Air Tightness Improvement of the United States Army Buildings

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Abstract

The Energy Policy Act of 2005 (EPAct05) requires that federal building energy-efficiency performance standards be revised. When shown to be life-cycle cost effective, new federal buildings must be designed to achieve energy consumption levels that are 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) 90.1 or the International Energy Conservation Code.

Along with improvements in energy consumption, building performance in hot humid climates has been a major concern of the Army. Barracks facilities in these environments often experience significant problems with interior mold and mildew as a result of the inability to control relative humidity within the buildings. The Army has been investing large sums of money to remediate mold and mildew damage and maintain these facilities in a healthful and comfortable state. It became clear in considering both issues that building envelope air leakage needs to be addressed.

A consensus standard for building envelope airtightness currently does not exist in the U.S. However there has been a recent groundswell within the building industry to establish such a standard. During the past several years ERDC CERL has been conducting investigations to develop design/construction strategies for improving the energy efficiency, preventing mold and improving indoor air quality in newly constructed buildings and buildings undergoing major renovations. In the course of these studies, it became clear that building envelope air leakage needs to be addressed. To this end, ERDC-CERL has conducted building envelope leakage tests on some existing facilities to gain understanding of the general leakiness of Army buildings, analyzed the effect of increased airtightness on the building energy consumption and developed airtightness criteria and performance requirements to be included into the design/construction strategies.

The paper presents results of airtightness tests on seven barracks and other representative Army buildings and comparison of these results with the data from 139 commercial and institutional buildings in the U.S. Effect of airtightness on the building energy use was studied in collaboration with the National Renewable Energy Laboratory by simulation of two types of buildings: barracks and office buildings using EnergyPlus software. Results of these studies are presented for 15 representative US and 16 Canadian and European climate conditions.

Based on the results of these studies The United States Army Corps of Engineers 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. The test is to be performed according to the outlined in the paper protocol developed by USACE ERDC together with industrial partners.

Air leakage test of selected Army facilities

The most widely accepted test method for using fan pressurization to determine total building leakage in the U.S. is the ASTM E779 *"Standard Test Method for Determining Air Leakage Rate by Fan Pressurization"* (ASTM). Using these procedures, the airtightness parameters of six buildings at four Army installations were determined. Except for one building, the entire conditioned space of each building was tested as a single zone using multiple door fan setups. In one multi-unit barracks, which had a configuration that prevented testing as a single zone, fans were balanced in order to neutralize the test pressure between zones, enabling individual measurements of each zone to be made. . The following steps were used to determine the air leakage parameters (Table 1):

- The envelope surface area and volume of conditioned space for each building were calculated based on review of as-built drawings and field measurements.
- The fan pressurization data was fit to the power law flow function using the equations provided in ASTM E-779-03. Calculations of the leakage airflow at 75 Pascals (Q_{75}) as well as any other leakage parameters can be obtained from the flow function. .
- Air changes per hour at 50 Pascals, and envelope air leakage for surface area at 75 Pa are all derived values.

For each of the buildings that were tested as a single zone, the setup consisted of placing a door fan 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 fans were measured using gauges. Depressurization tests, in which the fans were set to drive indoor air to the outdoors, 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 of the form ($Q = C(\Delta P)^n$. From this function, the two parameters that quantitatively describe the building air leakage, the air leakage coefficient (C) and the pressure exponent (n), were determined.

Prior to testing each building, the HVAC systems were shut down and appropriate sealing measures were performed 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. Mechanical rooms were excluded from the test envelope. In an attempt to adhere to ASTM E-779 preferred test conditions as closely as possible, testing was performed on days with winds typically less than 10 mph.

Barracks at Fort Myer

Fan pressurization tests were conducted on a barracks building at Fort Myer Virginia (Building A). The building (Figure 1) has three stories with exterior walls having a brick masonry cladding on the outside and concrete block on the interior.

Figure 1. Building A - *Barracks at Fort Myer*

Each floor has a central interior corridor with living quarters on both sides, and at each end of the building is a stairwell. The only outside air supplied to the building comes from six fan coil units – two on each floor. The individual vent supplying outside air to each of these units was fixed in the open position leaving a ¾ inch by 18 inch opening through the building envelope. These openings were left unsealed during testing. Fan pressurization tests were conducted with the building depressurized using a double- door fan setup at one end of first floor entry.

Three Barracks at Fort Bragg

Fan pressurization tests were conducted on two similar barracks buildings (Building B and C) at Fort Bragg, North Carolina (Figure 2).

Figure 2. Barracks undergoing renovation at Ft Bragg, NC.

These buildings have brick masonry cladding on the outside, concrete block on the interior and a steep-sloped asphalt shingle roof with a ventilated attic space beneath it. The two building have the same basic configuration. The main center part for both buildings, which is 16 feet shorter in length for Building C, has three stories with each floor having a center interior corridor. Located off of both sides of the corridor are several individual living quarters. Each end of both buildings has a one story annex which includes a day room, foyer and administration wing.

The configuration of each of the individual living quarters in Building B is a large sleeping area for multiple occupants and a shared bathroom along the corridor wall. A fan coil unit is located in one of the corners at the exterior wall. In Building C, the interior 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 located adjacent to the corridor wall. As part of the Building C renovation, each fan coil unit was replaced with an HVAC unit located in a utility closets with access via 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.

For both buildings, the test zone 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. Including the foyer at one end was necessary 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 door fan setups (total of four fans) in one of the double door entrances to the foyer.

Figure 3. Building D - Newly constructed barracks at Ft. Bragg,

Building D (Figure 3) was a newly constructed four storey barracks at Fort Bragg which was tested just prior to commisioning. It has a stairwell at both ends but unlike Buildings B and C it does not have the one storey sections. 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 which have the one plus one configuration.

Dining Facility at Fort Knox

Figure 4. Building E - Newly constructed Dining Facility at Fort Knox

Building E (Figure 4) is a newly constructed one storey dining hall at Fort Knox, Kentucky that includes the space and equipment for food storage and preparation, dishwashing, and dining. It is a brick masonry building with metal stud framing and interior walls of finished gypsum. The roofing system is a steep metal panel system on an insulated metal deck. The attic space above a suspended ceiling is conditioned space. The building required extensive sealing measures to mask the many kitchen hoods prior to testing. Fan Pressurization tests were conducted on the building shortly after completion and before commissioning.

Classroom Training Facility at Fort Leonard Wood

Building F is a classroom training facility at Ft. Leonard Wood, MO. The two storey building was constructed in 1997 and encloses approximately 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, which was not included as part of the test envelope. This area has several tall overhead doors and its own HVAC system. For this study, the CMU wall between it and the classroom wing is treated as part of the test envelope. During testing, air pressure in the high bay was kept at ambient.

The building exterior has brick-clad concrete masonry unit (CMU) walls. Interior walls are constructed of gypsum board attached to metal studs. The common wall between it and the high bay is constructed of CMU. A fluted steel roof deck supports rigid insulation board and a single-ply EPDM rubber membrane roof covering. The floors are poured concrete slabs.

Barracks at Fort Stewart

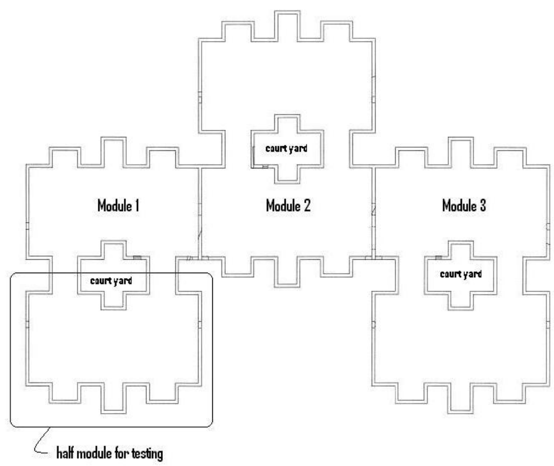

Figure 5. Building G - Barracks at Ft Stewart, GA: façade (left) , floor plan (right)

Building G (Figure 5) at Fort Stewart Georgia is one of several barracks having the same multiple module configuration that were built in the 1970s. It has three stories on slab foundation, exterior walls constructed of CMU and face brick, and concrete floor decks. The buildings underwent major renovation in the 1990s in which the room layouts were converted to their present configuration. As part of the renovation projects, the 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 not part of the conditioned space.

Building G is composed of three modules (Figure 6) 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 (Figure 7). 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. As an alternative test approach, balanced fan pressurization tests were simultaneously conducted on individual floors of a half module to eliminate interior leakage between floor and ceiling partitions. The leakages through the shared interior wall partitions of the adjacent module were assumed to be negligible. To be able to test in this manner, mock walls were erected at both ends of the breezeways of each floor. The walls were constructed of 2" x 3" framing lumber and 6 mil thick polyethylene sheeting. The three mock walls that were placed adjacent to the stairwell end had framed 3' wide openings for placement of a door fan apparatus. Tested in this manner, an entire floor of the half module functioned as a single zone with a door fan assembly placed on each floor being tested.

During testing, all three floors were depressurized 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. The parameters for the derived power law flow curve, shown in Table 1, represent the estimated envelope leakage.

Discussion of Results

The envelope leakage values (@ 75 Pa for the four barracks (Buildings A, B, C, D), which had interior entry ways, were in the same range - 0.56 to 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 that were constructed 30 years earlier. When examining the data for two buildings of like construction and configuration at Fort Bragg, the renovated Building C is more than a third leakier than the 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 building for several hours after sealing measures were performed and just prior to testing). The lower value for the flow exponent (near 0.5) gives some indication of this. The classroom training facility had the lowest envelope air leakage and the new dining hall was as leaky as the least airtight barracks that were tested.

Table 1. Test results for selected Army buildings

Bldg	Envelope Surface Area, ft^2	Envelope Volume, ft^3	ACH @ 50 Pa	Envelope Air Leakage @ 75 Pa (ft^3 / m-ft^2)
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

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

US Army requirements to air leakage

Since 2007 US Army Corps of Engineers require 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 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” w.g.(75 Pa). Different standards used for building envelope air tightness use different units. Comparisons between the USACE requirement and other standards is shown in Table 2. For the sake of comparison, a requirement of 0.25 cfm at 75 Pa/ ft^2 is converted to several commonly used units. Conversions will change for different buildings when comparing air change rates since volume and areas are not directly related. Where different reference pressures are used, conversion results will vary somewhat at the n value or exponent of the flow equation (flow = C x Pressure ^{n}).

Table 2. Units conversions for 0.25 CFM75/ft^2 to other common units made for a building 120 x 110 x 8 ft, 4 stories n=0.65

0.25 cfm/ ft^2 at 75 Pa	Used by ASHRAE and US Army Corp
0.19 cfm/ ft^2 at 50 Pa	Used by some US researchers and an ASHRAE article

1.06 in^2 EfLA/100 ft^2 at 4 Pa	Used by US building scientists to calculate natural air exchange in houses
2.53 in^2 EqLA/100 ft^2 at 10 Pa	Used in Canada and other countries
1.12 Air Changes per hour at 50 Pa	Widely used for houses, but not useful for comparisons in high rise buildings because volume to area ratios change so much.
3.51 $m^3/hr/m^2$ at 50 Pa	Used in the UK to rate the permeability of commercial buildings
1.27 liters/s/^{2} at 75 Pa	Used by researchers in US, Canada and Europe for high rise buildings

In Table 3, conversions of required air leakage levels are expressed in the same units of cfm/sq ft at a test pressure of 75 Pa.

Table 3.

Conversions made for a building, 120 x 110 x 8 ft, 4 stories n=0.65	**Test pressure (Pa)**	**cfm/ ft^2 @ 0.3 in.w.g. (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/ ft^2 @ 0.05 in. wc	12.5	0.32
ASHRAE 90.1, average	75	0.30
LEED,1.25 in^2 EfLA/100 ft^2 envelope	4	0.30
US Army standard is 0.25 cfm/ ft^2	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 in^2 EqLA/100 ft^2 envelope	10	0.13
ASHRAE 90.1, tight	75	0.10

The ASTM E779 and E1827 standards are widely used in the US 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.

To streamline the construction process and to provide a straight forward requirements for air tightness testing, USACE in collaboration with the private sector [ASHRAE 2009, WBDG], has developed a Protocol that gives the tester a step-by-step approach for preparing and testing buildings for air tightness. The test Protocol was developed by the US Army Corps of Engineers in collaboration with industrial partners: Retrotec Inc, USA; Professional Investigative Engineers (PIE), USA;

BCRA, USA; and Camroden Associates, USA to achieve meaningful and repeatable results on high rise commercial and residential buildings.

The Protocol uses ASTM E-779-03 as a basis, but includes numerous modifications and adjustments that are needed to:

(1) account for the large bias pressures (due to wind and stack) that are commonly found in high-rise buildings and

(2) strike a balance between accuracy, repeatability and ease of use with a variety of door fan equipment.

The Protocol requires that the test consists of measuring the flow rates required to establish a minimum of 12 positive and 12 negative building pressures in the following range of pressure differences ΔP: minimum ΔP of at least 25 Pa and a maximum pressure of at least 50Pa and up to 75Pa (if achievable). Uniform interior building pressure must be verified before the test. At least 12 bias pressure readings must be taken across the envelope and averaged over at least 20 seconds each before and after the flow rate measurements. None of the bias pressure readings must exceed 30 percent of the minimum test pressure. The mean value of the air leakage flow rate calculated from measured data at 0.3 in wg (75 Pa) must not exceed the specified value of 0.25 cfm per square foot of envelope area at standard conditions. The envelope area is to be supplied and/or confirmed by the architect of record (AOR).

The Protocol differentiates between buildings with a few doors to the outside (Figure 6) and buildings with individual spaces/apartments having doors to the outside (Figure 7)

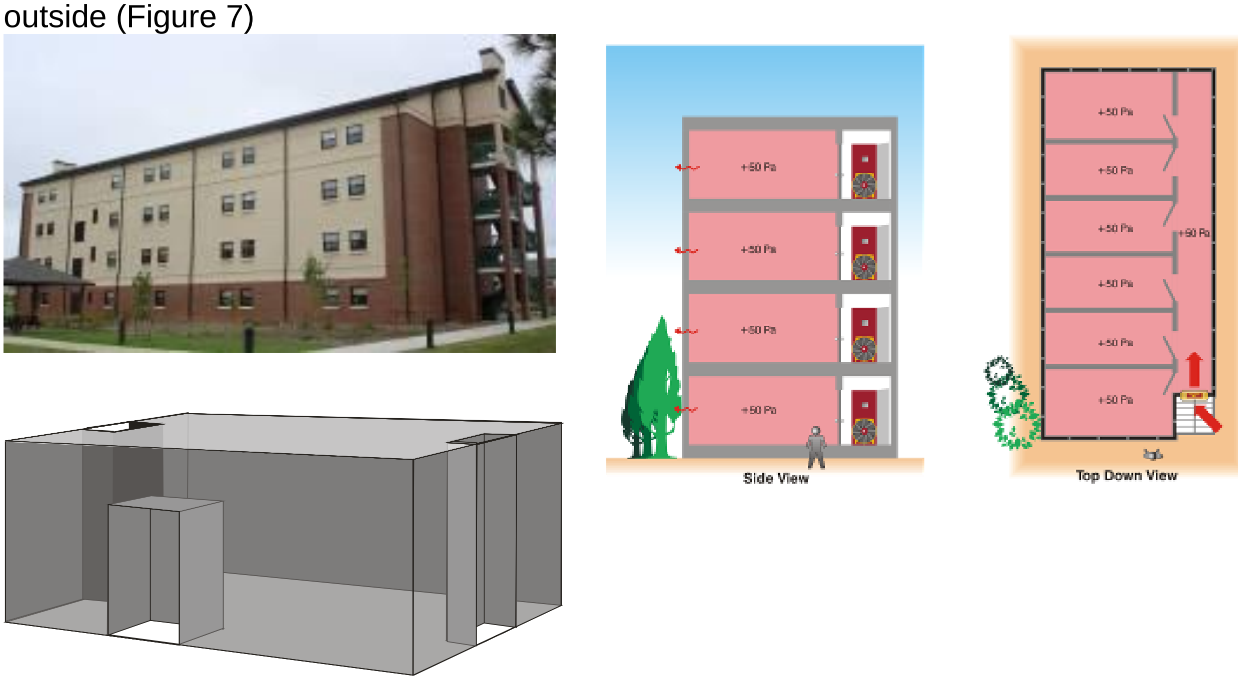

Figure 6: This four-story building (*top left*) has an enclosure that is described by the

shape (*bottom left*). It is accessed by an exterior stairway with no direct interior connection between floors and therefore must be tested with 4 door fans simultaneously to measure the total enclosure leakage (*top right*).

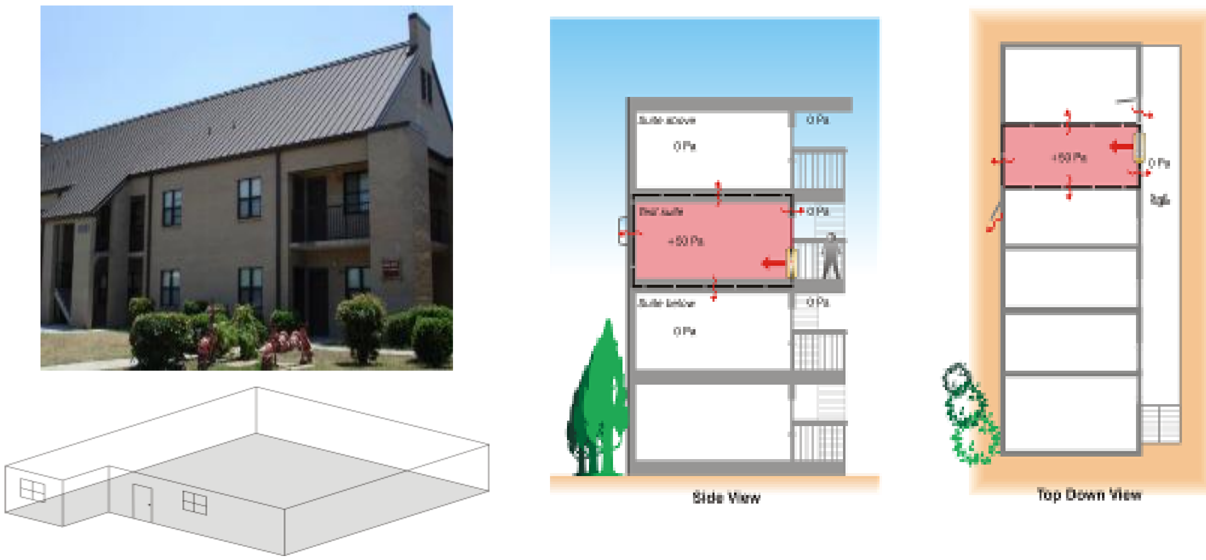

Figure 7: In buildings where individual apartments have doors to the outside (*top left*), the test must be performed on an individual apartment with the adjacent apartments open to outdoors. Perform door fan tests on all corner apartments plus a random 20% of those remaining. If they all pass then it can be assumed the rest of the apartments would also pass. Should any tests fail, test additional apartments until over 90% of all tested apartments pass.

Analysis of potential energy savings with improved air tightness

Uncontrolled air transfer through the building envelope markedly increases the energy required to heat, cool and control humidity in buildings. To estimate the achievable savings, a number of pre- and post-retrofit year-long simulations were performed using the EnergyPlus 3.0 building energy simulation software (DOE 2008), which models heating, cooling and ventilation flows through buildings, among other criteria. 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 to have been built prior to 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 8 AM – 5 PM Monday through Friday. Further details on the barracks and the baseline heating, ventilation, and air conditioning (HVAC) systems used are included in [Benne, 2009]. Analysis was conducted for fifteen U.S. locations and sixteen international locations. The 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). The climate characteristics, energy costs and building details and construction parameters of all 31 simulations are in [Benne, 2009].

Three representative air tightness levels were modeled as shown in Table 4. 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 exponent of 0.65. It is assumed that these fixed infiltration rates represent the average air leakage for the varying conditions.

Table 4 Infiltration Leakage Rates

Source	Leakage Rate at 0.3 in w.g. (75 Pa) cfm/ft^2 (L/s/m^2)	Leakage Rate at 0.016 in w.g. (4 Pa) cfm/ft^2 (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

Simulation Results

The results for improving the building air tightness for each climate zone are shown in Figures 8 through 10. 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, as shown in Figure 8. Expected savings from airtightness improvements decrease in warmer climates. These savings translate to roughly $0.10-$0.50 per sq.ft., according to Figure 9. 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 upon the needs of the building. For this analysis, the cost to achieve 0.50 cfm/sqft was estimated to be $15,700; to achieve 0.25 cfm/sqft, the cost was estimated to be $34,140. This includes attic sealing costs of $8,200 and top floor sealing costs of $7,500 to achieve 0.50 cfm/sqft. Additional weatherization for the two bottom floors and sealing doorways to achieve 0.25 cfm/sqft would add approximately $18,440. Figure 10 shows the average simple payback period for each climate zone studied. Improving building air tightness is usually cost-effective in all but mild climates.

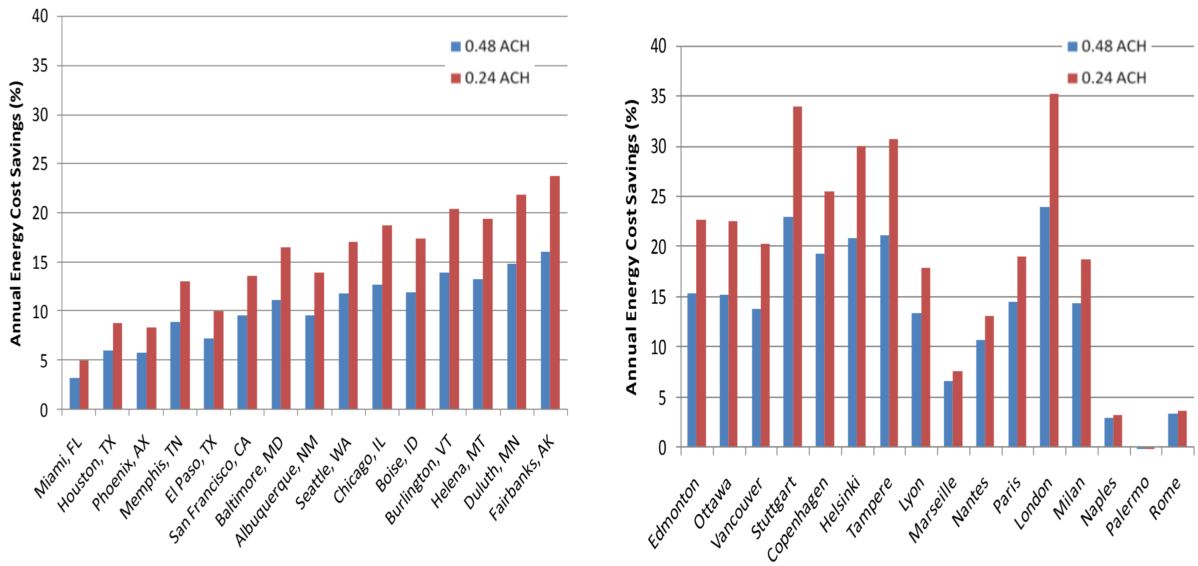

Figure 8: Percent Annual Energy Savings for U.S. (left) and International (right) Locations

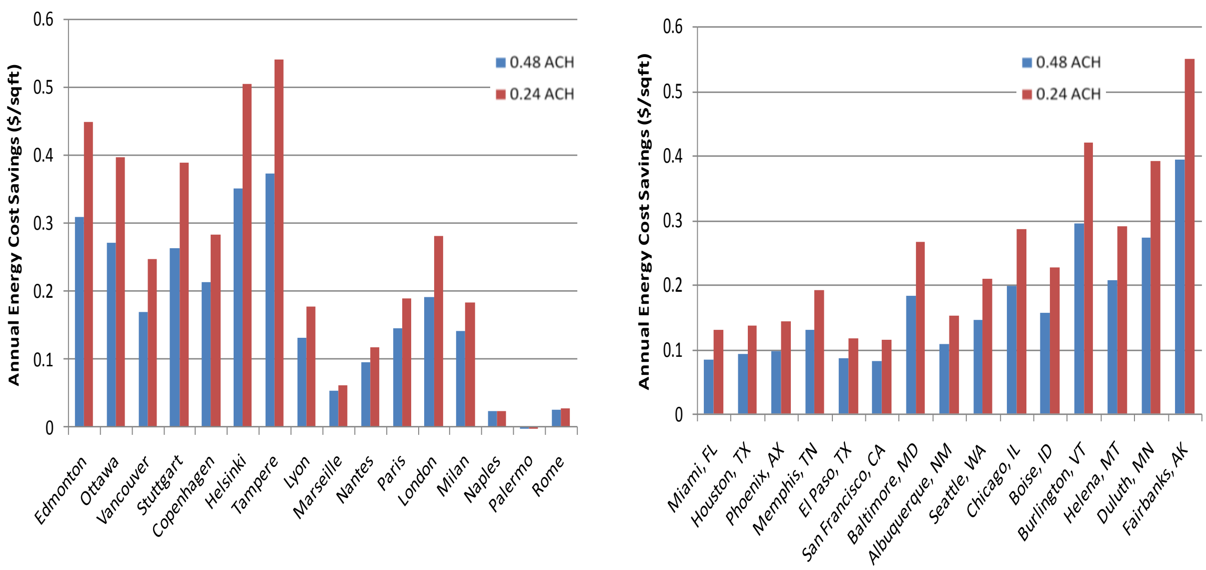

Figure 9: Annual Energy Cost Savings per Unit Area for U.S. (left) and International (right) Locations

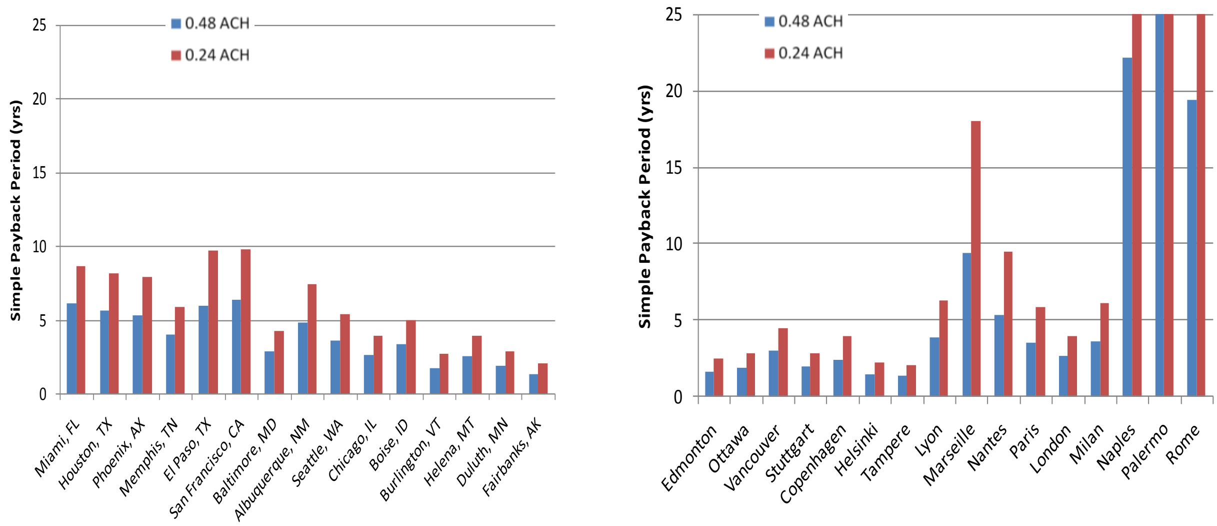

Figure 10: SPB Period for U.S. (left) and International (right) Locations

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 with 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).

Acknowledgement

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