Testing and Analyzing U.S. Army Buildings Air Leakage

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ABSTRACT

The Energy Policy Act of 2005 (EPAct05) requires that federal building energy-efficiency performance standards be revised. New federal buildings must be designed to achieve energy consumption levels at least 30 percent below the levels established in the currently applicable version of standards published by the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) Standard 90.1 or the International Energy Conservation Code. ERDC CERL has conducted investigations to develop design/construction strategies to improve energy efficiency, prevent mold, and improve indoor air quality in buildings newly constructed or undergoing renovations. Also, ERDC CERL researchers tested Army building envelopes to investigate building air leakage and analyzed effects of increased airtightness on the building energy consumption. As a result, they have developed airtightness criteria and performance requirements for inclusion in design/construction strategies. Results are presented for 15 representative U.S. and 16 Canadian and European climate conditions. Based on these results, the U.S. Army Corps of Engineers has set a requirement that all new buildings and buildings undergoing major renovation shall pass an air leakage test where the results are less than or equal to 0.25 cfm per square foot of exterior envelope at 0.3 inches of water gage (75 Pa) pressure difference.

KEYWORDS

Air leakage, airtightness requirements, energy conservation, mold prevention, blower door test, Army facilities

AIR LEAKAGE TESTS OF SELECTED ARMY FACILITIES

The most widely accepted test method for using fan pressurization to determine total building leakage in the United States is ASTM E779 *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization* (ASTM). These procedures were used to determine the airtightness of six buildings at four Army installations. Except for one building, the entire conditioned space of each building was tested as a single zone using multiple blower door fan setups. In one multi-unit barracks, which had a configuration that prevented testing as a single zone, balanced fan pressurization techniques were used to test three zones simultaneously to estimate leakage.

WHOLE BUILDING LEAKAGE TESTS USING SINGLE ZONE

For each of the buildings tested as a single zone, the setup consisted of placing a blower door apparatus in one or more doorways. The fans provided a pressure difference between the building interior and the surrounding ambient air while measurements of the pressure difference and volume of air moving through the fan were done using gauges. Negative pressurization tests were conducted on each building. Multi-point measurements of airflow rates at different pressure differences were taken for each test. The data were fitted to the power law flow function ($Q = C(\Delta P)^n$. The two parameters that quantitatively describe the building air leakage, the flow coefficient (C) and the flow exponent (n), were determined from this function. Before testing each building, the heating, ventilating, and air-conditioning (HVAC) systems were shut down and appropriate sealing measures were done to eliminate unwanted leakage contributions. Sealed components included supply air dampers, bathroom and kitchen exhausts vents, and air inlet grilles to fan coil units. Plumbing traps were filled. Windows and exterior doors were shut and interior doors were opened. Testing was done on calm days with winds typically less than 10 mph in an attempt to adhere to ASTM 779 requirements.

Barracks at Fort Myer. Fan pressurization tests were done on a barracks building at Fort Myer, Virginia (Building A). The building has three stories with brick masonry-clad exterior walls and concrete block interior walls. Each floor has a central corridor with sleeping rooms on both sides. The building has a stairwell at each end. Outside air is supplied to the building by six fan coil units (two on each floor). The single vent supplying outside air to each of these units was fixed in the open position, leaving a ¾- by 18-in. opening through the building envelope, which was left unsealed during testing. Fan pressurization tests were done with the building depressurized using a double fan blower door setup at one end of the first floor entry.

Three Barracks at Fort Bragg. Fan pressurization tests were conducted on two similar barracks buildings (Bldgs B and C) at Fort Bragg, North Carolina. Building C is 16 ft shorter than Building B. Both buildings have brick masonry-clad exterior walls, concrete block interior walls, and a steep-sloped asphalt shingle roof with a ventilated attic space. The main center part for both buildings has three stories. Each floor has a center hallway corridor; off both sides of the corridor are several individual units serving as living quarters. Each end of both buildings has a one-story annex that includes a foyer, day room, and administration wing.
Each of the individual living quarters in Bldg B is configured to include a large sleeping area for multiple occupants and a shared bathroom along the corridor wall. A fan coil unit is located in one corner at the exterior wall. The interior of Barracks Bldg C was recently renovated. The new layout of the individual living quarters have a “one plus one” configuration with two smaller single bedrooms located against the exterior wall and a shared kitchenette and bathroom adjacent to the corridor wall. As part of the renovation, each fan coil unit was replaced with an HVAC units located in a utility closets with access via hallway corridor doors. For both buildings, open plumbing chases extend from each gang of bathrooms on each floor up to the attic space. These chases and the attics were outside the test envelopes.
The test zone of both buildings consisted of the entire barracks area (all three floors), the day room and foyer of one end of the building, and just the day room of the other end. It was necessary to include the foyer at one end to maintain air connectivity

between the second and third floor living quarters and the first floor living quarters. For both buildings, the fan pressurization testing involved erecting two blower door setups and four fans in one of the double door entrances to the foyer.
Building D was a newly constructed, four-story barracks at Fort Bragg. It has a stairwell at both ends, but does not have one-story sections of Buildings B and C. The exterior walls are brick masonry and the roof is a metal panel system with a ventilated attic space. Each floor has a center corridor with rooms along both sides in a “one plus one” configuration.

Dining Facility at Fort Knox. Building E is a newly constructed, one-story-dining hall at Fort Knox, Kentucky that includes the space and equipment for food storage and preparation, dishwashing, and dining. The brick masonry building has metal stud framing and interior walls of finished gypsum; the roofing system is a steep metal panel roofing system on an insulated metal deck. The attic space above a drop down ceiling is conditioned space. Testing required extensive sealing measures to mask many kitchen hoods before testing. Fan pressurization tests were done on the building shortly after completion and before commissioning.

Classroom Training Facility at Fort Leonard Wood. Building F is a classroom training facility at Fort Leonard Wood, Missouri. The two-story building was constructed in 1997 and has about 30,000 sq ft of floor space. It includes an administration wing and a classroom wing, each with an upper and lower level. The two wings are connected on the upper level by a lobby. Three staircases and an elevator provide access between levels. The classroom wing is connected to a high bay area that has several tall overhead doors. The area has its own HVAC (not included as part of the test zone). During testing, ambient pressurization was maintained in the high bay. For this study, the concrete masonry unit (CMU) wall between the high bay and the classroom wing is treated as part of the building envelope. The building envelope has brick-clad CMU walls. Interior walls are of gypsum board attached to metal studs. The common wall between the building and the high bay is of CMU. The roof deck, which supports rigid insulation board and a single-ply EPDM rubber membrane roof covering is corrugated steel sheeting. The floors are poured concrete slabs.

WHOLE BUILDING LEAKAGE TEST USING BALANCED FAN PRESSURIZATION

Barracks at Fort Stewart. Barracks Building G at Fort Stewart, Georgia is one of several barracks of the same multiple module configuration were built in the 1970s. It has three stories on a slab foundation, CMU exterior walls (face brick), and concrete floor decks. The buildings underwent major renovation in the 1990s in which room layouts were converted to their present configuration. As part of the renovation, existing low-slope membrane roofs were converted to steep slope using aluminum metal panel systems supported by substructures attached to the concrete roof deck. The attic space between the original and current roof is ventilated and is not part of the conditioned space.
Building G is composed of three modules with courtyards that physically divide them into half modules. A half module contains 12 dorm units, four on a floor, serviced by a stairwell. On each of the floors, a pair of units is separated from the other pair of units by a breezeway. The entry doors for the units open to the breezeway. A utility chase

runs vertically from the ground floor to the concrete roof deck and is located in the common wall between adjacent dorm units.

With this configuration, equal pressurization for a single zone that included multiple dorm units was not achievable. There is only minor air connectivity between the units within a module via ducting for fresh air that leads to a rooftop ventilator. Alternatively, balanced fan pressurization tests were simultaneously conducted on individual floors of a half module to eliminate interior leakage between floor and ceiling partitions. Leakages through the shared interior wall partitions of the adjacent module were assumed to be negligible. To achieve this, mock walls were erected at both ends of the breezeways of each floor. The walls were constructed of 2 x 3-in. framing lumber and 6 mil thick polyethylene sheeting. The three mock walls that were placed adjacent to the stairwell had framed 3-ft wide openings for placement of a blower door apparatus. Tested in this manner, an entire floor of the half module functioned as a single zone with a blower door assembly placed on each floor being tested.

During testing, all three floors were pressurized simultaneously and flows were adjusted to achieve zero pressure differences between them as measurements were taken. Therefore, at each recorded pressure differential (with ambient air) at which flows were measured, leakage between the zones should be negligible, and the sums of the individual flows for each floor represented the total envelope leakage flow for the half module. Table 1 shows only values for envelope air leakage because the building does not function as a single conditioned zone.

DISCUSSION OF RESULTS

The envelope leakage values presented at the pressure difference of 75Pa in Table 1 for the barracks Buildings A, B, C, D, which had interior entry ways, were in the range between 0.56 and 0.77 $ft^3/m\text{-}ft^2$. The envelope of the modular barracks (Building F) with exterior entry ways was tighter, having an envelope leakage of 0.38 $ft^3/m\text{-}ft^2$. The newly constructed barracks (Building D) was no tighter than the other barracks constructed 30 years earlier. When examining the data for two buildings of like construction and configuration at Fort Bragg, (renovated) Building C is more than a third leakier than (unrenovated) Building B. This difference may have been due to unknown leak sources through the roof deck of the test zone via the newly installed HVAC system components or an anomaly such as an open window or an unmasked penetration that was previously sealed during test preparation. (Soldiers were allowed into the building for several hours after sealing measures were performed and just before testing.) The lower value for the flow exponent (near 0.5) indicates this. The classroom training facility had the lowest envelope air leakage and the new dining hall was as leaky as the least airtight barracks tested.

An analysis of data from 139 commercial and institutional buildings in the United States (Persily) showed the mean value of their envelope air leakage was 1.48 $ft^3/m\text{-}ft^2$. These buildings ranged in age from 4 years to several decades. The seven tested Army buildings were all below this value. indicating that typical Army construction is certainly no less airtight than other U.S. buildings. However, only two of the buildings meet the ASHRAE proposed airtightness requirement of 0.40 $ft^3/m\text{-}ft^2$.

U.S. ARMY AIR LEAKAGE REQUIREMENTS

Since 2007 the U.S. Army Corps of Engineers has required that in all new construction projects and major retrofits, building envelopes of office buildings, office portions of mixed office and open space (e.g., company operations facilities), dining, barracks and instructional/training facilities be fitted with a continuous air barrier to control air leakage into, or out of, the conditioned space. These buildings shall be tested to demonstrate that the air leakage rate of the building envelope does not exceed 0.25cfm/ft^2 at a pressure differential of 0.3 in. w.g.(75 Pa) in accordance with ASTM's E 779 (2003) or E-1827-96 (2002). Different standards used for building envelope airtightness use different units. Table 2 lists the USACE requirement alongside other standards where air leakage levels are expressed in the same units of cfm/sq ft at a test pressure of 75 Pa.

To streamline the construction process and provide straightforward requirements for airtightness testing, ERDC-CERL engineers, in collaboration with the private sector (ASHRAE 2009, WBDG) have developed a Protocol that gives a step-by-step approach to prepare and test buildings for airtightness. The Protocol uses ASTM E-779-03 as a basis, with modifications and adjustments to account for the large bias pressures (due to wind and stack) often found in high-rise buildings, and to balance accuracy, repeatability, and ease of use with a variety of door fan equipment. The Protocol differentiates between buildings with a few doors to the outside and buildings with individual spaces/apartments with doors to the outside.

ANALYSIS: POTENTIAL ENERGY SAVINGS WITH IMPROVED AIRTIGHTNESS

Uncontrolled air transfer through the building envelope markedly increases the energy required to heat, cool, and control humidity in buildings. To estimate achievable savings, a number of pre- and post-retrofit year-long simulations were done using the EnergyPlus 3.0 building energy simulation software, which models (among other criteria) heating, cooling, and ventilation flows through buildings. The baseline building is assumed to be an existing barracks, dormitory, or multi-family building built either to meet the minimum requirements of ASHRAE Standard 90.1-1989 (ASHRAE 1989) by climate zone (Baseline 1) or built before 1960 using typical construction practices of the time with little or no insulation (Baseline 2). The barracks are three stories high with an area of 30,465 ft^2 (2,691 m^2) and include 40 two-bedroom apartment units, a lobby on the main floor and laundry rooms on each floor. The barracks were assumed to be unoccupied during the hours of 8a.m.–5p.m. Monday–Friday. Benne (2009) gives further details on the barracks and the baseline HVAC systems used. Analysis was done for 15 U.S. locations and 16 international locations. U.S. locations were selected as representative cities for the climate zones by the Pacific Northwest National Laboratory. Flat utility tariffs were assumed for each location (i.e., no energy demand charges are included). The U.S. energy costs are based on Energy Information Administration (EIA) 2007 average data for commercial rates in each state and may not reflect the utility rates at a specific location (EIA 2008). Benne (2009) gives the climate characteristics, energy costs, and building details and construction parameters of all 31 simulations.

Three representative airtightness levels were modeled (Table 3). The first value is used as the baseline and comes from expert opinion of existing buildings based on pressurization tests. The other two values are considered to represent reasonable performance improvements achievable with a medium effort and a best effort for sealing existing buildings. The infiltration values at the leakage rates and pressures were calculated based on the total wall and flat roof area of the building then converted to a pressure of 0.016 in w.g. (4 Pa) assuming a flow coefficient of 0.65. It is assumed that these fixed infiltration rates represent the average air leakage for the varying conditions.

SIMULATION RESULTS

Figures 1, 2, and 3 show the results for improving the building airtightness for each climate zone. The energy savings are based on total building site energy consumption. The energy savings are based on total building site energy consumption. Energy savings of nearly 25% are seen in the coldest climates studied (Figure 1). Expected savings from airtightness improvements decrease in warmer climates. These savings translate to roughly $0.10-0.50/ft^2 (Figure 2). The results can vary significantly with the modeling assumptions; therefore, the results from real building projects will vary from the simulated results. Similarly, costs vary quite a bit depending on the needs of the building. For this analysis, the cost to achieve 0.50 cfm/ft^2 was estimated to be $15,700; to achieve 0.25 cfm/ft^2, the estimated cost was $34,140, including attic sealing costs of $8,200 and top floor sealing costs of $7,500 to achieve 0.50 cfm/ft^2. Additional weatherization for the two bottom floors and sealing doorways to achieve 0.25 cfm/ft^2 would add approximately $18,440. Figure 3 shows the average simple payback period for each climate zone studied. Improving building airtightness is usually cost-effective in all but mild climates.

Conclusions

Since introduction of the requirements to air barrier and a maximum allowable air leakage rate, several Army buildings were constructed and tested for airtightness. Some of them were proven to have an air leakage rate between 0.16 and 0.25 cfm/ft^2 at a pressure difference of 75Pa. Few buildings have to be sealed and re-tested to meet these requirements. This experience has proven, that when buildings are designed and constructed withy attention to details, U.S. Army requirements to airtightness can be met with a minimal cost increase (primarily for development of architectural details and testing).

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WBDG. U.S. Army Corps of Engineers Air Leakage Test Protocol (to be posted on the website).

TABLE 1: Test results for selected Army buildings

Bldg	Envelope Surface Area, (sq ft)	Envelope Volume (cu ft)	ACH @ 50 Pa	Envelope Air Leakage @ 75 Pa (cu ft/m-sq ft)
A	23,300	137,300	4.6	0.57
B	37,200	269,100	3.6	0.56
C	33,600	230,200	5.5	0.77
D	55,000	590,200	2.9	0.65
E	80,700	690,000	3.3	0.63
F	43,000	345,000	1.6	0.28
G	9,700	**	**	0.38

TABLE 2: Comparisons between the USACE requirement and other standards

Conversions made for a building, 120 x 110 x 8 ft, 4 stories n=0.65	Test pressure (Pa)	CFM75/ sq ft cfm/ sq ft at 75 Pa
ASHRAE 90.1, leaky	75	0.60
UK 5 $m^3/h/m^2$ Normal, offices and homes	50	0.36
Smoke control standards, 0.1 cfm/ sq ft @ 0.05 in. wc	12.5	0.32
ASHRAE 90.1, average	75	0.30
LEED,1.25 in2 EfLA/100 sq ft envelope	4	0.30
U.S. Army standard is 0.25 cfm/ sq ft	75	0.25
UK 3 $m^3/h/m^2$ Best practice, homes	50	0.21
UK 2 $m^3/h/m^2$ Best practice, offices	50	0.14
Canadian R-2000 1.0 in2 EqLA/100 sq ft envelope	10	0.13
ASHRAE 90.1, tight	75	0.10
The ASTM E779 and E1827 standards are widely used in the U.S. and CGSB 149.10 is widely used in Canada for testing houses. ATTMA TS-1 is used in the UK for commercial buildings and EN13829 is used in Europe for testing houses. The different levels of air leakage units required by certain programs and guidelines are shown. Notice in the differing test pressures that results are referenced to. The levels of air leakage required and the reference pressures both vary over a wide range.		

TABLE 3: Infiltration leakage rates

source	leakage rate at 0.3 in w.g. (75 pa) cfm/sq ft ($l/s/m^2$)	leakage rate at 0.016 in w.g. (4 pa) cfm/sq ft ($l/s/m^2$)	air changes per hour at 0.016 in w.g. (4 pa)
Baseline	1.0 (5.07)	0.15 (0.65)	0.97
Good practice for air sealing retrofit	0.50 (2.54)	0.074 (0.33)	0.48
Best practice for air sealing retrofit	0.25 (1.27)	0.037 (0.16)	0.24

source	leakage rate at 0.3 in w.g. (75 pa) cfm/sq ft (l/s/m^2)	leakage rate at 0.016 in w.g. (4 pa) cfm/sq ft (l/s/m^2)	air changes per hour at 0.016 in w.g. (4 pa)

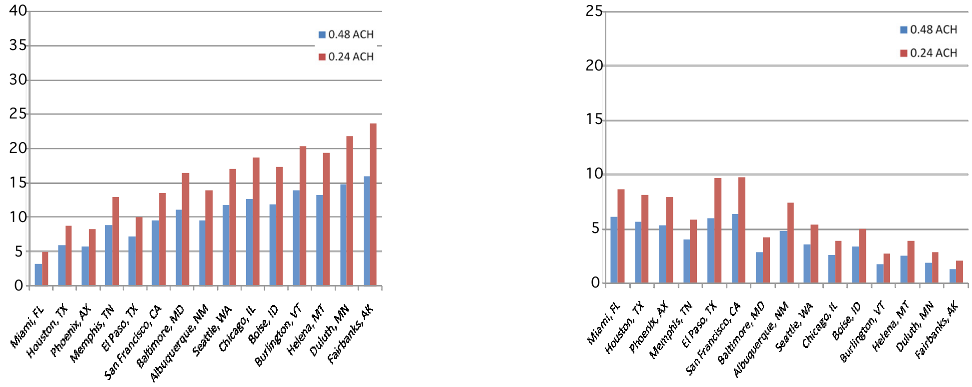

FIGURE 1: Percent annual energy savings for U.S. (left) and international (right) locations

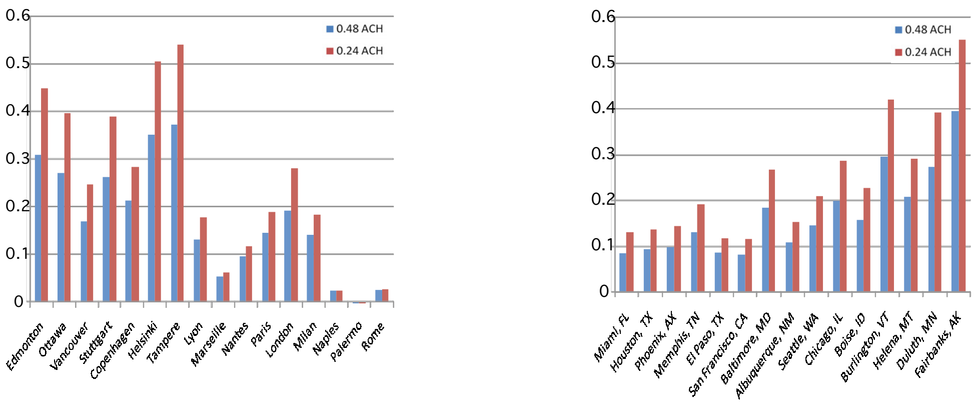

FIGURE 2: Annual energy cost savings per unit area for U.S. (left) and international (right) locations

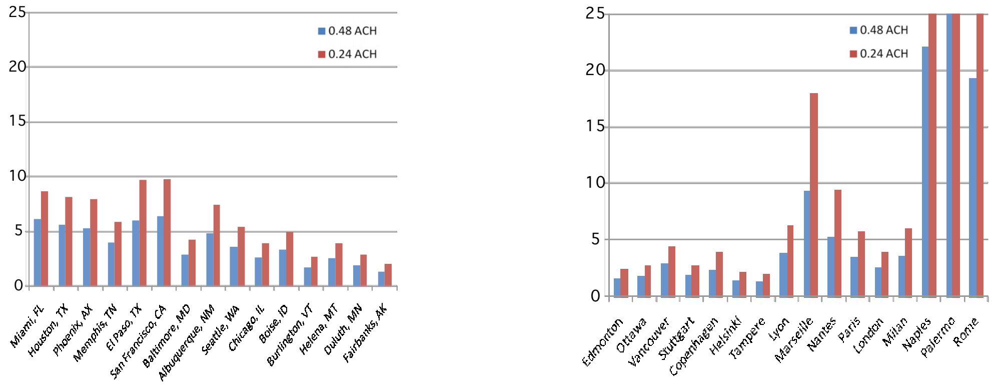

FIGURE 3: SPB period for U.S. (left) and international (right) locations