Tangible Benefits of Improved Building Airtightness

Alexander Zhivov, PhD1
Fellow Life ASHRAE member

Martin Page, Ph.D.

Yongkyu An

Nicholas Alexander, PE

ABSTRACT

In 2012 the United States Army Corps of Engineers (USACE) adopted an air barrier tightness standard that requires new buildings and buildings undergoing major renovation to be tested and subsequently to pass a stringent building air barrier tightness test to make sure the building air leakage does not exceed 0.25 cfm/ft^2 at 0.3 in. w.g. (4.6 m^3/h/m^2 at 75Pa) pressure difference between inside and outside air. Since the introduction of this requirement, more than 1000 buildings have been constructed and renovated with the average leakage rate of ~0.15 cfm/ft^2 at 0.3 in. w.g. (2.7 m^3/h/m^2 at 75Pa) after tightening. Analysis conducted by U.S. Army Engineer Research and Development Center (ERDC) researchers and USACE engineers shows that improved airtightness of the building envelope yields significant energy savings, especially in extreme (cold and hot/humid) climates, and also helps to reduce the risk of interstitial condensation and to improve building resilience (temperature degradation inside the building) when the building's power supply, heating, or cooling is interrupted. Improved airtightness also reduces the amount of outdoor air supply required for over-pressurization to prevent infiltration of outdoor air or contaminants. Based on a comprehensive review of research results and economic analyses, it is proposed that a more stringent requirement to building air tightness of 0.15 cfm/ft^2 at 0.3 in. w.g. (2.1 m^3/h/m^2 at 75Pa) be considered in the future, particularly for extreme climates. This paper describes recent research results that show the importance of improved building air tightness.

INTRODUCTION

Airtightness of the building envelope assists in providing various important building functions. Functions typically of the highest importance (and are of particular importance in cold climates) are the control of infiltration or exfiltration to reduce the risk of interstitial condensation, and the control of infiltration to reduce building energy consumption. Airtightness can also impact thermal comfort, indoor air quality, including reducing susceptibility to infiltration of particulate contaminants associated with wildfire smoke or potential chemical, biological and radioactive (CBR) releases, acoustic separation, and mechanical ventilation performance. The contribution of airtightness to thermal resiliency of buildings whereby a tighter building can maintain temperature longer during a power outage or heating, ventilating, and air-conditioning (HVAC) system failure is also of increasing importance.

---

[1]**Alexander Zhivov** is a Senior Research Engineer, Martin Page is a Senior Scientific Technical Manager, and Yongkyu An is a Research General Engineer, all at the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL), Champaign, Illinois. Nicholas Alexander is a Senior Construction Representative at the U.S. Army Corps of Engineers, Colorado Springs, CO.

Historically, the building industry has taken a component approach to airtightness, typically specifying the airtightness of individual materials, systems, or products that form part of the building air barrier systems. It is now well recognized that, while the airtightness of these elements is important, it is not solely sufficient to ensure that an airtight building envelope is achieved. This is because critical air leakage locations are typically found at the interfaces between these elements; reducing air leakage at these locations is highly dependent on design coordination and quality control through the construction process. As a result, more modern codes and standards have developed a preference for whole-building airtightness testing as a quality assurance measure to evaluate the adequacy of the installed air barrier system.

AIR BARRIER

Testing. Airtightness testing of large buildings in cold climate regions has been used for research purposes since the early 1970s in Canada by the National Research Council, and later in the mid-1980s in the United States by the National Bureau of Standards, and in Great Britain by the Building Services Research and Information Association (Potter 1998). On October 30, 2009, the United States Army Corp of Engineers (USACE) issued a directive in Engineering and Construction Bulletin (ECB) 2009-29, which required that the air leakage rate of all new buildings and of those undergoing major renovations not exceed set values when tested in accordance with the U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes (test protocol). This test protocol, which was developed with the assistance of private industry using ASTM E779, was updated in 2012 and subsequently became a part of Unified Facilities Criteria (UFC) 3-101-01, *Architecture*, which includes specifications that define U.S. Army, Navy, and Air Force requirements for continuous air barriers and pressure testing to determine overall air leakage in all new and major retrofit construction projects. ASTM E779-19, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, was also updated to include the information derived from thousands of recent case studies.

Between 2010 and 2014, the U.S. Department of Defense (DoD) published additional Unified Facility Guide Specifications (UFGSs) to improve Air Barrier Systems and Pressure Testing to contractually support performance requirements and to complement the testing protocol for DoD facilities (available via the *Whole Building Design Guide* website: https://www.wbdg.org/dod/ufgs). The contractual basis of this requirement was mandatory, and envelopes that failed the pressure testing were analyzed for deficiencies and corrected until a passing result was achieved. This shifted the responsibility for the success of pressure testing to the design and construction phases since, in many cases, both entities must coordinate to resolve issues related to a failed test. In a small number of cases, facilities were ultimately unable to meet the performance requirement. In these cases, the primary contributing factors are typically: (1) poor design documents due to a failure to properly detail the continuity of the envelope, (2) contractor and sub-contractor failure to maintain continuity during the construction phase, and (3) poor-quality workmanship. These issues are most often the direct result of a lack of knowledge and understanding of the requirement and the effort needed to achieve the performance standard. Nevertheless, in the United States the knowledge base in the area of envelope continuity and airtightness is slowly expanding to include the experiences of design, construction, and testing teams on DoD projects and in the private industry, driven by the growing development of state, county, and municipal requirements. Implementation of this broader knowledge base will improve the quality of building envelope airtightness and continuity, and further inform the concepts and requirements that support the performance standard.

In contrast, airtightness testing (termed “air permeability testing” in Europe) has developed into a robust building envelope commissioning industry that is used in conjunction with other commissioning tools to verify the air barrier and building envelopes overall performance. While all buildings will have some level of leakage, building envelope testing and commissioning requirements will significantly reduce the prevalence and significance of leaks, ultimately reducing moisture-related issues and energy loss associated with leaks. The air tightness performance requirement is a direct measure of the quality of the building envelope; as such, quality control measures and processes are critical across all phases of a project to ensure that the building successfully passes the airtightness test.

Quality Control and Quality Assurance. Airtightness testing should be used only as one part of a comprehensive Quality Control/Quality Assurance program, which also includes air barrier design development, review, air barrier inspections, infrared thermography, and other field level diagnostics or tests.

Designing continuous air barrier control layers and developing envelope continuity in the design documents is a critical step for success. Complete, comprehensive, detailed and coherent design documents set the basis for the contractor's bid and construction efforts for the project. The design team must use the concept of envelope continuity to develop drawings and specifications that maximize the continuity of the air barrier layer. Drawing details are of the utmost importance; they must result in building features that not only pass the pressure test, but that create a durable envelope that prevents moisture intrusion over the long term.

During the construction phase, field inspections should be performed by knowledgeable, qualified personnel to ensure that proper materials and installation techniques are being used and that continuity is being maintained. All of the critical interfaces, materials, and systems must be inspected during construction. Specification requirements and/or industry related standards or processes should be followed to both control and ensure good quality work. Air Barrier Association of America's (ABAA's) guidelines and Quality Assurance Program provide the basis for field quality control and quality assurance and are excellent tools for achieving the performance requirement. Overall, the quality control process should include observation and testing of a significant sample of details that cover typical weaknesses in the air barrier, including all transitions in geometry and materials. Infrared thermography should be used to locate and qualitatively ascertain the magnitude of air leaks. This can be done proactively before final testing if there are concerns regarding the quality of the work installed. When the testable envelope is complete, the building envelope pressure test should be performed according to the test standards and contract requirements. This ultimate test of the building envelope marks a major milestone in the overall project delivery process, i.e., when the pressure test is performed and the diagnostic investigation for leak detection is completed. While it is not possible to have a perfect air barrier, it is possible to fully achieve high levels of continuity with minimal defects. Even when a building has passed the airtightness test, result diagnostics should be performed to locate any locations that may still be incomplete, defective, or that may lead to long-term energy or moisture-related issues noted for correction. Careful attention to detail will ensure that the building both meets and surpasses the performance requirement.

Requirements for air tightness and test results. Since 2009, the U.S. Army Corps of Engineers (USACE) has implemented an airtightness requirement in nearly 2000 new construction and building envelope renovation projects. ECB 2012-16 (HQUSACE 2012) set levels of airtightness for building envelopes at the material, assembly, and system-level at a maximum air leakage of 0.25 cfm/ft^{2} ^{2} at 0.3 in. w.g. (3.5 m^3/h/m^2 at 75 Pa) for the six-sided building envelope (Zhivov et al. 2014). This airtightness requirement is comparable to England's H.M. Government Non-Dwelling Building Code Regulation, 2010-16 L2a, which currently requires 0.21 cfm/ft^2 at 0.3 in. w.g. (2.9 m^3/h/m^2 at 75Pa). ASHRAE 90.1-2022 has recently reduced its leakage requirement standard from 0.40 cfm/ft^2 at 0.30 in. w.g. (7.3 m^3/h/m^2 at 75Pa) to 0.35 cfm/ft^2 at 0.3 in. w.g. (6.4 m^3/h/m^2 at 75Pa), and has expanded its requirements for building envelope performance throughout the standard. ASTM E 3158 *Standard Test Method for Measure the Air Leakage Rate of Large or Multizone Building* (released in 2024) is a comprehensive new standard for building envelope pressure testing commensurate with the original USACE Building Envelope protocol. The new standard encompasses the critical points of the building envelope test and is a single standard for a building pressure test, for use across the spectrum of building types.

DoD projects have been required to implement building envelope airtightness requirements for nearly 2 decades, which has dramatically improved the level of understanding, design considerations, and construction methods of air barriers in the United States. Improvements in design, air barrier products, and installation practices have occurred during each construction cycle since 2009, resulting in a progressive learning curve for all parties involved (Leffel 2021).

Results derived from the testing of 768 buildings between 2009 and 2024 collected by USACE Omaha District have shown that air leakage in new and renovated buildings contracted to meet the USACE airtightness requirement of 0.25 cfm/ft^2 at 0.3 in. w.g. (4.6 m^3/h/m^2 at 75Pa) varied between 0.3 cfm/ft^2 at 0.3 in. w.g. (5.5 m^3/h/m^2 at 75Pa) and 0.25 cfm/ft^2 at 0.3 in. w.g. (4.6 m^3/h/m^2 at 75Pa) with an average air tightness of

0.17 cfm/ft^2 at 0.3 in. w.g. (3.1 m^3/h/m^2 at 75Pa). These results cover the full spectrum, including the envelope wall, different roof types, and a wide array of facilities, from hospitals and office type buildings to fire stations and barracks. One of the broad scale observations from this information is that the DoD performance requirement is readily achievable, but also that prevailing design and construction practices of building envelopes in the United States are functionally incomplete with regard to envelope continuity. In general, many of the defects that occur involve materials or locations where continuity should be an intrinsic feature resulting not just one with a performance requirement, but from a complete design and proper construction practices applicable to any building. More specifically, leakage points commonly occur in certain distinct locations where, with proper attention during design and construction, such faults can be prevented.

COMMON LEAKAGE LOCATIONS IN BUILDING ENVELOPE

Air leakage points in building envelopes can be grouped into several typical locations across the spectrum of building types. These leakage locations should be examined, evaluated, and noted during the building envelope pressure test performed under ASTM E 779, *Standard Test Method for Determining Air leakage by Fan Pressurization* or ASTM E 3158, *Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building*. The most common diagnostic method for identifying these areas is with a thermal imaging camera, as described in ASTM E 1186m *Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems*. In common practice, internal thermal examination and diagnostics are performed under negative pressure; conversely, the exterior is examined under positive pressure. Areas noted as having workmanship deficiencies or system discontinuity are to be noted in the final report so proper corrective action can be completed to ensure contract compliance and maximum continuity of the air, water, and vapor control layers, as feasible. This is of greater significance for buildings that reside in challenging environments, or that are of critical importance. Thermal images of common areas of concern are particularly helpful in exemplifying the significance and magnitude of leakage locations in building envelopes. It is critical that the Infrared Thermography Inspector have sufficient knowledge, experience, and familiarity with the project structure envelope and structure design to recognize the differences between thermal anomalies caused by air leakage and those caused by thermal bridging. Both types of thermal anomalies often occur at the same building envelope locations. Anomalies caused by air leakage can overlap, exaggerate, or even obscure anomalies from thermal bridging. Thermal bridging anomalies typically have shapes different from those of air leakage anomalies. Building components typically have straight edges so that anomalies resulting from thermal bridging are likely to consist of straight edges with more gradual transitions of temperature. Air leakage drawn across smooth surfaces tends to produce anomalies with wispy edges and feathery projections. Air leakage drawn through complex shapes causes the surfaces to absorb heat from the air and tends to have rounded shapes and smooth edges. For more detailed discussion of these differences and examples see Appendix H-4.2 of the *Deep Energy Retrofit Guide* (Zhivov and Lohse 2017).

The following Figures 1 to 4 show examples of these leakage locations that will help project delivery teams to achieve low leakage envelopes in any environment.

Roof-to-Wall Interface. The roof-to-wall interface is one of the most common areas for leakage of any location. The two main factors that create problems in this area are incomplete or incorrect design details and/or poor installation of the materials. The complicated geometry in this location adds to the difficulty as there are often structural elements, joist tails, or other assemblies that are overlooked or that are difficult to seal. It is critical that both designers and contractors pay special attention to this area. The thermal image depicted in Figure 1 clearly shows extensive air leakage at the roof-to-wall interface while the building is under positive pressure.

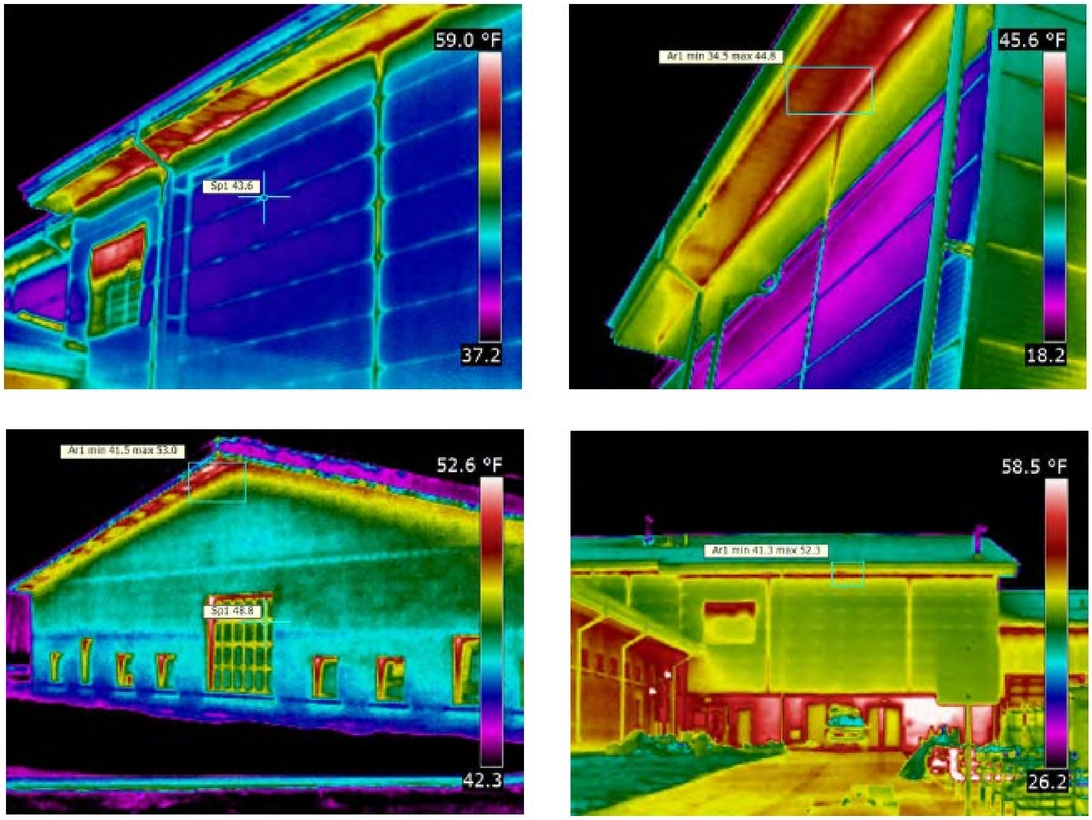

Figure 1 Air leakage at the wall to roof interface (Source: Nickolas Alexander)

Foundation-to-Wall Interface. The foundation-to-wall interface is a common area where significant leakage occurs. Improper flashing, flashing or sealant discontinuities, and poor detailing are the most common issues contributing to leakage in this location. Figure 2 depicts air leakage infiltrating the envelope while the building is under negative pressure. Note the feathery and wispy expression of the air leakage.

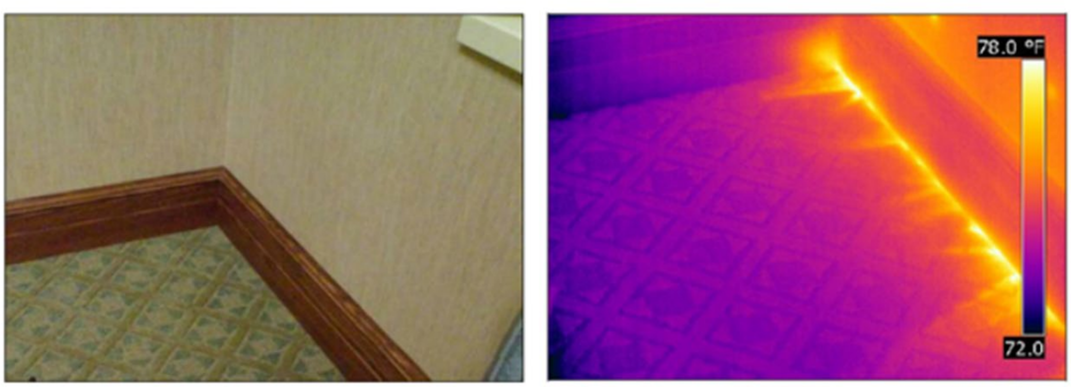

Figure 2 Air leakage at the wall-to-foundation interface (Source: Nickolas Alexander 2025)

Penetrations. Penetrations are likely the second most common area for leakage in building envelopes. Many of these penetrations are built haphazardly in the field and are overlooked and poorly detailed. Many of the contractors or subcontractors that make penetrations in the control layers of the building envelope are not fully aware of the implications of failing to seal the defects caused by cutting penetrations through the control layer and often leave damage and discontinuities that leak significantly. Figure 3 depicts a significant leak around an exterior electrical outlet while the building is positively pressurized. This leak is less wispy or feathery in its expression through the thermal camera. Figure 4 shows an example of a significant air leak at a column penetration through the building envelope during positive pressurization, indicated by the red arrow. Additionally, this figure shows thermal bridging on the steel column and the transitional thermal gradient change of thermal bridging from the envelope penetration of the column to just above the ground.

Figure 3 Air leakage identified around through-wall electrical and gas penetrations. (Source: Nickolas Alexander 2025)

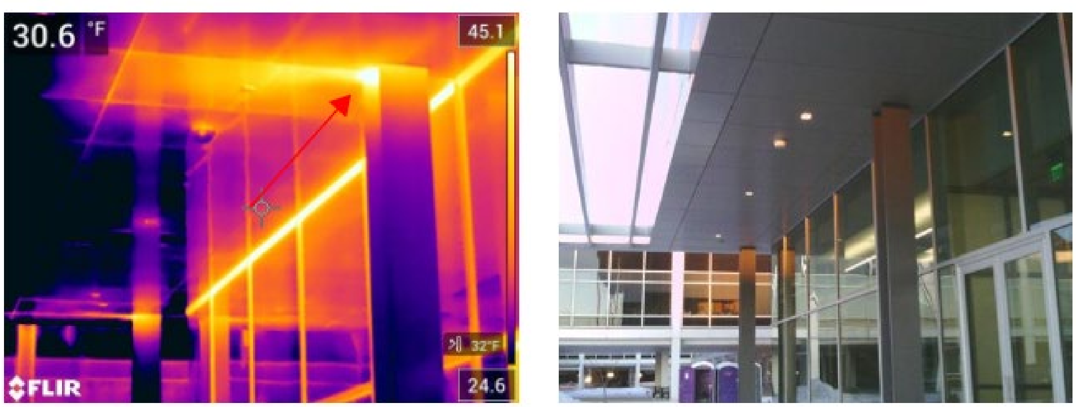

Figure 4 Air leakage identified at the interface of the sofit and structural columns (Source: Nickolas Alexander 2025)

BENEFITS OF AIR TIGHTNESS

Energy Savings. To estimate the achievable savings from reduced air leakage in newly constructed and retrofitted buildings, U.S. Army Engineer Research and Development Center (ERDC) and National Renewable Energy Laboratory (NREL) researchers conducted simulation studies using EnergyPlus 3.0 building energy simulation software (Zhivov et al. 2014). The baseline building was assumed to be an existing barrack, dormitory, or multi-family building built to meet the minimum requirements of ASHRAE Standard 90.1-1989. Four representative airtightness levels were modeled: 1.0, 0.4, 0.25, and 0.15 cu ft/m-ft^2 (at 75 Pa pressure difference). The first value, which was used as the baseline, was derived from expert opinion of existing buildings based on pressurization tests. The other three values represent reasonable performance improvements that may be achieved using low, medium, and best efforts to seal existing buildings. Figure 5 shows the results of an analysis for improving the building airtightness for each climate zone. The energy savings are based on total building site energy consumption.

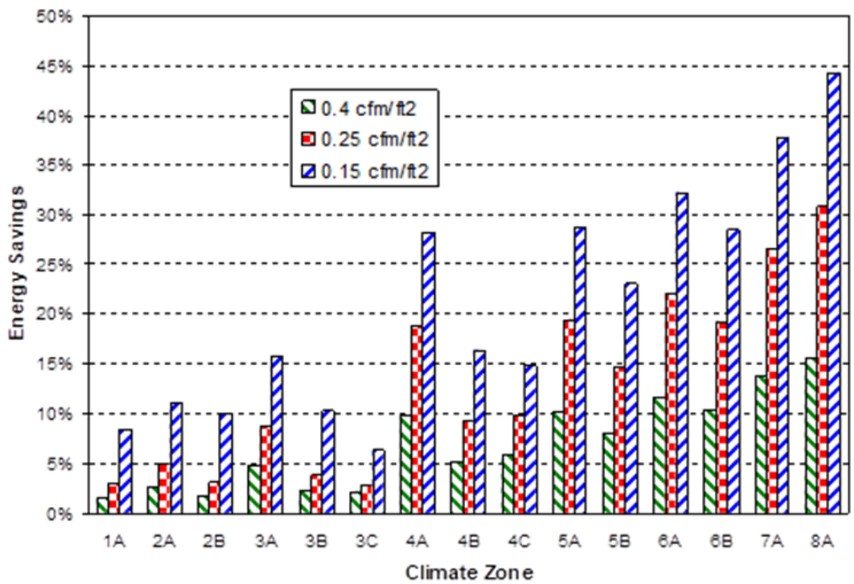

Figure 5 Percent annual energy savings in a reference barracks/multi-family building built to meet the minimum requirements of ASHRAE Standard 90.1-1989 with airtightness level of 1.0 cfm/ft^2, at 75Pa) due to air tightness improvement for U.S. climate zones. Source: Zhivov et al. (2014)

Energy savings range between 2 and 16% with the airtightness improvement to 0.4 cfm/ft^2 at 0.3 in. w.g. (5.6 m^3/h/m^2 at 75Pa); between 3 and 31% with the airtightness improvement to 0.25 cfm/ft^2 at 0.3 in. w.g. (4.6 m^3/h/m^2 at 75Pa); and between 8 and 44% with the airtightness improvement to 0.15 cfm/ft^2 at 0.3 in. w.g. (2.7 m^3/h/m^2 at 75Pa). The results are highest in the coldest climates and decrease in warmer climates. These savings translate to roughly $0.10-0.50 per ft^2 of floor area. The results can vary with the change of baseline building airtightness, types of HVAC systems used, and energy rates.

Mold control. Results of multiple studies show that air leakage through building envelopes, in cold climates, can cause condensation, mold growth, and damage to building materials, especially in lightweight wood frame constructions as demonstrated by Belleudy et al. (2015), Janssen and Hens (2003), Tenwolde and Rose (1996), Armstrong et al. (2010).

Table 1 lists example results of moisture transfer calculations for seven building types in Chicago, IL (Shrestha et al. 2019). A change in the building airtightness of the building envelope from 1.5 cfm/ft^2 at 0.3

in. w.g. (21.0 $m^3/h/m^2$ at 75Pa) to 0.25 cfm/ft^2 at 0.3 in. w.g. (4.6 $m^3/h/m^2$ at 75Pa) can reduce the moisture transfer through the cracks in the building envelope by 47 to 89% depending by the building type and therefore reduce the risk of mold.

Table 1. Moisture Transfer for Different Building Types at Two Different Airtightness Levels in Chicago (Shrestha et al. 2019)

Building Type	Moisture Transfer, kg/(m^2*year)		Reduction in Moisture Transfer. kg/(m^2*year) (% reduction)
	at 7.7 L/(s*m^2)	at 1.25 L(s*m^2)	
Standalone Retail	105.7	11.6	94.2 (89)
Mid-Rise Apartment	90.8	14.7	76.1 (84)
Medium Office	103.9	10.5	93.4 (90)
High-Rise Apartment	79.0	27.8	51.2 (65)
Hospital	73.1	12.1	61.0 (83)
Large Hotel	112.9	60.0	52.9 (47)
Secondary School	153.2	40.1	113.1 (74)
Note: 1 kg/(m^2•year) = 0.205 lb/(ft^2•year), 1 L/(s*^{m2}) = 0.2 cfm/ft^2.			

These studies concluded that air leakage is one of the primary causes of moisture damage in conventional light wood frame walls with exterior insulation.

Thermal energy system resilience. Thermal energy systems' resilience is especially important for extreme climates, such as arctic or hot and humid environments. While metrics and requirements for availability, reliability, and quality of power systems have been established (DoD 2020), similar metrics and requirements for thermal energy systems are not well understood. In one of the first attempts to address this deficiency, a study (Oberg et al. 2021; Liesen et al. 2021) was conducted to better determine the level of reliability required for energy supply systems that will be capable of supporting environmental conditions required for the facility's mission, occupant comfort, and sustainment of a building in arctic environments under predominant threat scenarios.

Results of a unique temperature decay test conducted during the winter, along with blower door tests on five representative military buildings in Alaska (Oberg et al. 2021) complemented by the modeling analysis (Liesen et al. 2021) were compared and calibrated to the experimental data collection for the thermal decay test (TDT). A reliable building model resulted from these studies allows us to predict the maximum time available to repair the heat supply system before the building must be evacuated, when damage is done to equipment or facilities critical to the building operations, or when damage is done to the building itself.

Table 2 lists the results of analysis conducted for two building archetypes: (1) high mass building (concrete masonry unit [CMU] and poured concrete slabs) and (2) light-frame buildings with the thermal envelope characteristics: ranging from (1) pre-1980 code construction, (2) current minimum energy efficiency requirements (lower efficiency), and (3) state-of-the-art energy efficient building characteristics (high efficiency), for the buildings constructed in the U.S. Department of Energy (DOE) Climate Zone 8. Results of these studies listed in Table 2 clearly show that high building air tightness (0.15 cfm/ft^2 at 0.3 in. w.g. [2.1 $m^3/h/m^2$ at 75Pa]) combined with a high building mass contributes significantly to the thermal resilience of the building. For example, in the case of simulated interruption of the mechanical heating supply during outside temperature conditions of -40 °F (-40 °C). In the airtight building with a mass structure, the indoor air temperature approached the habitability level of 60 °F (16 °C) 9 hours later than in a building with a less airtight building envelope, and 4 hours later in the case of the framed (i.e., lower thermal mass) building structure. The building sustainability threshold of 40 °F (4 °C) occurs 31 and 27 hours later, respectively, for the same scenarios. Modeling results in (Zhivov et al. 2022) show that the building air tightness has a similar effect on the temperature degradation buildings located in hot and humid climes.

Table 2. Parametric Study Results for the Maximum Allowable Time to Repair (Zhivov et al. 2021)

Building Parameters	Temp ODB	Mass Building Typical/ Post 1980	Mass Building Low Efficiency	Mass Building High Efficiency	Frame Building Typical/ Post 1980	Frame Building Low Efficiency	Frame Building High Efficiency
Walls (R-value, F·ft²·hr/Btu)		20.5	40	50	20.5	40	50
Roof (R-value, F·ft²·hr/Btu)		31.5	45	60	31.5	45	60
Air Leakage (cfm/ft² at 0.3 in. w.g. m³/h/m² at 75 Pa)		0.4/5.6	0.25/3.5	0.15/2.1	0.4/5.6	0.25/3.5	0.15/2.1
Window (R-value), F·ft²·hr/Btu, U-value, W/(m²·K)		Double Pane; R= 1.78 / U=0.56	Double Pane; R= 3.34 / U=0.3	Triple Pane; R= 5.25 / U=0.19	Double Pane; R= 1.78 / U=0.56	Double Pane; R= 3.34 / U=0.3	Triple Pane; R= 5.25 / U=0.19
MaxTTR Hab. (60 °F)	-60 °F (-51 °C)	< 1 hour	2 hours	5 hours	<< 1 hour	1 hours	2 hours
MaxTTR Sust. (40 °F)	-60 °F (-51 °C)	9 hours	28 hours	41 hours	4 hours	14 hours	21 hours
MaxTTR Hab. (60 °F)	-40 °F (-40 °C)	1 hour	3 hours	10 hours	< 1 hour	2 hours	4 hours
MaxTTR Sust. (40 °F)	-40 °F (-40 °C)	20 hours	36 hours	51 hours	10 hours	18 hours	24 hours
MaxTTR Hab. (60 °F)	-20 °F (-34 °C)	2 hours	6 hours	15 hours	1 hour	3 hours	6 hours
MaxTTR Sust. (40 °F)	-20 °F (-34 °C)	31 hours	46 hours	60 hours	15 hours	22 hours	28 hours
MaxTTR Hab. (60 °F)	0 °F (-18 °C)	3 hours	13 hours	29 hours	2 hours	5 hours	9 hours
MaxTTR Sust. (40 °F)	0 °F (-18 °C)	43 hours	59 hours	90 hours	21 hours	28 hours	33 hours
MaxTTR Hab. (60 °F)	20 °F (-6.6 °C)	10 hours	28 hours	45 hours	3 hours	8 hours	15 hours
MaxTTR Sust. (40 °F)	20 °F (-6.6 °C)	60 hours	78 hours	95 hours	28 hours	35 hours	40 hours
MaxTTR Hab. (60 °F)	40 °F (4.4 °C)	29 hours	54 hours	72 hours	8 hours	17 hours	23 hours
MaxTTR Sust. (40 °F)	40 °F (4.4 °C)	93 hours	112 hours	123 hours	41 hours	47 hours	50 hours

Building protection from external contaminants. During wildfires or accidental or premeditated external release of CBR agents, ventilation systems can be designed to supply outdoor filtered air in amounts sufficient to over-pressurize the building to reduce or prevent infiltration. Air tightening the building envelope can reduce the amount of air required to achieve over-pressurization. For a building of given size, shape, and surrounding landscape (which impacts wind pressure), infiltration of outdoor air and contaminants is often driven by wind pressure buoyancy forces created by outdoor and indoor air temperature difference. The range of outdoor air supply and controlled building exhaust parameters can be adjusted to over-pressurize the building against infiltration forces while also limiting pressure to the extent that doors can be safely opened and stay closed, and to avoid oversizing the ventilation system at potentially higher energy cost. Some ASHRAE publications recommend the use of a 10% difference between outdoor air supply and air exhaust rates. The range of pressurization proposed in (Deck and Jester 2024) falls between 0.02 in. w.g. (5 Pa) and 0.1 in. w.g. (25 Pa) with an ideal value of 0.05 in. w.g. (12.5 Pa). Any value greater than 0.1 in. w.g. (25 Pa) will over-pressurize the building, causing doors to swing open by themselves, leading to the inefficiency described above. Table 3 lists the level of building pressurization required for the wind gusts between 0 and 25 mph and an outside temperature between -30 °F and +95 °F (-3 °C and 35 °C) estimated using CONTAM modeling of a simulated generic barracks building (An et al. 2024).

Table 3. Example of Airflow Rates Required for Building Pressurization of a Modeled Residential Three-Story Building 295x262.5x29.5 ft (90x80x9 m) with a Minimum Outdoor Airflow Rate per ASHRAE Standard 62.1 Equal to 43527.9 cfm (1219 m^3/min)

Wind: 0 mph		Required Minimum Airflow Rate for a Building Over-Pressurization									
Building Envelope ($cfm/ft^2/m^3/h/m^2$)		0.15/2.7		0.25/4.6		0.4/7.3		0.8/14.6		1.2/21.9	
		cfm	%	cfm	%	cfm	%	cfm	%	cfm	%
T_{out} (°F)	95	382	0.9%	636	1.5%	1017	2.3%	2033	4.7%	3049	7.0%
	70	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	45	406	0.9%	676	1.6%	1081.	2.5%	2162	5.0%	3242	7.4%
	20	658	1.5%	1096	2.5%	1753	4.0%	3506	8.1%	5258	12.1%
	-5	886	2.0%	1477	3.4%	2362	5.4%	4724	10.9%	7086	16.3%
	-30	1108	2.5%	1847	4.2%	2954	6.8%	5908	13.6%	8862	20.4%
Wind: 10 mph		Required Minimum Airflow Rate for a Building Over-Pressurization									
Building Envelope ($cfm/ft^2/m^3/h/m^2$)		0.15/2.7		0.25/4.6		0.4/7.3		0.8/14.6		1.2/21.9	
		cfm	%	cfm	%	cfm	%	cfm	%	cfm	%
T_{out} (°F)	95	850	2.0%	1416	3.3%	2265	5.2%	4529	10.4%	6794	15.6%
	70	610	1.4%	1017	2.3%	1627	3.7%	3253	7.5%	4879	11.2%
	45	903	2.1%	1505	3.5%	2408	5.5%	4816	11.1%	7224	16.6%
	20	1141	2.6%	1901	4.4%	3041	7.0%	6082	14.0%	9123	21.0%
	-5	1368	3.1%	2280	5.2%	3648	.4%	7295	16.8%	10943	25.1%
	-30	1596	3.7%	2659	6.1%	4254	9.8%	8508	19.5%	12762	29.3%
Wind: 15mph		Required Minimum Airflow Rate for a Building Over-Pressurization									
Building Envelope ($cfm/ft^2/m^3/h/m^2$)		0.15/2.7		0.25/4.6		0.4/7.3		0.8/14.6		1.2/21.9	
		cfm	%	cfm	%	cfm	%	cfm	%	cfm	%
T_{out} (°F)	95	1229	2.8%	2049	4.7%	3278	7.5%	6555	15.1%	9832	22.6%
	70	1034	2.4%	1722	4.0%	2756	6.3%	5511	27%	8266	19.0%
	45	1307	3.0%	2178	5.0%	3485	8.0%	6970	16.0%	10454	24.0%
	20	1538	3.5%	2564	5.9%	4101	9.4%	8202	18.8%	12303	28.3%
	-5	1766	4.1%	2942	6.8%	4708	10.8%	9415	21.6%	14122	32.4%
	-30	1997	4.6%	3328	7.6%	5325	12.2%	10649	24.5%	15973	36.7%
Wind: 25mph		Required Minimum Airflow Rate for a Building Over-pressurization									
Building Envelope ($cfm/ft^2/m^3/h/m^2$)		0.15/2.7		0.25/4.6		0.4/7.3		0.8/14.6		1.2/21.9	
T_{out} (°F)	95	2140	4.9%	3567	8.2%	5706	13.1%	11412	26.2%	17118	39.3%
	70	2007	4.6%	3345	7.7%	5352	12.3%	10704	24.6%	16056	36.9%
	45	2276	5.2%	3793	8.7%	6068	13.9%	12135	27.9%	18202	41.8%
	20	2511	5.8%	4185	9.6%	6695	15.4%	13390	30.8%	20084	46.1%
	-5	2749	6.3%	4582	10.5%	7331	16.8%	14661	33.7%	21991	50.5%
	-30	2997	6.9%	4995	11.5%	7992	18.4%	15984	36.7%	23976	55.1%

The data in Table 3 indicate that the air required for building pressurization significantly depends on the building envelope airtightness and is 4.8 times higher for the leaky building (tested at 1.2 cfm/ft^2 at 0.3 in. w.g. [16.8 $m^3/h/m^2$ at 70Pa]) compared to the airflow rate required to the building built to the UFC requirement of 0.25 cfm/ft^2 at 0.3 in. w.g. (4.6 $m^3/h/m^2$ at 75Pa). The airflow rate can be further reduced by 1.7 times if the building is tightened to 0.15 cfm/ft^2 at 0.3 in. w.g. (2.7 $m^3/h/m^2$ at 75Pa). The data in Table 3 also indicate that the airflow rate required for building pressurization for the buildings meeting the current UFC requirement (0.25 cfm/ft^2 at 0.3 in. w.g.[3.5 $m^3/h/m^2$ at 75Pa]) does not exceed 11.5% of the minimum outdoor airflow rate required for ventilation. The airflow rate for building pressurization will increase to 55% of the ventilation rate for leaky buildings tested to 1.2 cfm/ft^2 at 0.3 in. w.g. (16.8 $m^3/h/m^2$ at 75Pa). If the airflow required for building pressurization is much lower than the required airflow rate for ventilation, significant energy savings can be achieved by heat recovery from the air exhausted by general ventilation system or by reducing energy for the outdoor air heating and cooling by using air recirculation with its filtration in gas filters.

CONCLUSIONS AND RECOMMENDATIONS

Air tightness of buildings has numerous advantages, which include:

- Energy and operational cost savings
- Better indoor air quality and comfort

- Reduced risk of mold, especially in cold and hot and humid climates
- More efficient building protection from external release of harmful matter.

Experience from USACE and the ABAA based on new and major renovation projects collected over the years has proven that building airtightness of 0.25 cfm/ft^2 at 0.3 in. w.g. (4.6 m^3/h/m^2 at 75Pa) is achievable in all types of buildings in all climate conditions and is cost effective.

When design UFGS and ABAA specification are followed, air tightness between 0.05 and 0.25 cfm/ft^2 at 0.3 in. w.g. (0.9 and 4.6 m^3/h/m^2 at 75Pa) has been achieved with the average leakage rate of 0.17 cfm/ft^2 at 0.3 in. w.g. (3.1 m^3/h/m^2 at 75Pa).

Building durability, indoor air quality, energy savings, and thermal resilience justify the need for more airtight building envelopes in extreme climate (cold/very cold and hot and humid regions).

Average test results in combination with airtightness levels shown to be achievable in building envelope airtightness testing around the world highlight a missed opportunity in building airtightness. For these reasons, it is recommended that airtightness requirements for extreme climate regions (cold and very cold, i.e., c.z. 6-8) and hot and humid (c.z. 0-3) be increased to 0.15 cfm/ft^2 at 0.3 in. w.g. (2.1 m^3/h/m^2 at 75Pa) for normal indoor wintertime relative humidity conditions, and 0.10 cfm/ft^2 at 0.3 in. w.g. (1.41 m^3/h/m^2 at 75Pa) for buildings humidified to 30% relative humidity or higher.

ACKNOWLEGEMENTS

This paper results of the research conducted under the U.S. Army "Cold Climate Thermal Resilience Criteria" project, and the International Energy Agency Energy in Buildings and Communities Program Annex 93. Portions of this study were funded by the Defense Threat Reduction Agency through the Enhanced Bioprotection for Facilities.

REFERENCES

An, Y., M.D. Ginsberg, A. Zhivov, D. Lorenzetti, M.A. Page, and M. Sohn. 2024. *Effect of Envelope Tightening on Collective Biological Protection of Buildings*. DTRA Chemical and Biological Defense Science & Technology Conference, Fort Lauderdale, December 2024.

ANSI/ASHRAE/IES Standard 90.1. 1989, 2022. *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Peachtree Corners, GA: ASHRAE.

Armstrong, M., W. Maref, M.Z. Rousseau, W. Lei, and M. Nicholls. 2010. *Effect of the Air and Vapour Permeance of Exterior Insulation on the Flow of Moisture in Wood Frame Walls in a Cold Climate*. International Conference on Building Envelope Systems and Technologies. Vancouver, Canada, 2010.

ASTM (American Society for Testing and Materials). *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*. ASTM E779-19. West Conshohocken, PA: ASTM International.

———. *Standard Test Method for Measure the Air Leakage Rate of Large or Multizone Building* (released in 2024). ASTM E 3158. West Conshohocken, PA: ASTM International.

Belleudy, C., A. Kayello, M. Woloszyn, and H. Ge. 2015. "Experimental and Numerical Investigations of the Effects of Air Leakage on Temperature and Moisture Fields in Porous Insulation." *Building and Environment*. 94:457-466.

Deck, Caleb, and Chris Jester. 2024. "Engineer's Guide to Accurate, Precise Building Pressurization." *ASHRAE Journal*. December 1, 2024.

Goel, S., R. Athalye, W. Wang, J. Zhang, M. Rosenberg, Y. Xie, R. Hart, and V. Mendon. 2014. *Enhancements to ASHRAE Standard 90.1 Prototype Building Models*. PNNL-23269. Richland, WA: Pacific Northwest National Laboratory.

HQUSACE (Headquarters, U.S. Army Corps of Engineers). 2009. Engineering and Construction Bulletin (ECB) No. 2009-29. Subject: Building Air Tightness Requirements. Washington, DC: U.S. Army Corps of Engineers. https://wbdg.org/FFC/ARMYCOE/COEECB/ARCHIVES/ecb_2009_29.pdf.

———. 2012. *Air Leakage Test Protocol for Building Envelopes*. Vol. 3. https://www.wbdg.org/pdfs/usace_airleakagetestprotocol.pdf.

Janssen, A., and H. Hens. 2003. "Interstitial Condensation Due to Air Leakage: A Sensitivity Analysis." *Journal of Building Physics.* 27(1):15-29.

Leffel, Emmett. 2021. "Building Enclosure Testing on Alaska Military Base Projects." *ASHRAE Transactions.* 127(1).

Liesen, Richard J., Brianna Morton, Brandy Diggs-McGee, and Alexander M. Zhivov. 2021. "Thermal Energy System Resilience: Thermal Decay Test (TDT) in Cold/Arctic Climates, Part II Modeling." *ASHRAE Transactions.* 127(1).

Oberg, Bjorn K., Angela Urban, Emmet Leffel, Jonathan Goebel, Matt Perry, Dragos Vas, Dayne Broderson, Richard Liesen, and Alexander Zhivov. 2021. "Thermal Energy System Resilience: Thermal Decay Test (TDT) in Cold/Arctic Climates, Part I Data Collection and Protocol." *ASHRAE Transactions.* 127(2).

Potter, I.N. 1998. *Air Tightness Specifications*. Building Services Research and Information Association, Bracknell, Berkshire.

Som Shrestha, Andre Desjarlais, Laverne Dalgleish, Lisa Ng, Diana Hun, Steven Emmerich, and Gina Accawi. December 2019. "Moisture Transfer in Commercial Buildings Due to Air Leakage: A New Feature in the Online Airtightness Savings Calculator." *Thermal Performance of the Exterior Envelopes of Whole Buildings.* XIV International Conference.

Tenwolde, A., and W.B. Rose. 1996. "Moisture Control Strategies for the Building Envelope." *Journal of Building Physics*. 19(3):206-214.

UFC 3-101-01. 2024. *Unified Facilities Criteria: Architecture*. Ch. 3-6. https://www.wbdg.org/FFC/DOD/UFC/ufc_3_101_01_2020_c4.pdf.

UFGS-07 27 10.00 10. 2019. UFGS (Unified Facilities Guide Specifications). *Building Air Barrier System*. UFGS-07 27 10.00 10. https://www.wbdg.org/FFC/DOD/UFGS/UFGS%2007%2027%2010.pdf.

Zhivov, A., D. Herron, J.L. Durston, M. Heron, and G. Lea. 2014. "Airtightness in New and Retrofitted U.S. Army Buildings." *International Journal of Ventilation*. 12(4):317–330. https://doi.org/10.1080/14733315.2014.11684026.

Zhivov, A., and R. Lohse. 2017. *Deep Energy Retrofit. A Guide to Achieving Significant Energy Use Reduction with Major Renovation Projects*. Springer. ISBN 978-3-030-306-78-6. https://www.wbdg.org/FFC/ARMYCOE/SDP/DER_Major_Renovations_Guide_2017-11-06.pdf.

Zhivov, Alexander (ed.). 2021. *Guide for Resilient Energy Systems Design in Cold and Arctic Climates*. November January 2021. Peachtree Corners, GA: ASHRAE.

———. 2022. *Guide for Resilient Energy Systems Design in Hot and Humid Climates*. November 2022. Peachtree Corners, GA: ASHRAE.