Infiltration Guidance for Buildings at Design Conditions

For the NYS Clean Heat Program

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Background

Infiltration is required as an input to heating and cooling design calculations. This value is often expressed as the natural (unpressurized) air changes per hour (ACH) at design conditions. In contrast the air tightness required by code for single family homes is expressed as the ACH with the building pressurized at 50 Pa (~0.2 inches water column). In current residential code, ACH50 values must be less than 3. Multifamily buildings borrow from the approach used in commercial buildings which expresses leakage as an airflow rate per square ft of surface area under pressurization of 75 Pa (~0.3 inches water column). Code requires the pressurized airflow in cfm per sq ft at 75 Pa be less than 0.4.

This document seeks to relate the tested airflow rates under pressurized conditions to natural or unpressurized air flow rates at both average and design conditions.

Appropriate Infiltration Levels

Many load calculation software tools provide guidance on appropriate infiltration levels. The Wrightsoft design software provides the guidance on infiltration levels below in Table 1 – in this case based on the ASHRAE CLTD Method (i.e., an obsolete commercial building load calculation method). Table 2 shows the more detailed guidance for homes from ACCA, Manual J, Table 5A. The Wrightsoft guidance is the high end of the ACCA Manual-J range. For "Tight" and "Average" the two tables approximately agree. The Manual-J "Loose" guidance appears to be in between "Poor" and "Loose" for Wrightsoft. The value 2.5 ACH for "Loose" from Wrightsoft appears to correspond to very loose "barn" construction (e.g., a building without interior finish). For context, a properly-vented attic for single family home is estimated to have a similar natural ACH, at about 2.4 ACH (Fugler 1999).

Table 1. Guidance from Wrightsoft / ASHRAE CLTD Method for Commercial Building Infiltration Levels

Infiltration Level	**Natural ACH at Heating Design**	**Natural ACH at Cooling Design**
Tight – Non-operating windows or best quality windows; sealed penetrations in envelope; vapor barrier	0.3	0.2
Average – Standard quality windows; major penetrations sealed; vapor barrier; glass less than 20% of wall area	0.6	0.4
Poor – Below standard windows; no vapor barrier; some unsealed crackage in the skin OR Average construction with operable glass exceeding 20% of wall area	1.0	0.6
Loose – Obvious cracks in windows and doors, unsealed cracks in skin, no vapor barrier, considerable loosely fitting glass	2.5	1.5

Table 2. Residential Infiltration Recommendations from ACCA Manual J, TABLE 5A, Default Air Change Rates

Infiltration Level	**Design Heating ACH**	**Design Cooling ACH**
Manual-J Tight	0.10 – 0.21	0.05 – 0.11
Manual-J Semi-Tight	0.19 – 0.41	0.10 – 0.22
Manual-J Average	0.28 – 0.61	0.15 – 0.35
Manual-J Semi-Loose	0.43 – 0.95	0.23 – 0.50
Loose	0.58 – 1.29	0.30 – 0.67

Ranges based on home sizes under 900 sq ft to homes over 3000 sq ft

Figure 1 shows the resulting distribution of hourly airflows using the AIM-2 infiltration model from the ASHRAE Fundamentals with TMY weather conditions for Atlanta (Henderson et al 2007). The results correspond to an ACH50 of about 3. The distribution of hourly ACH values implies that value at design conditions is approximately 50% greater than the annual average natural ACH (a recent analysis with TMY data by Bruce Harley confirmed this peak-to-average factor of 1.5).

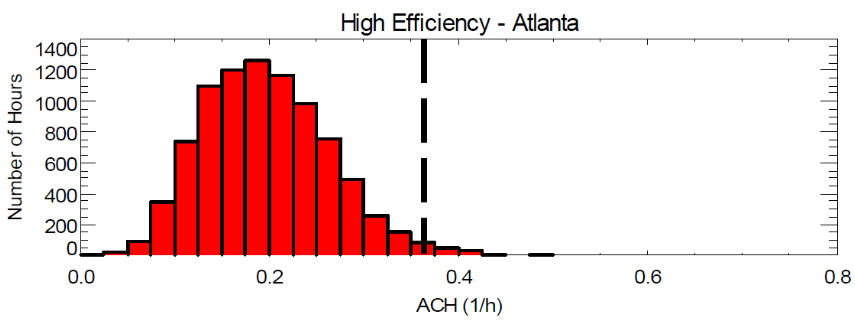

Figure 1. Typical Variation of Hourly ACH Rates Observed Across the Year using AIM-2 Infiltration Model (Henderson et al 2007)

Table 3 compares the calculated infiltration rates using the LBNL N-factors (Figure 2) based on ACH50 values to the ACCA Manual-J guidance. Generally, there is good alignment between the two. The code level home (ACH50=3) corresponds to Manual-J tight / semi-tight and the average home (ACH50=9) approximately corresponds to Manual-J average.

Low-rise residential buildings are typically "Well-shielded", while industrial/commercial buildings on open lots are often "Normal"

n-Factor Table

Zone ↓	# of stories →	1	1.5	2	3
1	Well-shielded	18.6	16.7	14.9	13.0
	Normal	15.5	14.0	12.4	10.9
	Exposed	14.0	12.6	11.2	9.8
2	Well-shielded	22.2	20.0	17.8	15.5
	Normal	18.5	16.7	14.8	13.0
	Exposed	16.7	15.0	13.3	11.7
3	Well-shielded	25.8	23.2	20.6	18.1
	Normal	21.5	19.4	17.2	15.1
	Exposed	19.4	17.4	15.5	13.5
4	Well-shielded	29.4	26.5	23.5	20.6
	Normal	24.5	22.1	19.6	17.2
	Exposed	22.1	19.8	17.6	15.4

Figure 2. LBNL N-Factors for Relating ACH50 Values to Natural Average ACH values (from BPI)

Table 3. Comparing Calculated ACH to Manual-J Recommended Values – Low-Rise Single-Family Houses

	Estimated Average Natural ACH	**Heating Design ACH (average x 1.5)**	**Cooling Design ACH (average x 0.84)**
Code Level Home (ACH50 = 3)[1]	0.13 to 0.19	0.20 to 0.29	0.11 to 0.16
Average Home (ACH50 = 9)[1]	0.40 to 0.60	0.60 to 0.86	0.34 to 0.50
Manual-J "tight"		0.10 - 0.21	0.05 – 0.11
Manual-J "semi-tight"		0.19 - 0.41	0.10 – 0.22
Manual-J "average"		0.28 – 0.61	0.15 – 0.35
Manual-J "loose"		0.58 – 1.29	0.30 – 0.67

Notes: 1 - assuming LBNL n-factors from 15.5 to 22.2 corresponding to weather zone 2, and "well-shielded," which is considered the standard for typical housing (Figure 2).

Measured Small Commercial Infiltration

A study of uncontrolled air flows for small commercial buildings funded by NYSERDA and the US DOE (Henderson et al 2007) measured air leakage rates in 26 small commercial buildings mostly under 10,000 sq ft. This study was conducted in response on previous studies in Florida and California that found that small commercial buildings were especially leaky. The study found that construction practices used in FL and CA that led to high leaks were less common in Upstate NY, due to its more severe climate. The average ACH50 for NY buildings was 11.4 air changes per hour, while the median was 7.4 ACH50. Construction details had a large impact on leakage rates. Four of these buildings, which had a T-bar (drop) ceiling with a vented attic, had an average ACH50 of 30. These buildings had a thermal barrier (fiberglass) at the drop ceiling but no air barrier. Buildings with gypsum board (or plaster) construction typically had values below 7 ACH50. The study also found that metal buildings with an indoor corrugated metal finish (e.g., a municipal equipment maintenance building or a retail garage) had leakage rates over 30 ACH50, mainly due to leakage at seams between metal panels.

Translating these values to natural ACH on an annual basis (using an n-factor of 18), the median building was 0.4 ACH and the leakiest buildings without an air barrier were 1.7 ACH.

Multifamily Infiltration

Information on measured infiltration from three field test studies on a diverse group of multifamily buildings are shown below (Bohac et al 2007; Feustel and Diamond 1996; Ueno and Lstiburek 2015). The data include nine individual buildings in Minneapolis and Boston, and third study that measured eight townhouses in Maryland. The eight Maryland buildings are combined in the table because they had very similar results. The median average ACH is about 0.3.

Table 4. Field Measurements of Natural Infiltration for Multifamily Buildings

Location		built	stories	CFM50	inter unit CFM50	ACH50	Average Natural ACH	Heating Design ACH
MN	8-plex	1970	2	1008	504	4.7	0.3	0.4
MN	12-plex	1964	3	917	506	4.0	0.3	0.4
MN	138-unit	1999	3	665	90	3.8	0.3	0.4
MN	178-unit	1982	11	454	141	2.4	0.3	0.4
MN	38-unit	2001	4	1156	0*	7.4	0.6	0.9
MA	150-unit	1974	11	tracer gas tests			0.2	0.3
MA	200-unit	1968	11	250	10	3.7	0.4	0.6
MA	~200?	1977	13	625	25	8.7	1.1	1.4
MD	Townhouses*	2014	3	1262	0*	4.8	0.3	0.4
Notes:	*includes inter-unit					Median	**0.29**	**0.43**
	Design ACH is 1.25 x avg for 4+ stories 1.5 x avg for <4 stories					Average	**0.43**	**0.58**

All the buildings except one had estimated "natural" air change rates well under 1.0, despite a range of construction types and ages. Most of the buildings had not had extensive weatherization or other air sealing retrofits previous to the measurements. Most also had adjustments based on measurements that allowed elimination of leakage from neighboring apartments, which is typically a source of leakage when field measurements are made but does *not* contribute to energy loads. Note that in the cases where inter-unit leakage was not measured, the estimates of natural air changes (ACH) would be higher than needed for design conditions. In all cases, however, the infiltration model used to calculate the natural ACH – or the tracer gas measurements – would be based on seasonal averages, and thus underestimate infiltration at design conditions. All of these buildings except the MD study were built before 2000, so they can be considered typical of "existing" unweatherized multifamily buildings.

The Simulation Guidance document from the NYSERDA Multifamily Performance Program (MPP) from 2020 recommends default infiltration values for use building simulation tools that compare base case and improved buildings. They recommend that the base case natural infiltration rate not exceed 0.6 ACH. They saw this as the highest typical value based on the review of a range of field studies. The NYSERDA MPP program requires explicit documentation of leaks if base case infiltration is assumed to be above 0.6 ACH. The MPP simulation guidance also assumes the largest possible improvement in airtightness in retrofit applications is to reduce air leakage by 38%.

Generally all these results are consistent with the Manual-J categories of “Tight” and “Average”. The Wrightsoft “Loose” category (from Table 1) is outside this range by a factor of 2.5.

For high rise multifamily buildings, we assume that weather-driven ACH variations are smaller than stack effect and mechanical ventilation interactions. Therefore, we assume the design ACH is 25% more than the average natural ACH.

Table 5. Comparing Calculated ACH to Field Study NYSERDA MPP Values – Multifamily

	Estimated Average Natural ACH	**Heating Design ACH (average x 1.25)**	**Cooling Design ACH (average x 0.7)**
Code Level Multifamily (0.4 cfm/ft2 at 75 Pa)	0.14 (10 flrs) 0.21 (3 flrs)	~0.17-0.26	~0.08-0.15
NYSERDA MPP simulation guidance – high avg / default	0.6	~0.75	~0.42
NYSERDA MPP simulation guidance – max possible	1.0	~1.25	~0.70
Field Study Results (Boston, Minneapolis, MD)	0.3 median	~0.38	~0.21

Overall Guidance

Manual J software tools usually require the natural or unpressurized ACH at design conditions. Care should be taken <u>not</u> to confuse the pressurized values specified by buildings codes (i.e., the ACH50 or CFM75) with annual average or design ACH values at natural or unpressurized conditions. Figure 1 above shows how to convert between pressurized and unpressurized values for low rise and single-family buildings. We recommend:

- For new construction, current energy codes support a maximum design natural ACH of no more than 0.3 (heating) or 0.17 (cooling) for residential single- and multi-family, and commercial buildings.
- For existing buildings, the design ACH should not exceed 0.7 (heating) or 0.4 (cooling). If a higher value is used, then documentation must be provided to justify the higher value

In general, some building characteristics that might justify using an ACH value exceeding 0.7 heating / 0.4 cooling include:

- Buildings that do NOT have gypsum board or plaster interior walls and ceiling
- Buildings that have window sashes or glass panes that move freely (lack weather stripping)
- Buildings with cracks or openings that allow daylight to pass through
- Buildings that use T-bar or drop ceilings without an air barrier
- Buildings with corrugated metal as the interior finish

Extreme values over 2 ACH heating / 1.1 ACH cooling are conceivable but correspond to a well vented attic or a building without interior finish.

References

Multifamily

Bohac, D., M. Hewett, J. Fitzgerald, and D. Grimsrud. 2007. Measured Change in Multifamily Unit Air Leakage and Airflow Due to Air Sealing and Ventilation Treatments. ASHRAE Buildings X. www.mncee.org/sites/default/files/report-files/Measured-Change-in-Multifamily-Unit-Air-Leakage-and-Airflow-Due-to-Air-Sealing-and-Ventilation-Treatments-%281%29.pdf

Feustel, H. and R. Diamond. 1996. Diagnostics and Measurements of Infiltration and Ventilation Systems in High-Rise Apartment Buildings. ACEEE Summer Study. Pages 1.95 to 1.102. www.aceee.org/files/proceedings/1996/data/papers/SS96_Panel1_Paper10.pdf

Ueno, K. and J. Lstiburek. 2015. Field Testing of Compartmentalization Methods for Multifamily Construction. Building Science Corporation. Building America Report – 1506. March/. www.buildingscience.com/file/5760/download?token=QKe3TcLo

Multifamily Performance Program, Simulation Guidelines for Multifamily Building Solution Providers. July 2020. https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Programs/MPP-Existing-Buildings/library/Simulation-Guidelines-v81.pdf

Infiltration

Fugler, D. 1999. Conclusions from Ten Years of Canadian Attic Research. ASHRAE Transactions. CH-99-11-1. Vol. 105. Pt. 1. P 819.

Henderson, H. and D. Shirey and R. Raustad. 2007. Closing the Gap: Getting the Full Performance from Residential Central Air Conditioners. Task 4 – Develop New Climate Sensitive Air Conditioner, Simulations Results and Costs Benefit Analysis. FSEC-CR-1716-07. http://www.fsec.ucf.edu/en/publications/pdf/fsec-cr-1716-07.pdf

Small Commercial

Henderson, H.I., A.C. Walburger, J.B. Cummings, C. Withers, L. Gu, J. Zhang, M. Bomberg, M. Salonvaara, T. Brennan, M. Clarkin. 2007. 'Mitigating the Impacts of Uncontrolled Air Flow on Indoor Environmental Quality and Energy Demand in Non-Residential Buildings'. Final Report DOE Project No. DE-FC-36-02GO12012. April. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1744-07.pdf

Appendix: Using Building Pressurization Measurements to Predict Design Infiltration Rates for Use in Building Design Load Calculations

In some buildings, airflow-pressurization measurements from blower door testing are available to quantify infiltration and estimate leakage rates at heating and cooling design conditions. This appendix describes how blower door test data can be transformed between various levels of building pressurization and used to predict peak or design infiltration rates. Design infiltration rates are used in calculations to determine design heating and cooling loads for buildings.

Blower Door Testing

Blower door testing of residential and commercial buildings should be completed according to ASTM Standard E779-19. Testing should be conducted to determine the airflow rate (or leakage) through the building envelope at various levels (i.e., a multi-point test) for both pressurization and de-pressurization. For the test results to be valid, mechanical vents should be masked off, interior doors blocked open, and pressure mapping used to confirm uniform interior pressures. To be meaningful, the range of pressures should span the range of interest (e.g., usually from zero to 75 Pa). If the highest achieved pressures are lower than the nominal points of 50 and 75 Pa, then ratio of the maximum and minimum pressure should be greater than 4. The relationship between airflow (Q) and pressure (Δp) should conform to the following equation:

$$Q = K \cdot \Delta p^{n}$$

Regression analysis can be used to fit the measured data to the equation above and determine the coefficient (K) and exponent (n) for both pressurization and de-pressurization. The exponent n should generally be greater than 0.6 and less than 0.7. Values near 0.5 indicate that the air leakage is due to a large opening (e.g., an open window, as opposed to a series of narrow cracks). The regression analysis should also indicate the R-squared for the regression model as well as the confidence interval for the parameters K and n.

The blower door test report should also include: a building photo, gross floor area (ft^2), building interior volume (ft^3), exposed envelope surface area (ft^2), and the characteristic or representative building height (ft) of the building zone. In multi-story buildings over 3 floors, testing must confirm that there is very little air flow between floors, so that the characteristic height is then one story (8-10 ft).

Using Blower Door Data

Often the test results need to be translated from one level of pressurization to another. The regression equation above can be used, where K and n are determined by the analysis and Δp is the desired building pressure for leakage reporting.

If the regression results K and n are different for pressurization and de-pressurization tests, then the results from each test should be separately evaluated with the regression equation and then the two resulting values averaged together. If the multi-point testing was not sufficient to determine an exponent n (for example, inadequate blower door flow for a high degree of leakage), then a default value of 0.6 should be used.

The equations below can be used to translate a leakage air flow rate (cfm_A) at building pressure A (P_A) to the new leakage rate (cfm_B) at new building pressure B (P_B):

$$\frac{cfm_A}{cfm_B} = \left(\frac{P_A}{P_B}\right)^n$$

or:

$$cfm_B = cfm_A \cdot \left(\frac{P_B}{P_A}\right)^n$$

An Example Calculation

A commercial building in Upstate NY has 81,250 sq ft of floor area, 1805.5 lineal feet perimeter, and is 3 stories (32 ft) tall. The building volume is 2,600,000 ft^3 and the thermal envelope area is 220,275 ft^2. The building is in an open, unsheltered field. The test report shows the flow-pressure relationships and reports the leakage rate at 75 Pa. We take the average of the two test conditions to get 13,121 cfm75, and 0.06 cfm75 per sq ft of building thermal envelope area.

Test Condition	**Flow-Pressure Equation**	**Leakage flow at 75 Pa** (from equation)	**Leakage flow at 50 Pa** (from equation)
Depressurized	Cfm = 805.0 x P^0.655	13,613 cfm75	10,438 cfm50
Pressurized	Cfm = 835.5 x P^0.629	12,629 cfm75	9,786 cfm50
Average		13,121 cfm75	10,112 cfm50

The goal is to transform the test data to determine the ACH50 for the building and then use the LBNL N-Factors in Figure 2 above to predict the natural infiltration rate. The calculations below convert the cfm75 to the airflow cfm at 50 Pa, and divides by the building volume to find the ACH50.

Depressurized = 13,613 x (50/75)^0.655 = 10,438 cfm50

Pressurized = 12,629 x (50/75)^0.629 = 9,786 cfm50

Average = 10,112 cfm50

Air changes per hour = 10,112 cfm x 60 / 2,600,000 ft^3 = 0.23 ACH50

The factor of 60 converts minutes to hours. We now use Figure 2 in the white paper to find the N-factor that converts to average natural infiltration. The building is in Zone 2, is 3 stories in height, and has “normal” shielding to find the N-factor of 13.0. (Note that we recommend “well-shielded“ by convention for residential homes in the white paper above, and for commercial buildings in a densely developed area. For a commercial building in an open field, we recommend “normal”. “Exposed” generally should not be used.)

From this we can determine the average natural air changes per hour (ACHn) is 0.23 / 13 = 0.018. Based on the discussion in the white paper above, we can estimate the ACH at the heating and cooling design conditions:

ACH at Heating Design 0.018 x 1.5 = 0.023

ACH at Cooling Design 0.018 x 0.84 = 0.015

If the load calculation software requires cfm as an input rather than ACH at design conditions, we would take the cfm50 and divide by the N-factor: CFMn = 10,112 / 13 = 778, and the estimate of design conditions would then be:

cfm at Heating Design	778 x 1.5	=	1,167
cfm at Cooling Design	778 x 0.84	=	653

The N-factor approach (LBNL model) considers the building height and terrain details to find the natural (and then design) infiltration rate. Approaches that simply assume the design infiltration rates correspond to the air flow at an operating pressure of 4 Pa do not consider height and terrain, and therefore overpredict the design infiltration rate, often by a factor of 2 or more.