NIST Infiltration Tools for Commercial Buildings

Lisa Ng, PhD
Member ASHRAE

Som Shrestha, PhD, BEMP
Member ASHRAE

Brian Polidoro

W. Stuart Dols
Member ASHRAE

Steven J. Emmerich
Fellow ASHRAE

ABSTRACT HEADING

The Department of Energy estimates that infiltration through building envelopes accounted for 6 % of the total energy consumed by commercial buildings and 21 % of the heating and cooling energy. Air barrier requirements are now being included in ASHRAE Standards 90.1 and 189.1 and other construction requirements. The energy impacts of unintended infiltration on building energy use can be significant, but current energy simulation software and design methods are generally not able to accurately account for envelope infiltration and the impacts of improved airtightness. NIST has been developing tools to better account for infiltration in building energy models. The tools that will be discussed in this paper include: CONTAM Results Export Tool; weather-correlated infiltration inputs for prototype commercial buildings and the associated Open Studio Measures; and a web-based tool to evaluate the energy savings of building envelope airtightening, which was developed with the Oak Ridge National Laboratory and the Air Barrier Association of America. This paper briefly describes each tool, their applications, and the benefits of using each. All of the tools are publicly available at no cost.

INTRODUCTION

Heating, ventilating, and air-conditioning (HVAC) systems in buildings are designed to provide acceptable thermal comfort and indoor air quality (IAQ). The energy cost of operating these HVAC systems is 37 % of the primary energy consumed in the U.S. (EIA 2019). Infiltration through building envelopes alone accounted for 6 % of the total energy consumed by commercial buildings (DOE 2014). Given the current emphasis on reducing building energy consumption and associated environmental impacts, the use of energy simulation software has increased to investigate different design options and in some cases, to comply with energy design standards (ASHRAE 2016; CEC 2016). One design option to reduce building energy use is the improvement of building envelope airtightness. Existing data show that unless efforts are made to design and build tight building envelopes, commercial buildings could be leakier than typically assumed by energy modelers (Emmerich et al. 2007; Emmerich et al. 2014). Thus, the energy impacts of infiltration are often underestimated during design.

Current energy simulation software and design methods generally do not accurately account for envelope infiltration, and therefore the impacts of airtightness on energy may not be fully captured. A review of the airflow analysis capabilities of energy simulation software tools found that many of the empirical infiltration models employed in these tools are based on calculation methods developed for low-rise, residential buildings (Ng et al. 2011). These empirical infiltration models also require the user to specify air leakage coefficients that are obtained from building pressurization tests (ASTM 2010), which are not available for all commercial buildings (Emmerich et al. 2014). While

Lisa Ng and **W. Stuart Dols** are mechanical engineers, **Brian Polidoro** is a computer scientist, and **Steven Emmerich** is the group leader of the Indoor Air Quality and Ventilation Group at the National Institute of Standards and Technology, Gaithersburg, MD. **Som Shrestha** is an R&D staff member of Building Technologies Research and Integration Center at Oak Ridge National Laboratory, Oak Ridge, TN.

some energy simulation software tools can simulate infiltration using multizone airflow models, the capabilities of the airflow calculations are often limited and can be difficult for users to employ (Dols et al. 2016a; Dols et al. 2015; Jokisalo et al. 2008; Kalamees et al. 2010).

The National Institute of Standards and Technology (NIST) has developed several tools to better account for infiltration in building energy models. The tools are based on CONTAM simulations of the prototype commercial buildings developed by Pacific Northwest National Laboratory (PNNL) for the U. S. Department of Energy (DOE) (Ng et al. 2012a; Ng et al. 2012b; Ng et al. 2013). CONTAM is a multizone, indoor air quality (IAQ), and ventilation analysis program developed by NIST to simulate airflows and contaminant concentrations in buildings (Dols et al. 2016b). CONTAM calculates infiltration, exfiltration, and room-to-room airflow rates driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by temperature differences between zones, including the outdoors. CONTAM is one of the few simulation tools that accounts for the dynamic interaction of HVAC systems, weather and infiltration in a computationally efficient manner. CONTAM has been validated with data from both controlled experiments and real-world experiments (Chung 1996; Emmerich 2001; Emmerich et al. 2004; Haghighat et al. 1996). An example of a building model developed using the CONTAM interface is shown in **Figure 1**. It is of a medium office building that has four perimeter zones, one core zone, a restroom and shafts for the elevator and stairwell. **Figure 1** also shows HVAC supplies, a bathroom exhaust system, air leakage paths between zones, and air leakage paths between perimeter zones and the outside.

Generally, CONTAM implements a well-mixed zone assumption by considering each zone, e.g., a room, as being represented by a single temperature, pressure, and contaminant concentration at each time step during the simulation, although pressure varies hydrostatically within each zone to capture buoyancy induced flows, i.e., the stack effect. In CONTAM the interzone airflow rate is a nonlinear function of the pressure difference across airflow paths between the zones. A system of equations for the airflows between zones is formulated and solved by nonlinear methods to determine the zone pressures that satisfy mass balance of airflows into and out of all zones of the building. Driving forces of wind, buoyancy and HVAC systems (supply, return, and exhaust) are all accounted for in this system of equations. Thus, imbalances in HVAC system flows are inherently accounted for in the network formulation. This modeling approach contrasts with computational fluid dynamics (CFD), which provides detailed airflow and contaminant concentrations within a zone (Wang et al. 2010). While CONTAM does provide for coupled multizone-CFD analysis within a single zone, or to determine external wind pressures and contaminant concentrations at the openings of a building envelope (Wang et al. 2010), this article focuses on tools based on the multizone approach of CONTAM. CONTAM does not perform heat transfer calculations, so indoor temperatures must be input by the user (typically scheduled to reflect thermostat setpoints). Similarly, HVAC fan operation is also scheduled in CONTAM. It would not cycle on and off depending on the thermostat and internal loads, as it would in a building energy simulation program. Whole-building infiltration rates are calculated taking into consideration wind speed, wind direction, and indoor/outdoor temperature difference.
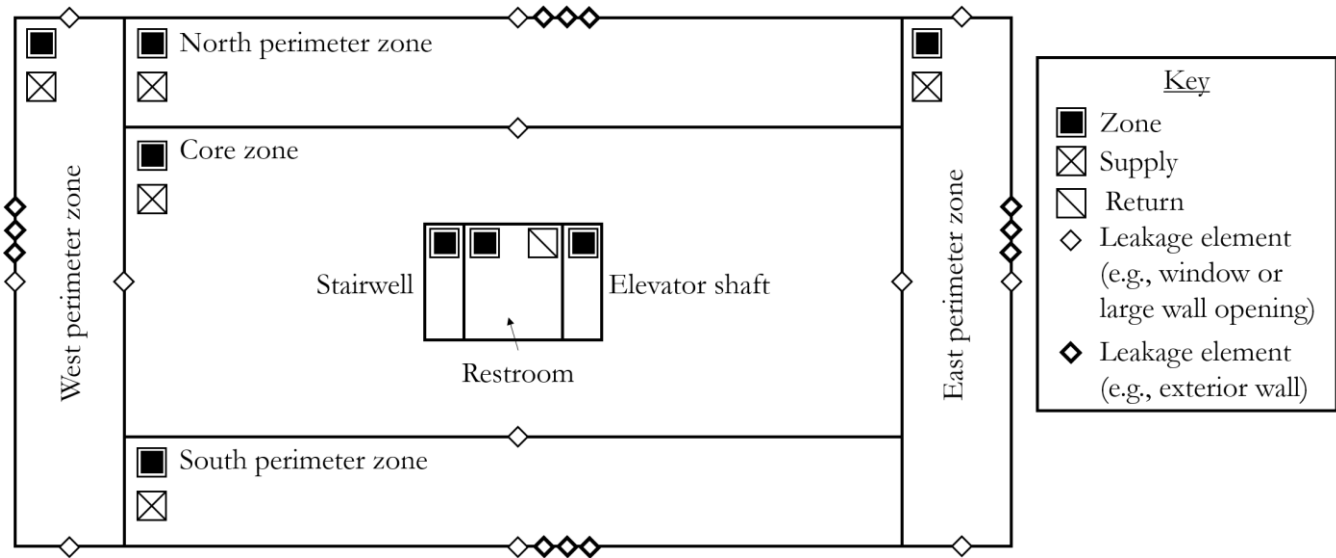
Figure 1 CONTAM model of a medium office building (icons enlarged for clarity)

Sixteen commercial building prototypes were developed by DOE in EnergyPlus (Deru et al. 2011), in part to support the development of ANSI/ASHRAE/IES Standard 90.1 *Energy Standard for Buildings Except Low-Rise Residential Buildings*. To conduct airflow and IAQ analyses of the prototype buildings, NIST created CONTAM models of them (available for download from the NIST Multizone Modeling Website). There are sixteen ASHRAE Standard 90.1-2004 building types available, which are described in Ng et al. (2012a). Five of them were also updated to ASHRAE Standard 90.1-2013 (Hospital, Medium Office, Primary School, Small Hotel, and Stand Alone Retail), described in more detail in Ng et al. (2018). Six more ASHRAE Standard 90.1-2013 building types were also created: Highrise Apartment, Large Hotel, Midrise Apartment, Secondary School, Small Office, and Strip Mall. They can all be found on the NIST Multizone Modeling Website.

These CONTAM models of the prototype buildings have supported the development of tools to better account for infiltration in building energy models. While the tools were developed specifically for use with EnergyPlus, their results could also be applied to other energy modeling tools. The three tools described herein are:

1. The CONTAM Results Export Tool
2. Weather-Correlated Infiltration Inputs developed for the DOE commercial prototype buildings
3. Energy Savings Calculator for Building Envelope Air Tightness

This paper briefly describes the tools, their application, and the limitations of each. All of the tools and associated documentation are publicly available on the NIST Multizone Modeling Website.

ENERGYPLUS INFILTRATION MODEL USED IN THE NIST INFILTRATION TOOLS

The tools to be discussed were developed for use with one of the infiltration models available in EnergyPlus, though the conceptual framework for the tools could be applied to a wide variety of energy simulation software. The EnergyPlus object, `ZoneInfiltration:DesignFlowRate`, was used in the NIST infiltration tools and calculates infiltration rates using the following empirical equation:

$$\text{Infiltration (normalized by units of } \textit{Design Flow Rate Calculation Method}) = I_{\text{design}} \cdot F_{\text{schedule}} \left[A + B|\Delta T| + C \cdot W_s + D \cdot W_s^2 \right] \quad (1)$$

where I_{design} is the airflow through the building envelope under design conditions, e.g. a 4 Pa pressure difference

between indoors and outdoors. I_{design} is a user-specified value for each zone of the building that can be provided as *AirChanges/Hour* (h^{-1}), *Flow/Zone* (m³/s), *Flow/Area* (m³/s•m²), *Flow/ExteriorArea* (m³/s•m²), or *Flow/ExteriorWallArea* (m³/s•m²) depending on the *Design Flow Rate Calculation Method* selected within EnergyPlus. Zones may be assigned different I_{design} values. The I_{design} values for every timestep may also be contained in $F_{schedule}$. The CONTAM Results Export Tool uses both the *Flow/ExteriorArea* or *Flow/Zone* method. The Weather-Correlated Infiltration Inputs and Energy Savings Calculator for Building Envelope Air Tightness use the *Flow/ExteriorArea* method. However, users of the Energy Savings Calculator for Building Envelope Air Tightness do not need to interact with CONTAM or EnergyPlus because the simulations have already been performed and the results are accessible through the web interface. How the normalized infiltration rates in Eq. (1) are converted to an infiltration rate into each zone for each tool is described below.

CONTAM RESULTS EXPORT TOOL

Using CONTAM, infiltration rates can be simulated for timesteps from one second to one hour, for a period of up to one year based on desired weather data and user-defined HVAC system fan operating schedules. Once these simulations are complete, the [CONTAM Results Export Tool](#) is used to export schedules of either (1) whole building air change rates (*Flow/ExteriorArea*) or (2) zone-specific air change rates (*Flow/Zone*) (**Figure 2**). Exported rates only include envelope infiltration, i.e., they do not include outdoor air intake via the mechanical ventilation system.

If the whole building air change rate option is selected, the exported values are infiltration rates normalized by the building exterior surface area. In this case, $F_{schedule}$ in Eq. (1) is in units of m³/s•m². To obtain the infiltration rate into each zone in units of m³/s, the left-hand side of Eq. (1) is multiplied by each zone's exterior surface area within EnergyPlus. If the zone-specific air change rate option is selected, the exported infiltration rates are in units of m³•s⁻¹ and can be used directly as $F_{schedule}$ in Eq. (1). The left-hand side of Eq. (1) is multiplied by 1.0. For the zone-specific air change rate option, there is a different $F_{schedule}$ for each perimeter zone of the building. For both export options, $I_{design}=1$, $A=1$, $B=C=D=0$. Detailed steps are provided in Polidoro et al. (2016).
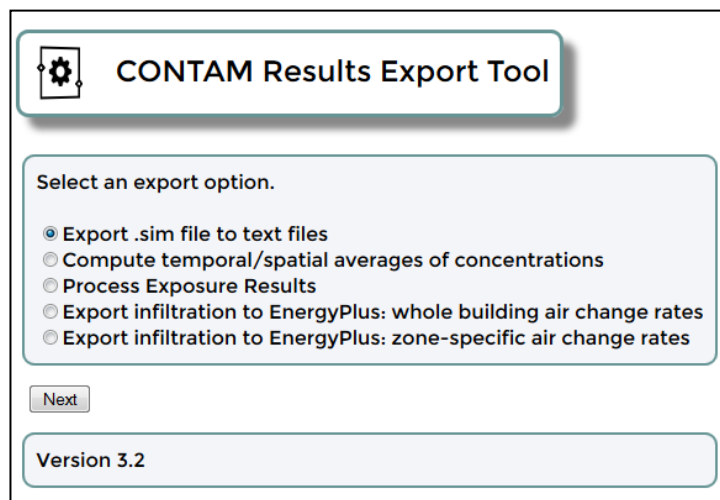
Figure 2 Features in CONTAM Results Export Tool

Limitations of CONTAM Results Export Tool

There are several limitations when using the [CONTAM Results Export Tool](#). When exporting whole building infiltration rates, it is assumed that the infiltration is uniformly distributed around the building envelope because EnergyPlus does not utilize wind direction in its determination of infiltration (Eq. (1)). In other words, while

CONTAM does account for wind direction on infiltration (e.g., windward walls will have infiltration while leeward walls will have exfiltration), when the whole building infiltration rates are exported, each exterior wall in EnergyPlus will be modeled with the same infiltration per unit area. On the other hand, when exporting zone-specific infiltration rates, the impact of wind direction will be captured in EnergyPlus since the net infiltration (infiltration minus exfiltration) into each zone (oriented differently than others) is provided to EnergyPlus. While this may not affect the total building energy usage, differences in infiltration rates between zones on different sides of the building may result in different interior thermal conditions. This could affect whether thermal loads can be met in the zones with greater infiltration and increasing the conditioning load on these zones.

Another limitation is that the infiltration rates calculated by CONTAM will be based on indoor-outdoor temperature differences that may be different than those calculated by EnergyPlus. This is because CONTAM does not perform heat transfer calculations and the indoor temperatures are scheduled, such as according to thermostat setpoints. In EnergyPlus, the simulated indoor temperature may not remain at the setpoint during the entire scheduled period, e.g., if the thermostat incorporates a deadband. These temperature fluctuations are not typically included by CONTAM modelers.

Lastly, since CONTAM does not perform heat transfer calculations, the HVAC system-on times are not likely to exactly match the system-on times simulated in EnergyPlus. Indoor temperatures were scheduled in the CONTAM models according to the thermostat setpoint schedules in the EnergyPlus models in order to account for buoyancy and stack effects on airflow. Thus, infiltration may be underestimated during times when the EnergyPlus simulation has determined no HVAC fan use is needed, but it has been scheduled to be on in CONTAM. A fully coupled CONTAM-EnergyPlus would better capture the full interaction of airflow and thermal loads (Dols et al. 2016a). Nevertheless, the use of the infiltration rates simulated using CONTAM (uncoupled) are useful for determining infiltration rates for a specific building that takes into account HVAC system operation and weather.

WEATHER-CORRELATED INFILTRATION INPUTS

As an alternate to the approach just described, the EnergyPlus object `ZoneInfiltration:DesignFlowRate` can be employed by inputting values to the coefficients *A*, *B*, *C*, and *D* in Eq. (1). Values for these coefficients are suggested in the EnergyPlus user manual (DOE 2013), however, those values are based on studies in low-rise residential buildings.

Given the challenges in determining valid coefficients for a given building, a common strategy used by EnergyPlus users for incorporating infiltration is to assume fixed infiltration rates, i.e., *A*=1 and *B*=*C*=*D*=0. However, this strategy does not reflect known dependencies of infiltration on weather and HVAC system operation. Thus, NIST determined coefficients in Eq. (1) that account for wind, indoor-outdoor temperature difference, and HVAC system operation (Ng et al. 2018). As an example, the weather-correlated infiltration inputs for five prototype commercial buildings in Chicago (ASHRAE Climate Zone 5 (ASHRAE 2016)) are given in Table 1 and divided into System On and System Off coefficients. Because the wind pressure on a building surface is defined in the ASHRAE Handbook of Fundamentals as a function of the square of the wind speed (ASHRAE 2013), *C* in Eq. (1) is set to zero in our studies. When the HVAC system is off, it was assumed that *A*=0. The Hospital and Small Hotel had HVAC systems that operated 24 hours a day. Inputs for seven other climate zones and two levels of building envelope airtightness are reported in Ng et al. (2018) and available in a spreadsheet from the NIST Multizone Modeling Website. Also included on the website are coefficients for six additional buildings.

The weather-correlated inputs in Table 1, along with those for seven other climate zones and two levels of building envelope airtightness and six additional buildings, have been incorporated into an Open Studio Measure (NREL 2017). The Measure provides a convenient method to implement these correlations in an EnergyPlus simulation. After applying the NIST Measure to the Open Studio project (as shown in **Figure 3**), the user selects a schedule that best represents the fan operation of the building. This schedule determines whether the "System On" or "System Off" coefficients (such as those in Table 1) are used to determine infiltration. The user then enters an I_{design}

value, which can be determined with pressurization tests or from a relevant design standard. Note that pressurization test results are often reported at 75 Pa (0.30 in. w.c.) reference pressure, while EnergyPlus recommends entering an I_{design} value based on a 4 Pa (0.02 in. w.c.) reference pressure. Equation (2) can be used to convert a 75 Pa value to a 4 Pa value,

$$\text{Infiltration} = I_{\text{design}} = Q_{ref}\, \Delta p^n / \Delta p_{\text{ref}}^{\ n}. \tag{2}$$

For example, a target airtightness of 2.0 L/s·m² at 75 Pa, an $n = 0.65$, would convert to:

$$I_{\text{design}} = 2.0 \cdot 4^{0.65}/75^{0.65} = 0.30 \text{ L/s·m}^2 \text{ at 4 Pa} \tag{3}$$

Table 1.   Weather-Correlated Infiltration Inputs for Prototype Buildings in Chicago

Coefficient	Hospital	Medium Office	Primary School	Small Hotel	Stand Alone Retail
			System On Value		
A	0.0477	-0.0445	0.0025	0.0403	-0.0274
B	0.0028	0.0055	0.0034	0.0079	0.0065
D	0.0107	0.0295	0.0340	0.0078	0.0374
Coefficient			System Off Value		
A	#N/A	0.0000	0.0000	#N/A	0.0000
B	#N/A	0.0155	0.0066	#N/A	0.0102
D	#N/A	0.0344	0.0423	#N/A	0.0504

Then, the user selects the Building Type (currently available: Highrise Apartment, Hospital, Large Hotel, Medium Office, Midrise Apartment, Primary School, Secondary School, Small Hotel, Small Office, Stand Alone Retail, and Strip Mall) and Climate Zone (currently available: ASHRAE Climate Zones 1 through 8). Finally, the user can check the box that uses correlation values for "buildings with an air barrier". A detailed discussion on which buildings fall into that category can be found in Ng et al. (2018). The Measure is available on the [Building Component Library website](#).
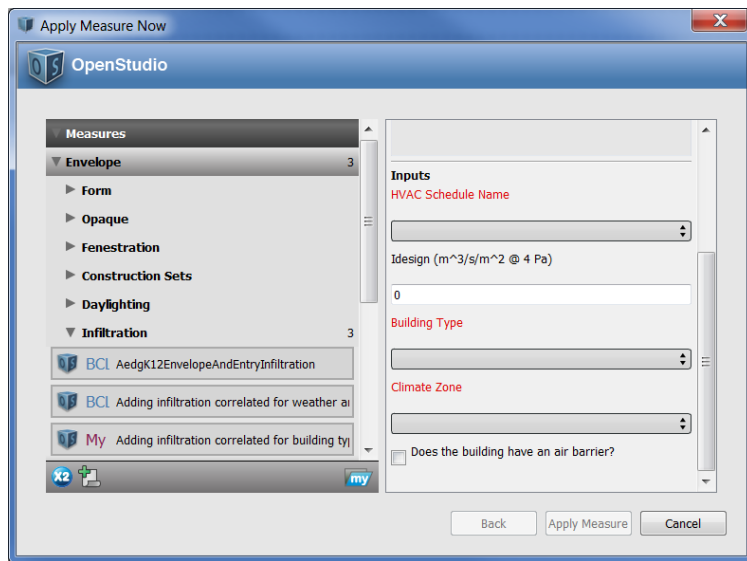
Figure 3   Open Studio Measure for weather-correlated infiltration inputs

Limitations of weather-correlated infiltration inputs

The weather-correlated infiltration inputs are useful to users who want infiltration estimates that are specific to a prototype building but do not want to run CONTAM on their own. However, inputs have only been developed for 11 of the 16 available prototype buildings, eight of the 17 climate zones, and two levels of building envelope airtightness. Additional studies are needed to evaluate if the inputs can be generalized to buildings that are not part of the "prototype" set, and for buildings that are either tighter or leakier than assumed for the existing correlations.

Previous work by the authors have generalized the weather-correlated infiltration inputs for a subset of the ASHRAE 90.1-2004 versions of the DOE commercial reference buildings Ng et al. (2015). The coefficients A, B, and D in Eq. (1) (C=0) were correlated with building height, surface-to-volume ratio, and HVAC system pressurization. This way, users can calculate values for A, B, and D for any building. An Open Studio Measure is also available for this method of determining the coefficients.

The generalized infiltration inputs showed promise when tested in building models that were outside of the commercial reference buildings set, and for building models that were leakier than the commercial reference buildings. Thus, there are plans to generate generalized infiltration inputs for the ASHRAE 90.1-2013 buildings.

ENERGY SAVINGS CALCULATOR FOR BUILDING ENVELOPE AIR TIGHTNESS

NIST, Oak Ridge National Laboratory (ORNL), the Air Barrier Association of America (ABAA), and the US-China Clean Energy Research Center for Building Energy Efficiency Consortium partnered to develop an online calculator that provides estimates of the potential energy and cost savings and reduction in moisture transfer in 52 U.S., five Canadian, and five Chinese cities from improvements in airtightness (Shrestha et al. 2019; Shrestha et al. 2016). It is a web-based tool available at the ORNL website and accesses a database of pre-run CONTAM and EnergyPlus simulation results for seven prototype buildings: Medium Office, Midrise Apartment, Stand Alone Retail, Highrise Apartment, Hospital, Large Hotel, and Secondary School.

The user selects "base" and "target" building envelope airtightness values for comparison. The default "base" building envelope airtightness is 9 L/s·m² at 75 Pa for a 5-sided envelope based on the average leakage of the buildings shorter than four stories in Emmerich et al. (2005). The user also inputs the electricity and natural gas rates that will be used to estimate the annual savings in HVAC energy cost (electrical, gas, and total) as a result of increasing the building airtightness (**Figure 4**). Additional details of the tool can be found in Shrestha et al. (2016).

Limitations of Energy Savings Calculator for Building Envelope Airtightness

The Energy Savings Calculator for Building Envelope Air Tightness is useful to those that need an estimate of the potential savings from building envelope airtightening. However, the tool only includes seven prototype buildings simulated at four levels of building envelope airtightness. Energy savings for each prototype building in each city are normalized by floor area within the tool. The tool then applies the user-entered floor area to calculate total predicted savings.

CONCLUSION

As buildings are designed and required to be tighter, the impact on energy use needs to be better captured by building modelers. Therefore, NIST has developed a relatively simple-to-use set of tools to better account for infiltration in building energy models. These tools are based on the results of CONTAM simulations of DOE prototype building models. The tools discussed include the CONTAM Results Export Tool, Weather-Correlated Infiltration Inputs, and the Energy Savings Calculator for Building Envelope Air Tightness. Each has its own application, benefits, and limitations. Nevertheless, each can help users explore the consequences of improving building envelope airtightness.
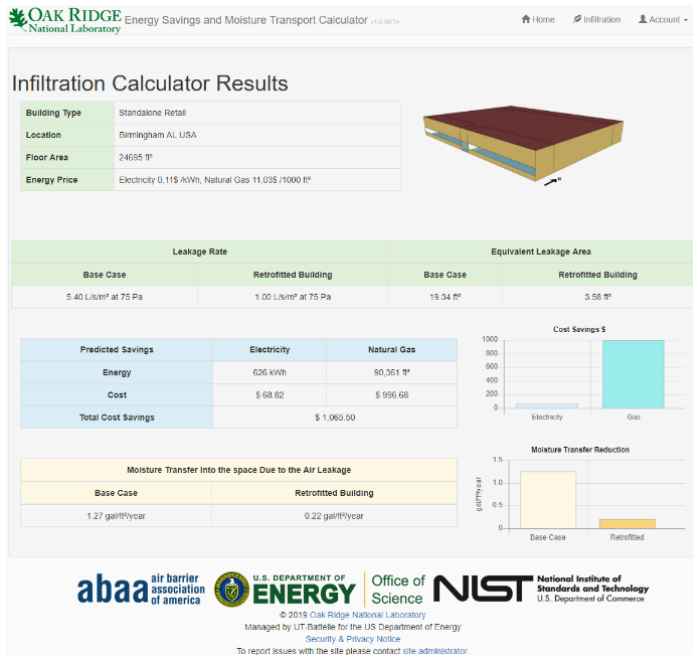
Figure 4 Airtightness Savings Calculator

ACKNOWLEDGMENT

NIST would like to acknowledge its partners on the [Energy Savings Calculator for Building Envelope Air Tightness](#), Oak Ridge National Laboratory and the Air Barrier Association of America.

NOMENCLATURE

A = constant in Eq. (1)

B = temperature constant in Eq. (1)

C = wind speed constant in Eq. (1)

D = wind speed squared constant in Eq. (1)

I_{design} = airflow through the building envelope under design conditions in Eq. (1), units dependent on *Design Flow Rate Calculation Method*

F_{schedule} = schedule factor between 0.0 and 1.0, to account for the impacts of fan operation on infiltration, or a schedule of infiltration values in Eq. (1)

Q_{ref} = leakage rate (m³/s) at a reference differential pressure Δp_{ref} (such as 75 Pa)

W_s = local wind speed (m/s)

n = flow exponent (typically 0.65)

Δp = pressure difference (Pa)

ΔT = absolute indoor-outdoor temperature difference in °C

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