Letter Report to Construction Engineering Research Laboratory (CERL)
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Building Air Change Rate Estimates for CBR Analysis

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Andrew Persily
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

Introduction

Building air change rates impact energy consumption for space conditioning and indoor contaminant levels in relation to general indoor air quality issues as well as occupant exposure to airborne chemical, biological and radiological (CBR) agents. With respect to contaminant levels, air change rates impact both the entry and subsequent dilution of agents with outdoor sources and the dilution of those released internally. The air change rate of a given building at a given time is a function of building layout, HVAC (heating, ventilating and air-conditioning) system design and operation, the operation of other building systems such as exhaust fans and vented combustion equipment, building envelope airtightness, exterior weather conditions, and occupant actions, e.g. window and door opening. These dependencies can lead to 10-to-1 or even larger variations in the air change rate of a given building, and even larger variations between buildings. The most reliable means of determining a building's air change rate under specific conditions is to measure it with a tracer gas technique. Other measurement methods exist but they do not necessarily characterize all of the relevant airflows (e.g., outdoor air intake traverses that don't account for envelope infiltration) or are often associated with higher levels of measurement uncertainty. Nevertheless, air change rate measurements need to be repeated under a range of conditions to generate a complete characterization of a building's air change rates. Alternatively, modeling approaches exist that can predict these rates with an acceptable level of accuracy, assuming the required input data has been determined for the building of interest (ASHRAE 2005). Measurement and modeling is not always an option in a given building, and generic values may be more useful than building-specific rates to support certain types of analyses. Since such estimates are not building-specific, they are associated with a significant level of uncertainty, but they are still useful as long as their approximate nature is understood.

This letter report presents air change rate estimates for a number of different building types: offices, homes, schools (including child development centers), barracks, multi-family residential buildings, retail buildings, restaurants, theaters, hospitals, gymnasiums, warehouses, and commissaries. A table is presented for each building type based on design requirements in ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standards 62.1 and 62.2 as appropriate (ASHRAE 2007a and 2007b), the limited measurements available (which do not exist for some building types), and engineering judgment. In each table, the air change rate values are color coded to indicate the associated level of confidence. Air change rates based on design values or field measurements are shown in **black** and are associated with an uncertainty of about +/- 25 %, though in some cases the uncertainty could be larger. Those shown in **blue** are based on very limited measurements or design considerations, and are noted to have an uncertainty of roughly +/- 50 %. The values in **red** are noted as being very speculative and are associated with an uncertainty of +/- 100 %. These uncertainty values are all approximate and in some cases are quite large due to the limited number of field studies and due to building, weather and system operation impacts on air change rates. As already noted, without building and condition specific measurements, air change rates estimates are inherently approximate but can still be useful for certain analyses.

Offices

Table 1 presents the air change rate values for office buildings. These values fall into several categories, the first three being mechanical ventilation, infiltration and open windows. In each of these cases, the air change rates are associated with only that mechanism in effect. The Standard 62.1 minimum rate corresponds to roughly 10 L/s (20 cfm) per person of outdoor air ventilation, 5 occupants per 100 m^2 (1000 ft^2) of floor area and a 2.4 m (7.9 ft) ceiling height. Other ventilation rates, occupant densities and ceiling heights correspond to different air change rates per the following formula:

$$\text{Air change rate} = 0.036\ Q\ N\ /\ H$$

where Q is the outdoor air ventilation rate per person in L/s, N is the number of occupants per 100 m^2 of floor area and H is the ceiling height in m. The next two entries in the table under the Standard 62.1 category, underventilation and overventilation, correspond to values that are 50 % below and 50 % above the Standard 62.1 air change rate. Given the realities of system operation and maintenance, outdoor air intake rates often deviate from their design values, and a 50 % deviation is not unreasonable based on the results of existing field studies (Persily and Gorfain 2004). A third condition is included under mechanical ventilation, which is a range of rates under economizer operation in which the outdoor air intake fraction is increased to cool the building as an energy savings measure relative to using mechanical cooling equipment. Note that not all buildings are equipped with an economizer cycle. Note also that a specific building may or may not have been designed to comply with Standard 62.1-2007, but rather with an earlier version, some of which had outdoor air requirements as low as 2.5 L/s (5 cfm) per person in office space.

The three cases for infiltration correspond to three generic levels of building tightness and include a very simple dependence on weather from calm to severe. These characterizations of building tightness and weather are inherently approximate and are not based on any specific numerical values or simulations, and therefore the air change rates are noted as less certain than the design based values. The open windows values are even more approximate than the infiltration-only cases as they ignore the wide variation in window opening patterns that might occur in a given building and because of the lack of measurements of office building air change rates under these conditions.

Additional values are included for mechanical ventilation in combination with envelope infiltration for three levels of building tightness and three levels of weather. An additional set of values is included for mechanical ventilation in combination with open windows and three levels of weather. The final two rows of the table present the mean air change rate (and the standard deviation) from the U.S. Environmental Protection Agency BASE (Building Assessment Survey and Evaluation) study (Persily and Gorfain 2004). The BASE study was conducted in a random sample of 100 office buildings across the United States, and the values in the table correspond to the measurements made in that study. The first of the two rows is based on all these data, while the last row includes only measurements conducted under minimum outdoor air intake.

Table 1 Office building air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation Only				
Standard 62.1 minimum rate	**0.75**			
Standard 62.1, underventilation	**0.38**			
Standard 62.1, overventilation	**1.13**			
Economizer operation	**3 to 5**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**0.75**	**0.9**	**1.1**
Average tightness		**0.9**	**1.1**	**1.5**
Very leaky		**1.1**	**1.5**	**2.0**
Mechanical combined with open windows		**1.5**	**2.5**	**3.5**
EPA BASE study				
All data – mean (S.D.)	**1.8 (2.1)**			
Minimum outdoor air – mean (S.D.)	**0.5 (0.4)**			

Based on measured or design values, +/- 25 %
Based on limited measured or design values, +/- 50 %
Very speculative, at least +/- 100 %

Homes
Table 2 presents the air change rates for single-family homes. The first set of entries correspond to mechanically ventilated buildings in which a mechanical system brings outdoor air into the home. Note however that very few single-family homes in the U.S., even new ones, use mechanical systems for outdoor air ventilation. These first three entries present the ventilation requirements in ASHRAE Standard 62.2, which depend on house size and number of bedrooms per the following equation:

$$\text{Air change rate} = 3.6\,[0.05\,A_f + 3.5\,(n_b + 1) + 0.1\,A_f] / (A_f\,H)$$

where A_f is the floor area in m^2, n_b is the number of bedrooms and H is the ceiling height in m. The third term in the square brackets ($0.1\,A_f$) is an infiltration credit that the standard uses to account for an assumed level of infiltration air entering the building that contributes to meeting the overall ventilation requirement. The next entry is the mechanical ventilation requirement for manufactured homes contained in the HUD (U.S. Department of Housing and Urban Development) Manufactured Housing Construction and Safety Standards (HUD 1994). The HUD outdoor air ventilation requirement of 0.018 L/ s•m^2 (0.0035 cfm/ft^2) is based only on floor area, and therefore there is only a single entry assuming a ceiling height of 2.4 m (7.9 ft). The next three entries are for envelope infiltration only, for three different cases of airtightness and three cases of weather conditions. These values are followed by a very speculative set of values for ventilation via open windows.

Table 2 Single-family home air change rates

	Weather independent	Weather Calm	Weather Moderate	Weather Severe
Mechanical Ventilation				
Standard 62.2 requirements				
150 m^2, 2 bedrooms	**0.32**			
200 m^2, 4 bedrooms	**0.35**			
300 m^2, 6 bedrooms	**0.34**			
HUD manufactured house requirements	**0.26**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.6**
Average tightness		**0.25**	**0.6**	**1.0**
Very leaky		**0.5**	**0.9**	**1.5**
Open Windows Only		**1**	**3**	**5**
Mechanical ventilation (Standard 62.2) combined with infiltration				
Very tight building		**0.25**	**0.4**	**0.7**
Average tightness		**0.35**	**0.7**	**1.1**
Very leaky		**0.6**	**1.0**	**1.6**
Mechanical ventilation (HUD) combined with infiltration				
Very tight building		**0.3**	**0.4**	**0.75**
Average tightness		**0.4**	**0.8**	**1.2**
Very leaky		**0.7**	**1.0**	**1.7**
Mechanical (62.2) combined with open windows		**1**	**3**	**5**
Mechanical (HUD) combined with open windows		**1**	**3**	**5**
NIST U.S. homes analysis				
All data – median	**0.45**			
Built before 1940 – median	**0.60**			
Built between 1941 and 1969 – median	**0.55**			
Built between 1970 and 1989 – median	**0.35**			
Built after 1990 – median	**0.25**			
Pandian U.S. homes database				
All data – median	**0.50**			

Based on measured or design values, +/- 25 %
Based on limited measured or design values, +/- 50 %
Very speculative, at least +/- 100 %

Additional values are included for mechanical ventilation in combination with envelope infiltration for three levels of building tightness and three levels of weather. These values are presented first with the mechanical ventilation rate based on Standard 62.2 and then with the rate derived from the HUD standard. In the case of the Standard 62.2 combined mechanical and infiltration values, the Standard 62.2 "infiltration credit" is replaced with an infiltration rate that depends on building tightness and weather conditions. This adjustment is more realistic than a single value, but still oversimplifies reality. Two values are also included for the two mechanical ventilation rates in combination with open windows.

The last two sections of Table 2 present the results for two key studies of residential ventilation rates. The first is a based on a collection of about 200 residences defined to represent 80 % of the U.S. housing stock (Persily et al. 2006). This set of dwellings was defined based on an analysis of national housing surveys and subsequently used to develop a national frequency distribution of building ventilation rates under infiltration-only conditions (Musser 2008). Median values are presented for all the single-family homes in the analysis and for those homes broken down by year of construction. Note that these median values are much lower than many of the estimates earlier in the table, particularly those corresponding to more severe weather. However, given the relative infrequency of severe weather, those high rates do not occur very often and therefore do not impact the median rate very significantly. The final entry in Table 2 is the median air change rate from a database of measured air change rates in almost 3000 homes located throughout the U.S. (Pandian et al. 1998). Note that the homes considered in this database are not statistically representative of the U.S. housing stock and the measurements were made under weather conditions that do not fully characterize the climatic variations over a year.

Schools

There have been very few ventilation measurements in schools. In addition, the great variety of building configurations and system types makes any generalization even more difficult. Table 3 presents air change rates based primarily on the design requirements in ASHRAE Standard 62.1, with some speculative estimates of the impacts of infiltration and natural ventilation through open windows. This table covers elementary classrooms, lecture classrooms and child care centers separately, with the design rates based on the following three formulas;

Elementary classrooms: Air change rate = 0.036 [5 D + 60] /H

Lecture classrooms: Air change rate = 0.036 [3.8 D + 30] /H

Child care centers: Air change rate = 0.036 [5 D + 90] /H

where D is the number of occupants per 100 m^2 of floor area and H is the ceiling height in m.

Table 3 Educational building air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
ELEMENTARY CLASSROOM				
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**3.2**			
Standard 62.1, underventilation	**1.6**			
Standard 62.1, overventilation	**4.8**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**3.2**	**3.4**	**3.6**
Average tightness		**3.4**	**3.6**	**4.0**
Very leaky		**3.5**	**4.0**	**4.5**
Mechanical combined with open windows		**4**	**5**	**6**
LECTURE CLASSROOM				
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**2.8**			
Standard 62.1, underventilation	**1.4**			
Standard 62.1, overventilation	**4.2**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**2.8**	**3.0**	**3.2**
Average tightness		**3.0**	**3.2**	**3.6**
Very leaky		**3.2**	**3.6**	**4.0**
Mechanical combined with open windows		**3.5**	**4.5**	**5.5**
CHILD CARE CENTER				
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**4.2**			
Standard 62.1, underventilation	**2.1**			
Standard 62.1, overventilation	**6.3**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**4.2**	**4.3**	**4.5**
Average tightness		**4.3**	**4.5**	**5.0**
Very leaky		**4.5**	**5**	**5.4**
Mechanical combined with open windows		**5**	**6**	**7**

Based on measured or design values, +/- 25 %
Based on limited measured or design values, +/- 50 %
Very speculative, at least +/- 100 %

Barracks and Multi-Family Residential

Table 4 presents the air change rates for barracks buildings. The first entry under mechanical ventilation with no infiltration is based on the requirements in ASHRAE Standard 62.1 of 2.5 L/s (5 cfm) per person plus 0.30 L/s per m^2 (0.06 cfm/ft^2) of floor area, assuming an occupant density of 10 people per 100 m^2 of floor area and a ceiling height of 2.4 m (7.9 ft). Other occupant densities and ceiling heights correspond to different air change rates as follows:

Air change rate = 0.036 [2.5 D + 30] /H

where D is the number of occupants per 100 m^2 of floor area and H is the ceiling height in m. The values in Table 4 fall into three categories: mechanical ventilation, infiltration only and open window, similar to those used in the previous tables. There is not a body of ventilation rate measurements in barracks, therefore all but the values based on Standard 62.1 are presented as very speculative.

Table 4 Barracks building air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**0.8**			
Standard 62.1, underventilation	**0.4**			
Standard 62.1, overventilation	**1.2**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**0.8**	**1.0**	**1.2**
Average tightness		**1.0**	**1.2**	**1.5**
Very leaky		**1.2**	**1.5**	**2.0**
Mechanical combined with open windows		**1.5**	**2.5**	**3.5**

Based on measured or design values, +/- 25 %

Very speculative, at least +/- 100 %

Table 5 presents the air change rates for multi-family residential buildings. The first entry under mechanical ventilation with no infiltration is based on the requirements in ASHRAE Standard 62.1 of 2.5 L/s (5 cfm) per person plus 0.30 L/s per m^2 (0.06 cfm/ft^2) of floor area for a dwelling unit in a multi-family residential building. This entry is based on an assumed occupant density of 2 people per 100 m^2 (1000 ft^2) of floor area and a ceiling height of 2.4 m (7.9 ft). Other occupant densities and ceiling heights will correspond to different air change rates as follows:

Air change rate = 0.036 [2.5 D + 30] /H

where D is the number of occupants per 100 m^2 of floor area and H is the ceiling height in m.

Like the other tables in this report, Table 5 includes mechanical ventilation, infiltration only and open windows. There is not a significant body of ventilation measurements in multi-family residential buildings, therefore all but the values based on Standard 62.1 are presented as very speculative.

Table 5 Multi-family residential building air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**0.5**			
Standard 62.1, underventilation	**0.25**			
Standard 62.1, overventilation	**0.75**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**0.5**	**0.7**	**0.9**
Average tightness		**0.7**	**0.9**	**1.2**
Very leaky		**0.9**	**1.2**	**1.5**
Mechanical combined with open windows		**1.3**	**2.3**	**3.3**

Based on measured or design values, +/- 25 %
Very speculative, at least +/- 100 %

While the ventilation requirement in ASHRAE Standard 62.1 for multi-family buildings is for an individual dwelling unit, the values in Table 5 are presented as whole building values. It should be noted that individual units in a multi-family building may be characterized by very different ventilation rates than the whole building value. For example, under heating conditions, units located on the lower floors of a high-rise building are going to have higher outdoor air entry rates than those located on the upper floors to the stack effect.

Retail, Restaurants and Theaters

Tables 6 through 8 present air change rates for retail buildings, restaurants and theatres. The first entry in each table, mechanical ventilation with no infiltration, is based on the requirements in ASHRAE Standard 62.1. These requirements are 3.8 L/s (7.5 cfm) per person in all three space types, plus 0.60 L/s per m^2 (0.12 cfm/ft^2) of floor area in retail, 0.90 L/s per m^2 (0.18 cfm/ft^2) in restaurants and 0.30 L/s per m^2 (0.06 cfm/ft^2) in theaters. The default occupant density in the standard is 15 people per 100 m^2 (1000 ft^2) of floor area in retail spaces, 70 people per 100 m^2 (1000 ft^2) in restaurants, and 100 people per 100 m^2 (1000 ft^2) in theaters. The assumed ceiling height is 2.4 m (7.9 ft) in retail and restaurants and 3.65 m (12.0 ft) in theaters. Other occupant densities and ceiling heights correspond to different air change rates per the following formulas:

Retail: Air change rate = 0.036 [3.8 D + 60] /H

Restaurants: Air change rate = 0.036 [3.8 D + 90] /H

Theaters: Air change rate = 0.036 [3.8 D + 30] /H

where D is the number of occupants per 100 m^2 of floor area and H is the ceiling height in m.

The values in Tables 6 through 8 fall into three categories: mechanical ventilation, infiltration only and open windows. There is not a significant body of ventilation rate measurements in retail spaces, restaurants or theaters, therefore all but the values based on Standard 62.1 are presented as very speculative.

Table 6 Retail air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**1.8**			
Standard 62.1, underventilation	**0.9**			
Standard 62.1, overventilation	**2.7**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**1.8**	**2**	**2.2**
Average tightness		**2**	**2.2**	**2.5**
Very leaky		**2.2**	**2.5**	**3**
Mechanical combined with open windows		**2.5**	**3.5**	**4.5**

Based on measured or design values, +/- 25 %
Very speculative, at least +/- 100 %

Table 7 Restaurant air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**5**			
Standard 62.1, underventilation	**2.5**			
Standard 62.1, overventilation	**10**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**5**	**5.2**	**5.4**
Average tightness		**5.2**	**5.4**	**5.7**
Very leaky		**5.4**	**5.7**	**6**
Mechanical combined with open windows		**5.8**	**6.8**	**7.8**

Based on measured or design values, +/- 25 %
Very speculative, at least +/- 100 %

Table 8 Theater air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**4**			
Standard 62.1, underventilation	**2**			
Standard 62.1, overventilation	**6**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**4**	**4.2**	**4.4**
Average tightness		**4.2**	**4.4**	**4.7**
Very leaky		**4.4**	**4.7**	**5**
Mechanical combined with open windows		**4.6**	**5.6**	**6.6**

Based on measured or design values, +/- 25 %

Very speculative, at least +/- 100 %

Hospitals, Gymnasiums, Warehouses and Commissaries

Tables 9 through 12 present the air change rates for hospitals, gymnasiums, warehouses and commissaries. The first entry in each table, under mechanical ventilation with no infiltration, is based on ASHRAE Standard 62.1. These requirements are 8 L/s to 15 L/s (15 cfm to 30 cfm) per person in hospitals, depending on the room type, with a default occupant density of 10 people to 20 people per 100 m^2 (1000 ft^2), again depending on the room type. The ventilation requirements in gymnasiums and warehouses are 1.5 L/s per m^2 (0.30 cfm/ft^2) of floor area and 0.30 L/s•m^2 (0.06 cfm/ft^2) respectively, with no dependence on the number of occupants. The air change rates for commissaries are based on the requirements for supermarkets, which are 3.8 L/s (7.5 cfm) per person and 0.30 L/s per m^2 (0.06 cfm/ft^2) of floor area, with a default occupancy of 8 people per 100 m^2 (1000 ft^2). The assumed ceiling height is 2.4 m (7.9 ft) in hospital patient and treatment rooms and 3.65 m (12.0 ft) in operating rooms and the other three building types. Other occupant densities and ceiling heights will correspond to different air change rates as follows:

Hospitals: Air change rate = 6.1 D /H

Gymnasiums: Air change rate = 5.4 /H

Warehouses: Air change rate = 1.1 /H

Commissaries: Air change rate = 0.036 [3.8 D + 30] /H

where D is the number of occupants per 100 m^2 of floor area and H is the ceiling height in m. The equation for hospitals is based on a generalized space type corresponding to 10 L/s (20 cfm) per person and an occupant density of 17 per 100 m^2 (1000 ft^2) of floor area.

The values in Tables 9 through 12 fall into three categories: mechanical ventilation, infiltration only and open windows only. There is not a body of ventilation rate measurements in these building types, therefore all but the values based on Standard 62.1 are very speculative.

Table 9 Hospital air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**2.5**			
Standard 62.1, underventilation	**1.3**			
Standard 62.1, overventilation	**3.7**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**2.5**	**2.7**	**2.9**
Average tightness		**2.7**	**2.9**	**3.3**
Very leaky		**2.9**	**3.3**	**3.6**
Mechanical combined with open windows		**3**	**4**	**5**

Based on measured or design values, +/- 25 %
Very speculative, at least +/- 100 %

Table 10 Gymnasium air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**1.5**			
Standard 62.1, underventilation	**0.8**			
Standard 62.1, overventilation	**2.3**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**1.5**	**1.7**	**1.9**
Average tightness		**1.7**	**1.9**	**2.3**
Very leaky		**1.9**	**2.3**	**2.6**
Mechanical combined with open windows		**2.2**	**3.2**	**4.2**

Based on measured or design values, +/- 25 %
Very speculative, at least +/- 100 %

Table 11 Warehouse air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**0.3**			
Standard 62.1, underventilation	**0.2**			
Standard 62.1, overventilation	**0.5**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**0.3**	**0.45**	**0.6**
Average tightness		**0.45**	**0.6**	**1.0**
Very leaky		**0.6**	**1.0**	**1.5**
Mechanical combined with open windows		**1**	**2**	**3**

Based on measured or design values, +/- 25 %
Very speculative, at least +/- 100 %

Table 12 Commissary air change rates

	Weather independent	Weather		
		Calm	Moderate	Severe
Mechanical Ventilation				
Standard 62.1 rate no infiltration	**0.9**			
Standard 62.1, underventilation	**0.5**			
Standard 62.1, overventilation	**1.4**			
Infiltration Only				
Very tight building		**0.1**	**0.25**	**0.5**
Average tightness		**0.25**	**0.5**	**1.0**
Very leaky		**0.5**	**1**	**1.5**
Open Windows Only		**1**	**2**	**3**
Mechanical ventilation (Standard 62.1) combined with infiltration				
Very tight building		**0.9**	**1.1**	**1.3**
Average tightness		**1.1**	**1.3**	**1.5**
Very leaky		**1.3**	**1.5**	**1.8**
Mechanical combined with open windows		**1**	**2**	**3**

Based on measured or design values, +/- 25 %
Very speculative, at least +/- 100 %

SUMMARY

The building air change rates presented in this report are based on a combination of the ventilation requirements in ASHRAE Standards 62.1 and 62.2, the limited number of measurements conducted in the field and a significant amount of engineering judgment. Any use of these rates must be fully informed by their limitations, particularly their lack of specificity to any particular building, system design or operating conditions, or weather conditions and by their limited basis in actual measurement. For many of the building types or conditions (e.g., open windows), few if any air change rate measurements even exist. Nevertheless, these rates may prove useful for certain types of analysis where there is no need to differentiate between building types, system operation and weather conditions. The noted gaps in measured ventilation rates also highlights the need for more field studies and simplified calculation tools to determine building ventilation rates particularly in buildings other than offices and residences.

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REFERENCES

ASHRAE. 2005. ASHRAE Fundamentals Handbook, Chapter 27 Ventilation and Infiltration. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2007a. ANSI/ASHRAE Standard 62.1-2007 Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE, 2007b. ASHRAE Standard 62.2-2007 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

HUD. 1994. Manufactured Home Construction and Safety Standards. U.S. Department of Housing and Urban Development

Pandian, M.D., Behar, J.V., Ott, W.R., Wallace, L.A., Wilson, A.L., Colome, S.D. and Koontz, M. 1998. Correcting Errors in the Nationwide Data Base of Residential Air Exchange Rates, Journal of Exposure Analysis and Environmental Epidemiology. 8(4) 577-591.

Persily, A., and Gorfain, J., 2004. Analysis of Ventilation Data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study, National Institute of Standards and Technology, NISTIR 7145.

Persily, A. K., Musser, A., and Leber, D., 2006. A Collection of Homes to Represent the U.S. Housing Stock. NISTIR 7330, National Institute of Standards and Technology.

Musser, A. 2007. Ventilation Rate Frequency Distributions for U.S. Housing Stock. NIST Contractor report, PWS NB863060-7-03758.