a reference house situated in reference surroundings for all calculations and most infiltration measurements are short term averages — reflecting the variability of weather — while our calculation is for an entire heating season.

4.1 Corrections for Non-reference Cases

We have so far explained how to calculate the infiltration for the reference house. Few houses, however, meet our definition of the reference; accordingly, we must correct the reference results for actual structural parameters. The parameters that are used to correct the specific infiltration are the height of the structure, the fraction of leakage that is in the floor and ceiling, and the terrain and shielding classes of the environment. A more detailed description of the correction procedure is given in the references[8], and will not be presented here.

4.2 Example Calculation

In order to demonstrate how easily the infiltration model can be applied in for a specific house, we will work through one example house in Philadelphia, Pa. Referring again to Table 1, we see that the specific stack and wind infiltration for Philadelphia is 0.18 and 0.26 $m^3/hr/cm^2$, respectively. If the structure under consideration matched the criterion for the reference house we could simply combine these two number to get the total specific infiltration (i.e. the total specific infiltration would be 0.32 $m^3/hr/cm^2$). The corrections to the stack and wind infiltration can be made graphically using Figure 2, which was reproduced from ref. [8].

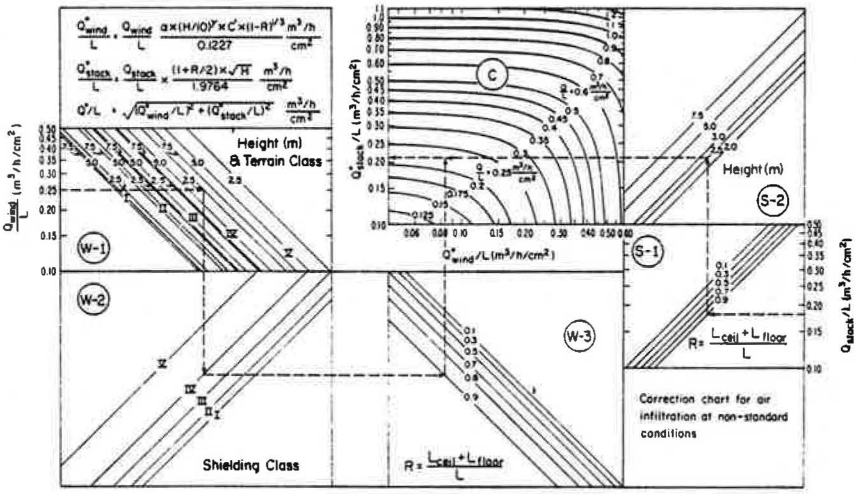

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Figure 2. A graphical means to correct specific stack and wind infiltration for non-reference conditions with specific example.

If we assume our example house is 2.5m high, has 90% of the leakage in the floor and ceiling, and in terrain and shielding class IV we can follow the dashed line on the left side of Figure 2 from 0.25 $m^3/hr/cm^2$ (the reference specific stack infiltration) to 0.083 $m^3/hr/cm^2$ (the corrected specific stack infiltration). In a similar manner, we can follow the right hand dashed line to correct the specific stack infiltration from 0.18 $m^3/hr/cm^2$ to 0.215 $m^3/hr/cm^2$. Combining the two corrected specific infiltration values yields a combined specific infiltration of 0.23 $m^3/hr/cm^2$, which is 28% lower than the specific infiltration for the reference house.

5 DISCUSSION

This model represents a useful tool for standardizing the leakiness of residences in many ways. For example, one could require that in each location the leakage area of a new house be no more than that leakage area which would give the reference house some arbitrary air change rate (e.g. 0.5 ach). This requirement places a maximum limit on the ratio of leakage area to the volume of the structure; that ratio, however, will vary from region to region depending on the weather conditions. Another possible form for a standard would be to mandate a maximum infiltration-related energy load over the heating season. Thus, for this hypothetical standard, there would be a maximum seasonal infiltration allowed for each climate, depending on the outside temperature.

The former standard would be more advantageous towards large structures (because of their larger surface to volume ratio) and the latter would be more advantageous towards smaller structures. Furthermore, because the latter standard is not normalized by any structural parameter, it can be more easily calculated. Accordingly, Figure 3 shows the maximum infiltration allowed assuming a 15 gigajuole yearly average infiltration load.

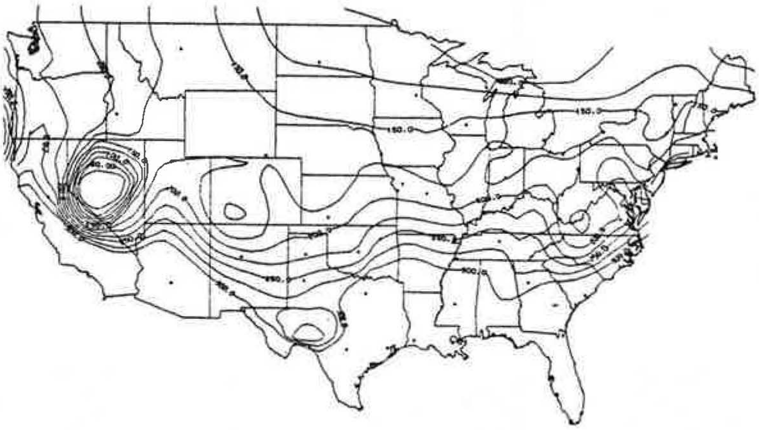

Figure 3. Contours of maximum allowable infiltration for the reference house in 59 U.S. cities assuming a 15 GJ infiltration budget. (m^3/hr)

The specification of a maximum allowable infiltration for energy conservation purposes is not a new concept; but, until now there has been no way to demonstrate that a particular structure meets any given infiltration standard. However, by using the infiltration model we can convert a standard based on energy or infiltration (the target quantity) into a standard for leakage area (the quantity). Specifically, we can calculate a maximum allowable leakage area, maximum allowable infiltration and the specific infiltration from the infiltration model. Figure 4 shows the maximum leakage area allowed assuming, again, a 15 GJ infiltration load, by dividing the maximum allowed infiltration by the specific infiltration.

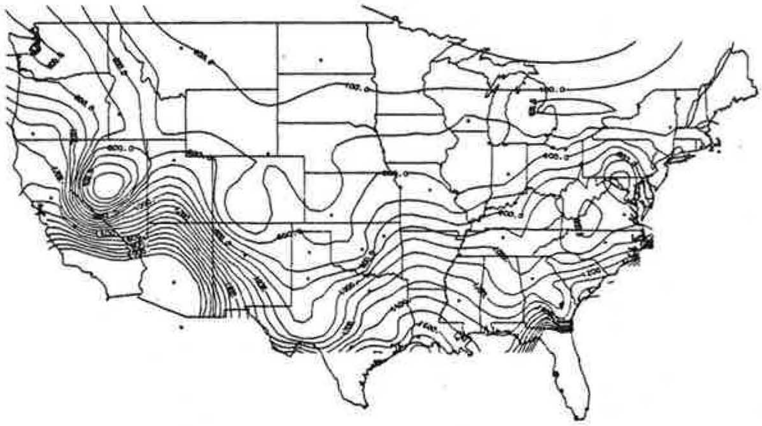

Figure 4. Maximum leakage area allowed for 15 GJ load due to heating season infiltration for 59 U.S. cities. (cm^2)

we hope to have demonstrated how an infiltration standard could be based on a target infiltration. The only measurement that must be made directly on the structure is the leakage area measurement; the target infiltration is obtained by correcting the reference value of specific infiltration for the nearest city from our infiltration model, and multiplying it by the measured leakage area.

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