BUILDING ENERGY RESEARCH GRANT (BERG) PROGRAM

FINAL REPORT

Energy and Demand Savings from Sealing Exhaust

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Abstract

The goal of this project was to help the state of California address the energy losses associated with leakage in exhaust ductwork in commercial buildings and dormitory style residences. The study coupled computer modeling of zone pressures and flows as impacted by transient meteorological conditions with field research to answer a number of questions about the potential for energy savings from sealing leaks or reducing flows in exhaust ducts. Computer simulations were conducted in a multizone airflow modeling package and used to characterize the relationship between outdoor air infiltration and changes in exhaust flow. A simple series of equations were developed to estimate this relationship based on climate zone and exhaust flow rate. Field testing of several hotels and dormitories was used to test multiple simplified exhaust flow diagnostic techniques and compare their results to the current industry standard method; one method developed proved to consistently estimate duct leakage to within 5 percent of the total flow. Results from field diagnostics also indicate that exhaust systems in buildings constructed within the last decade are not necessarily any tighter than older systems. The analysis indicates that sealing a system with 25 percent leakage should reduce heating and cooling energy by 20 percent and fan energy by 50 percent. In California, the return on investment for such a system is estimated to be approximately 40 percent, and the payback period could be as short as 2 years, depending on the climate zone leakiness and initial flow rate of the exhaust fan.

Key Words: exhaust, duct leakage, leak sealing, leak measurement, energy efficiency, infiltration, aerosol sealing

Executive Summary

Introduction

This research study coupled multizone building airflow simulations with field analysis of several multistory residential buildings to study the energy impacts of air leakage and unnecessary flows in central exhaust ducts. Leaks in exhaust ducts mean that fans must draw more air than necessary in order to meet minimum ventilation rate requirements measured at the exhaust inlet; this has significant energy implications related to fan power, and the heating and cooling of excess infiltration air.

Objectives

The goals of this project were organized into seven objectives as follows:

- Objective 1: Demonstrate that a simple tool can be used to analyze the savings potential of exhaust duct sealing – tool must agree with detailed simulations to within 10 percent.
- Objective 2: Confirm that exhaust duct leakage can be determined cost-effectively – test must take less than 1.5 hours.
- Objective 3: Gather additional field data on leakage levels in exhaust duct systems, particularly for recently constructed buildings.
- Objective 4: Compile "best-estimate" leakage, flow and cost data
- Objective 5: Quantify the savings that can be achieved by sealing various levels of exhaust duct leakage in California buildings.
- Objective 6: Calculate the cost effectiveness of exhaust duct sealing in different applications
- Objective 7: Deliver a code change proposal to the California Energy Commission related to exhaust duct leakage

Outcomes

Objective 1

A generic building prototype representative of high-rise multifamily residential was developed and simulated in a multizone building modeling program (NIST 2008) for several different California Climate Zones to study the relationship between reduction in exhaust flow and changes in air infiltration rates. The ratio between these parameters, $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$, is the key to estimating the heating and cooling load reduction achieved by exhaust duct sealing; and it is impacted by several factors including wind speed, ambient temperature, and exhaust flow rates. Through analysis of a range of simulation results, a simple model to estimate the annual average $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ was developed to escape the need for complex airflow simulations by reducing the result to a series of second order polynomials. The specific set of polynomial equations to estimate annual average $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ with R^2=0.99 for the range studied, and an explanation of how and why to calculate hourly air change rates is presented in *Project Outcomes* in Equations 18 and 19.

Objectives 2 and 3

Several different methods for measuring leakage in exhaust ducts were field tested and compared to the current industry standard calibrated fan pressurization test. One method, the Blocked Grille Test, rose above the rest in reliability, simplicity and accuracy compared to the current standard. Based on these results the researcher recommends amending Appendix NA2 of the California Building Energy Efficiency Standards to include the simplified technique as an acceptable procedure for duct leakage diagnostic testing. Through the process of testing each diagnostic technique, exhaust systems from several building across California were analyzed to develop an indication of leakiness in existing building stock. Of the 8 buildings and 17 systems tested, 10 systems in 4 buildings tested less than ten percent leakage, and 7 systems in 4 buildings tested more than 15 percent leakage; 3 systems from a single dormitory complex constructed in 1965 measured greater than 20 percent leakage.

Objectives 4, 5 and 6

A cost effectiveness analysis was conducted to develop an indication of the economic savings that could be had from sealing exhaust systems given a range of different existing conditions. Results indicate that payback and return on investment are more sensitive to the severity of leakage and the total exhaust flow rate than to the average meteorological conditions encountered in California. An average building, with 15 percent exhaust leakage and an hourly air change rate of 0.9, could expect a 4 year payback and 30 percent return on investment. In a very leaky building, such as the 3 systems tested in the dormitory complex, payback could be as quick as two years and return on investment could exceed 40%.

Objectives 7

This objective has not been completed, since an official code-change proposal has yet to be filed, but future action will incorporate the results of objectives 1-6 into a code-change proposal to address exhaust duct leakage in new construction, as well as in alterations. The key changes to be suggested include amendment of the standard leakage diagnostic test procedures and inclusion of maximum leakage rates for exhaust ducts in new and renovated buildings, similar to existing codes related to leakage in supply systems.

Conclusions

Results of this effort indicate that, depending on climate zone and the initial exhaust flow rate, sealing exhaust systems with 25 percent leakage should save nearly 50 percent on fan energy, and 20 percent on heating and cooling costs.

Further, field research indicates that at least half of exhaust systems leak by more than 10 percent, and many leak by more than 20 percent. There is no clear correlation between system age and duct leakage, and most importantly it doesn't seem that new buildings are necessarily less leaky. Also, through the series of field studies, the researcher tested several different simplified diagnostic methods to determine duct leakage quickly and cost effectively. At least one of these tests, the Blocked Grille technique, provides results that are reliably consistent with the current industry standard, which is a calibrated-fan pressurization test.

Based on the calculations for energy savings, a simple cost effectiveness analysis was made to determine the payback and return on investment for sealing exhaust duct leaks. The analysis, based on price data from Carrier-Aeroseal, indicates that for exhaust systems drawing typical air change rates (~0.9 a*ir change per hour* for a 450 *square foot* hotel with 0.15 *cubic feet per minute per square foot* ventilation rate) the payback period is between 3 and 5 years, and return on investment is between 20 percent and 40 percent.

Recommendations

As a result of this study, the researcher recommends that California Building Energy Efficiency Standards be revised to include requirements for exhaust duct integrity in new buildings, standards for reducing leakage and rebalancing fans in existing-building renovations, and guidelines for simple and proven diagnostic test techniques. Finally, the research center intends to work with California Investor Owned Utilities to integrate the lessons from this research into energy efficiency programs and building energy audit efforts.

Public Benefits to California

Were exhaust duct sealing adopted as a Title 24 requirement, at least 50 percent of California's commercial building stock would benefit from energy and cost savings of the retrofit energy efficiency measure. Based on indications from this research about the distribution of exhaust performance, and drawing from information about energy use in California's commercial building stock (Itron 2006) and information about the carbon dioxide emissions from California electricity and natural gas (CAT 2007), sealing exhaust ductwork statewide could avoid approximately 2 percent of California commercial electricity consumption, 3 percent of California commercial building natural gas consumption, and avoid 677,000 metric tons of carbon dioxide equivalent greenhouse gas emissions.

Introduction

This project addresses the issue of energy consumption in California, specifically electricity consumption and demand, and natural gas consumption as a result of air leakage in exhaust duct systems, and builds upon earlier research on duct leakage in buildings other than single-family residences (Cummings, Withers et al. 1996; Delp, Matson et al. 1998; Delp, Matson et al. 1998; Franconi, Delp et al. 1998). As such, this project addresses issues 2 through 6 identified by the PIER Buildings End-Use Energy Efficiency Program (Commission 2009):

- The research addresses the need for affordable and effective tools to respond to time dependent price structures for electricity by developing a simple means to measure the need for and cost effectiveness of sealing leaks in exhaust systems.
- The project addresses the need for low first cost energy efficiency products by focusing attention on sealing leakage in exhaust ducts rather than supply systems since doing so is simpler, less costly, and provides significant energy savings.
- The need for reducing energy consumption while maintaining non-energy considerations such as health and safety is central to this research since leaks in exhaust ductwork impact energy consumption and ventilation quality; in some buildings, such as hospitals, properly functional exhaust is critical for health, safety, and environmental quality.
- Since the existing building sector is so large and there is a need for efficiency products appropriate in retrofit application, this research develops understanding of the appropriateness and potential energy impacts of a technology designed to seal existing ductwork without intensive building demolition or redesign.
- The research addresses the need for tools to easily diagnose equipment performance degradation due to improper installation, poor maintenance, or system aging by developing simplified methods for exhaust system diagnostics and a straightforward function to estimate the energy impacts of exhaust sealing for a variety of different conditions.

The project relied heavily on earlier research which included a characterization of the stock of duct systems in large commercial buildings (Modera, Xu et al. 1999), characterization of duct leakage levels and efficiency-rating yardsticks for commercial building thermal distribution systems (Diamond, Wray et al. 2003), field testing of the impacts of supply duct sealing an office building (Diamond, Wray et al. 2003) and a light commercial building (Sherman, Xu et al. 2002), as well as the development and field testing of a version of an aerosol-based leak sealing technology applicable to large commercial buildings (Diamond, Wray et al. 2003). In addition, considerable efforts were devoted to the development and application of detailed simulation tools for commercial-building thermal distribution systems (Wray 2003; Wray and Matson 2003). The research reported herein focuses on a particular subset of duct systems that have seen very little investigation in the prior research, specifically, exhaust duct systems.

Exhaust Duct Systems

There are several reasons to focus on exhaust systems, including:

1. Sealing exhaust ducts allows you to reduce exhaust flow.
2. Fan power for exhaust systems scales with the cube of the airflow rate. Comparatively, supply systems generally scale with airflow raised to a power closer to 2.5.
3. Exhaust systems are present in almost all large buildings. They are needed for toilets and showers, even in buildings without central heating and cooling systems (e.g. hotels) .
4. Exhaust systems seem to leak more consistently than supply systems in these types of buildings.
5. Exhaust duct leaks are equivalent to air flows directly to outdoors, as long as those leaks come from the conditioned space.
6. Exhaust systems in existing buildings are simpler to seal with aerosol technologies than supply systems, both because of the lack of coils and variable air volume (VAV) boxes, and because most of the ductwork is often vertical, which means that gravity helps transport the particles to the leaks.

Unlike supply duct systems, exhaust systems generally do not contain coils or filters, which means that all of the pressure drop that the fan needs to overcome is either turbulent friction in the ducts, or inertial losses through intakes and exhausts, both of which scale with the square of the flow rate. Thus, as the fan power is the product of the pressure drop and the flow, it scales with the flow cubed, thereby making small increases in required fan flow cause large increases in fan power. Since these fans generally operate at constant speed for 24 hours per day, these increases in power are seen at peak demand periods. Duct sealing, which impacts fan power uniformly throughout the day, will have the same impact on peak fan power demand as it does on energy use. Finally, the thermal impacts of excess exhaust flow are tied to the outdoor air conditions, and therefore have the greatest impact during periods of peak electricity demand for cooling.

Sealing Exhaust Duct Systems

The simplicity of exhaust duct system construction is one of the factors that make aerosol duct sealing more cost effective for exhaust systems than supply systems. The lack of coils means that the entire exhaust system can be injected from single point. When sealant is injected from the top of the system into mostly vertical exhaust ducts, lower flows can be used for the injection as the sealant particles generally drift down towards the leaks. Horizontal ducts commonly found in supply systems are more difficult to seal since particles must be held aloft by mild turbulence, which requires higher flows and sometimes creates the need for additional equipment. Finally, since many buildings have multiple exhaust shafts terminating at the same location, such as a roof or penthouse, set-up time for aerosol sealing is reduced when sealing multiple exhaust systems.

Over the past couple years, about 20 exhaust systems in large buildings have been sealed using the aerosol sealing technique. These efforts led to several conclusions:

1. Sealing these systems is more straight-forward than sealing supply systems
2. These systems seem to leak more consistently as compared to supply systems, and
3. The market impediments for sealing these types of systems are a lack of credibility in the marketplace, and the need for a cost-effective means for identifying which systems require sealing. This credibility issue stems from a general lack of awareness of the significance of the problems and energy waste associated with duct leaks in large buildings, compounded by a lack of credible third-party studies or information demonstrating the effectiveness of sealing techniques.

Technical Challenges

There were two key technical obstacles to be overcome by this project. The first obstacle is that the energy implications of exhaust duct leakage generally require complex modeling. This project aimed to overcome this challenge by developing a simplified model that can be used to determine the energy savings for different applications. The second obstacle is the need for a quick, low-cost technique for reliably determining the leakage of exhaust duct systems for code compliance purposes and building-owner investment decisions. This lack of low-cost, reliable diagnostic techniques has been the key obstacle to widespread adoption of duct sealing in general. A number of promising simplified leakage-measurement technologies is one of the reasons for focusing this research on exhaust duct systems.

Project Objectives

The primary purpose of this project was to determine the impacts of leakage in duct systems on energy use and peak demand in California. The theory presented in the original proposal is that leakage from the exhaust ductwork of a building, which basically amounts to a direct connection between inside and outside air in cases where conditioned air is exhausted, accounts for a large percentage of the wasted energy in building operations. This is due to the fact that the power requirements of an exhaust fan scale with the cube of the exhaust flow, meaning that a small reduction in the necessary exhaust flow rate due to sealing translates into significant power and cost savings.

The seven objectives of this project were as follows:

- Objective 1: Demonstrate that a simple tool can be used to analyze the savings potential of exhaust duct sealing – tool must agree with detailed simulations to within 10%.
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Project Approach

Comparison of Simplified Analysis Tool with Detailed Simulations

The original strategy proposed for improving the state of the art for exhaust duct leakage was to use EnergyPlus (DOE 2009) to evaluate the validity of a simplified model to determine energy impacts of sealing leaks in exhaust systems. However, analysis of the problems inherent in evaluating energy impacts revealed that Energy Plus was not the best reference tool. Since the key issues for analysis of energy implications of changes to exhaust system performance are related to air flow through the building shell, simulations were conducted in CONTAM 2.4c (NIST 2008), a public-sector multi-node air flow simulation program developed by the National Institute of Standards and Technology (NIST).

Simulation of Air Flows in an Apartment Building

To address the first technical impediment to exhaust duct sealing, the potential need for complex modeling and/or extensive data input to determine the thermal energy implications of changes in exhaust flow, it is first necessary to determine how exhaust flows interact with natural air infiltration flows under a range of meteorological conditions. A prototype six-story building model was developed in CONTAM 2.4c (NIST 2008) and used to simulate pressures and airflow through the building as a function of several different variables. This effort had two parts:

1. *Factorial Analysis* – Simulations illustrated the individual and combined effects of each variable of interest by computing steady-state building response to specific combinations of input conditions.

2. *Transient Weather Analysis* – Simulations computed building pressure and airflow response to transient meteorological conditions for one typical year of hourly weather data in each CA climate zone. The hourly results were analyzed to characterize the impact of actual meteorological conditions on building pressures and airflow and to describe the relationship between exhaust flow adjustments and outdoor air infiltration rates.

Once the relationship between exhaust flow adjustments and natural air infiltration rates is understood the calculation of thermal energy implications is relatively straightforward – as discussed in the section *Simplified Model for Energy Savings from Exhaust Sealing*.

CONTAM Building Model

The six-story prototype building model developed in CONTAM 2.4c most closely resembles a dormitory, hotel, condominium, or apartment building. Analysis of the infiltration implications of adjustments to exhaust flow for exhaust systems in other applications, namely for toilet or general exhaust in office or laboratory buildings, does not require as complex modeling since pressure in these buildings is usually controlled, which means that a change in exhaust flow roughly translates to an equal change in outdoor air infiltration – especially for 100% outside-air buildings such as laboratories and hospitals. A screenshot of the CONTAM 2.4c interface for the prototype building model is presented in Figure 1.

The building model includes the following characteristics:

- Two exhaust fans on independent risers. Each exhaust fan serves one room per story in a vertical stack for all six stories. The model assumes constant flow through fans for each simulation.
- Eighteen zones, three zones on each floor.
- Two zones representing "rooms" on each floor, each connected to separate exhaust risers.
- A central "hallway" zone on each floor without direct exhaust ventilation, but connected to rooms by airflow pathways.
- Airflow pathways in the building envelope between each zone and ambient, located 0.1 *m* from the floor and 0.1 *m* from the ceiling on each level.
- Airflow pathways through interior walls between the "hallway" and "rooms" on each floor.
- Airflow pathways through the ceiling/floor between vertically adjoining zones, and through the roof between each zone on the sixth floor and ambient.

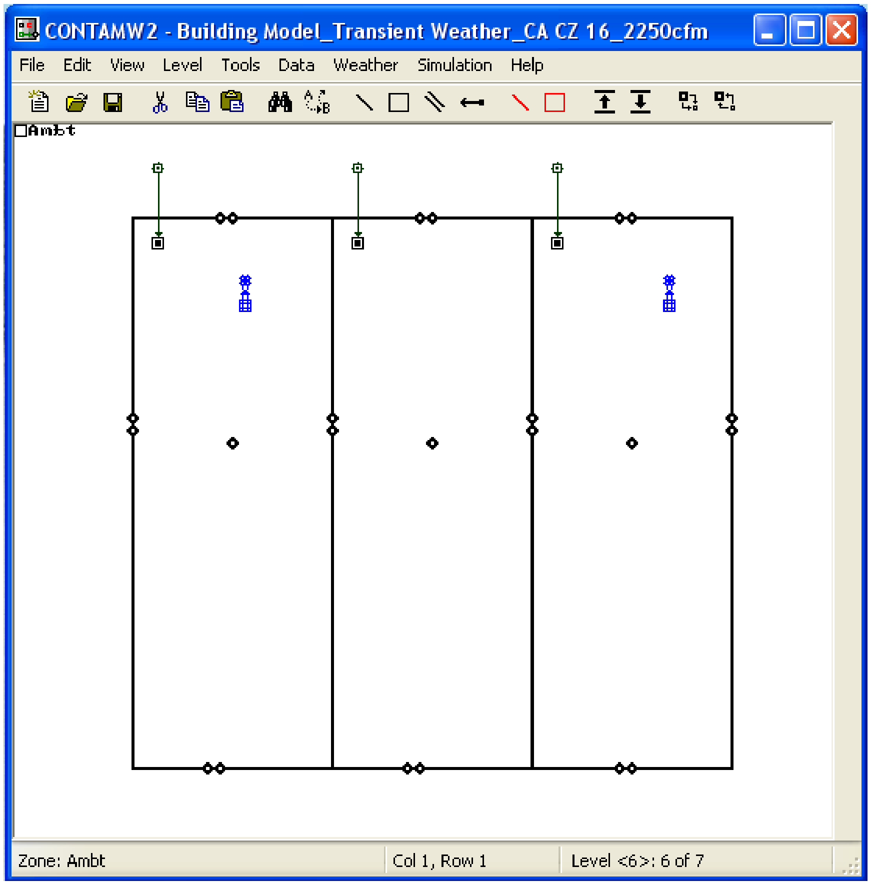

Figure 1: CONTAM 2.4c interface for prototype building model

- Airflow through pathways was modeled as one-way flow using a power law equation:

$$Q = C(\Delta P)^n \quad (1)$$

The exponent (*n*) was set to 0.65 for all pathways, a value representative of flow through irregularly shaped leaks. The coefficient (*C*) was defined for each pathway based on flow values for typical building elements and was varied as part of the factorial analysis to illustrate the effect of tight and loose floor conditions. Tight floor conditions were defined such that without wind or stack induced pressure effects, on average, less than 1% of air exhausted from each zone arrives by diffusion through ceilings or floors. For loose floor conditions, which were used in all transient weather simulations, approximately 15% of air exhausted from each zone flows through ceilings or floors from vertically adjacent zones.

- Ducts were modeled without leakage. Since the focus of simulations was to characterize the relationship between adjustments to exhaust flows and infiltration flows, leakage from ducts within the building envelope is of no consequence.

- The cross sectional area of ducts and free face area of registers was varied as part of a factorial analysis to illustrate the effect of tight and loose grille conditions. Tight grille conditions were set to produce an average pressure difference across grilles of ~5-25 *Pa*, depending on exhaust flow; loose grille conditions produced a pressure difference of ~0.1-1 *Pa*. All transient weather simulations were run for tight grille conditions.
- For steady state simulations the indoor temperature was maintained at a constant 20 ℃. For transient weather simulations indoor temperature was modulated between two set points on an hourly basis as a logical function of ambient temperature. For hours with ambient temperatures above 24 ℃ indoor space was cooled to 26 ℃; for hours with ambient temperatures below 18 ℃ indoor space was heated to 20 ℃. The difference between indoor temperature set points and ambient temperature trigger points represents a rough estimate for temperature difference due to solar gains. For hours with ambient temperatures between 18 ℃ and 24 ℃ indoor temperatures were allowed to float 2 ℃ warmer than ambient. This logic roughly reflects the control strategies recommended by Title 24.

Factorial Analysis

To illustrate the individual and combined effect of each driving variable the researchers designed a full factorial framework to guide steady state-simulation set points. Factorial analysis is generally used as a statistical tool in experimental applications to indicate the presence of unexpected variables, to illuminate the relationships between variables that might be difficult to describe theoretically, and to grasp the degree of error in experimental measurements. In this case the results do not have an error, since they are derived from theoretical calculations alone; the framework merely provides a convenient approach to illustrate and interpret the main effects of each variable, identify the interdependence of variables, and establish representative values for constant parameters to be used in transient weather simulations. The factors and levels simulated are summarized in Table 1:

	Levels		
Factor	*High*	*Mid*	*Low*
Exhaust Registers and Ductwork	Tight	N/A	Loose
Airflow Paths Between Floors	Tight	N/A	Loose
Outdoor Temperature	40 °C	20 °C	0 °C
Wind Speed	20 *mph*	N/A	0 *mph*
Wind Direction	90°	45°	0°

Table 1: Parameters and Values for Factorial Analysis

The exhaust flow rate and magnitude of change in exhaust flow rate from duct sealing were not considered as factors in the factorial analysis, since the effort was aimed at interpreting the effects of environmental variables. However, in hindsight it would have been illustrative to include those variables as well. All simulations were run at 1800 *cfm* and 900 *cfm* to yield a flow reduction achieved from duct sealing of ΔQ_{exh}= 900 *cfm*.

Steady state simulations were run in CONTAM 2.4c for all 48 possible combinations of factors and levels. Two factors with three levels and three factors with two levels yields 72 permutations, but there is no need to model different permutations of wind direction at zero wind speed. For all permutations, the metric of concern for analysis was the ratio of the change in infiltration flow to an imposed change in exhaust flow:

$$\frac{\Delta Q_{inf}}{\Delta Q_{exh}} = \frac{Q_{inf}^{initial} - Q_{inf}^{final}}{Q_{exh}^{initial} - Q_{exh}^{final}} \qquad 2$$

where $Q_{exh}^{initial}$ and Q_{exh}^{final} are, respectively, the exhaust flow rates before and after duct sealing and subsequent fan adjustment. $Q_{inf}^{initial}$ and Q_{inf}^{final} are the rates of air infiltration before and after duct sealing. Since infiltration air must be heated or cooled to maintain indoor temperatures, the difference represents a thermal energy savings. In pressure controlled, 100% outside air buildings this ratio is safely assumed to be 1, but the value for multi-zone negative pressure exhaust driven buildings is not well understood.

Transient Weather Analysis

The factorial analysis reveals some information about how the metric of interest, $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$, responds to specific combinations of independent variables, but to develop a simplified model that estimates energy savings from exhaust fan flowrate adjustments it is necessary to understand how infiltration flow changes in response to an actual distribution of meteorological conditions. That is, while a factorial analysis clearly illustrates that the ratio of change in infiltration flow to change in exhaust flow approaches unity when exhaust flow is high, wind is low, and indoor to outdoor temperature difference is small, it does not reveal how the ratio typically changes over time according to actual meteorological driving forces, and it does not illustrate how the ratio behaves on average throughout the year.

Therefore, a range of transient weather simulations were conducted in CONTAM 2.4c with the prototype six-story building model. Each transient simulation is actually a series of steady state calculations computed for an array of hourly meteorological inputs. It does not account for time dependent variables such as heat transfer phenomena or air contaminant concentrations; instead the model calculates the pressure and flow for each zone and element in the building as constant values for each hour completely independent of previous hours.

In order to eventually determine annual energy savings, each transient weather simulation was carried out for one entire year of hourly meteorological inputs – a series of 8760 data samples beginning January 1st at 00:00:00, and ending December 31st at 24:00:00. Meteorological information was obtained from the US Department of Energy's EnergyPlus Weather Data online resource which maintains sets of typical annual climate data for more than 2000 climate zones and regions around the world (DOE 2009). To determine how the ratio $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ differs across California regions with varied meteorological patterns. To test the gamut of possible magnitudes for the ratio $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ the researchers also simulated the prototype building in Juneau Alaska, US Climate Zone 1.

For each hour in the transient weather simulations indoor temperature was controlled as a function of ambient temperature. For cooling hours the space was maintained at 26 ℃, for heating hours the indoor temperature is set to 20 ℃, for hours in between ambient trigger temperatures the indoor temperature was allowed to float as described in the section *CONTAM Building Model*. This indoor temperature modeling strategy is not perfectly representative of actual heating and cooling cycles in hotel or dormitory buildings, but it provides a rough estimate that accounts for differences in seasonal indoor temperature set points.

Since $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ is a ratio of differences every simulation must be repeated at multiple exhaust flow rates; then the results for Q_{inf} can be compared to one another and related to the corresponding difference in Q_{exh}. Simulating a range of exhaust flow rates for each climate zone also allowed analysis of the affects of the magnitude of exhaust flow rate and the magnitude of change in exhaust flow rate on the ratio $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$. These two factors turned out to be important in developing a simple function for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ and subsequently, thermal energy savings. For each climate zone the transient weather simulations were repeated with a total exhaust flow rate of 112.5, 225, 450, 900, 1350, 1688, 1800, 2250, 2588, and 2700 *cfm* and a change in exhaust flow from duct sealing of 112.5, 450, and 900 *cfm*. Since there were 12 rooms in the prototype building model this roughly corresponds to a range of 10-225 *cfm* per exhaust register, which more than spans the range observed in field tests.

Input variables and raw results from these transient simulations were imported into a spreadsheet program for comparison, analysis, and interpretation. The meteorological data, constant parameters, and pressure and flow values produced by CONTAM for each zone were plugged into a suite of calculations to compute several metrics that help to illustrate characteristics of the system.

$\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$, as defined by equation 2, is the primary value of interest since it is necessary to determine how much heating and cooling energy would be saved through avoided air infiltration by sealing leaky exhaust ducts. Since the main objective of this exercise was to develop a simplified model for the ratio so that complex air flow simulations need not be conducted, and since the ratio varied significantly across the range of meteorological conditions encountered, the values of $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ were compared to metrics to evaluate probable driving conditions.

For example, the air flow rates throughout the building are driven by pressure differences. A portion of that driving pressure is induced by the exhaust fan, while a portion is induced by wind, and a portion by temperature driven stack effects. The fraction of total driving pressure induced by the exhaust fan certainly affects the magnitude of air infiltration, so $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ was compared against ratios of the wind induced pressure, stack induced pressure, and exhaust induced pressure to illustrate the role of each component.

While CONTAM calculates air pressure for every zone and flow between each zone for each hour simulated, the model cannot attribute portions of each pressure to certain driving variables the way one might assign partial pressures to each component of a gas mixture. Moreover, the wind pressure, stack pressure, and exhaust pressure components each differ between zones, and vary continuously according to building geometry, temperature profile, and wind speed profile, so it can be difficult to assign a particular value to each for the building as a whole based on the actual pressures in each zone. However, characteristic parameters for the wind, stack, and exhaust induced pressures can be calculated that are generally representative of conditions. Even if these values don't represent a single measurable point, comparison against $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ allows for interpretation of trends and relationships.

The characteristic wind pressure is calculated according to (ASHREA 2005):

$$P_{wind} = \frac{1}{2}\rho {U_{roof}}^2 \quad (3)$$

where:

ρ is the ambient air density

U_{roof} is the wind speed at the height of the building

The characteristic stack pressure is calculated:

$$P_{stack} = \rho g H_{roof} \left(\frac{T_{amb} - T_{in}}{T_{amb}} \right) \qquad 4$$

where:

ρ is the ambient air density
g is the gravitational constant
H_{roof} is the height of the building
T_{amb} is the ambient temperature (absolute)
T_{in} is the indoor temperature (absolute)

The exhaust induced pressure was calculated through CONTAM by conducting a steady state simulation with zero wind pressure and zero stack pressure, thereby isolating the pressure effects of the exhaust; this was done for every magnitude of exhaust flow.

Simplified Model for Energy Savings from Exhaust Sealing

The intent of this research was to distill results from complex transient weather simulation efforts into a simple model that could be used to quickly estimate energy savings from exhaust sealing. The core of the model is a simplified function for the infiltration interaction factor $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ – the relationship between change in infiltration flow and change in exhaust flow:

$\frac{\Delta Q_{inf}}{\Delta Q_{exh}} = f(ACH, CZ)$, discussed in *Project Outcomes* and defined by Equation 19

Determination of the total energy impacts of exhaust sealing then consists of the sum two separate analyses:

1. Calculation of the fan energy savings from the reduction in total exhaust flow
2. Calculation of the heating and cooling energy savings achieved by reduction in total exhaust flow and thus reduction of infiltration air that must be conditioned

$$E_{total}^{savings} = E_{fan}^{savings} + E_{inf}^{savings} \qquad 5$$

The fan energy savings can be determined straightforwardly according to a cube law relationship between fan flow and power as follows:

$$E_{fan}^{savings} = E_{fan}^{initial} - E_{fan}^{initial}\left(\frac{Q_{exh}^{final}}{Q_{exh}^{initial}}\right)^{3}\left(\frac{\eta_{fan}^{final}}{\eta_{fan}^{initial}}\right) \qquad 6$$

where:

$E_{fan}^{savings}$ = exhaust fan energy savings from duct sealing

$E_{fan}^{initial}$ = exhaust fan energy use prior to duct sealing

Q_{exh}^{final} = exhaust flow rate after duct sealing

$Q_{exh}^{initial}$ = exhaust flow rate prior to duct sealing

η_{fan}^{final}= exhaust fan efficiency at after duct sealing

$\eta_{fan}^{initial}$ = exhaust fan efficiency at flow prior to duct sealing

Calculation of the heating and cooling energy savings from the reduction in total exhaust flow is proportional to the simplified infiltration interaction factor, $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ defined by equation 19, the number of heating and cooling degree days, and the energy efficiencies of heating and cooling devices:

$$E_{inf}^{savings} = \Delta Q_{exh}\,\frac{\Delta Q_{inf}}{\Delta Q_{exh}}\,C_v\,(\frac{HDD}{\eta_{heating}} + \frac{CDD}{\eta_{cooling}}) \qquad 7$$

where:

ΔQ_{exh}= change to exhaust flow achieved by sealing leaks

$\frac{\Delta Q_{inf}}{\Delta Q_{exh}} = f(ACH, CZ)$, discussed in *Project Outcomes* and defined by Equation 19

HDD = number of heating degree days, *°K-days*

CDD = number of cooling degree days, *°K-days*

C_v = volumetric heat capacity of air, *kJ/m3-°K*

$\eta_{heating}$= efficiency of heating equipment

$\eta_{cooling}$= efficiency of cooling equipment

Field Test of Leakage Measurement Techniques

To address the need for a quick, low-cost method to determine the leakage of exhaust systems three simplified techniques were developed, field tested, and compared to results from a standard calibrated-fan pressurization test.

The objectives of this portion of the project were:

1. To find a technique that provides acceptable accuracy and precision to assure code compliance for new systems and qualify existing systems for sealing, while keeping the testing costs to a minimum.
2. To get an indication of whether or not new construction is performing better than the existing building stock.

The simplified techniques evaluated include:

1. *The Pressure Drop Test:* block all intake grilles with the exhaust fan in operation, measure the pressure at several grilles distributed between the top and bottom of the system, compare data to pressure distribution patterns from systems with known leakage
2. *The Flow Difference Test:* compare difference between exhaust outlet flow and register inlet flow to determine leak percentage
3. *The Blocked Grille Test:* Block all intake grilles with the exhaust fan in operation, then measure the average pressure in the system and the flow leaving the blocked exhaust system

In addition to comparing the performance of these techniques relative to a standard calibrated-fan pressurization test, an additional objective was to determine the amount of time required to conduct each test. The target was to validate a simple test that would take less than 1.5 hours.

Methods for Leakage Measurement Techniques

This study examined three different methods for determining the leakage rate in the exhaust systems of multi-story buildings. Two methods, the flow difference test and the blocked grille test, were tested against a control method, the duct-blaster test, which is the current industry standard for determining duct leakage.

Equipment

The comparison of leakage test techniques utilized the following equipment:

- Duct Blaster: The Minneapolis Duct Blaster, manufactured by The Energy Conservatory, is the current industry standard used to determine leakage in exhaust duct systems. The duct blaster consists of a fan with an extendible flex duct that can be affixed to an exhaust register. A flow ring with a known area is inserted into the fan, as well as a flow straightener ring that is used for depressurization tests. The pressure difference across the fan is measured using a monometer and two pressure ports on the duct blaster, one on the side of the fan and another on the side of the flex duct.

- Vane Anemometer: The simplified tests used an AV-2 vane anemometer manufactured by AIRFLOW™. It consists of a small ducted metal fan and a computer capable of reading and interpreting the velocity of flow through the fan. Fluid flow causes the fan to rotate and flow velocity is determined by a small magnet in the duct housing which measures electric pulses caused by the fan blades moving past the magnet. The vane anemometer also includes several extendible arms so that the technician performing measurements can avoid disturbing the fluid flow.
- Monometer: The monometer used for this experiment was a Digital Pressure Gauge manufactured by The Energy Conservatory, which has two pressure reading channels and two range settings. Pressure tubes can be fixed to ports on the monometer and then placed into the fluid streams, where they can be used to measure either static or stagnation pressure.
- Pitot Tube: In situations when exhaust discharge vents were inaccessible, and flow measurement with an anemometer would be difficult to obtain, a pitot tube was used to measure flow through the exhaust fan. The pitot tube measures stagnation pressure and static pressure, from which dynamic pressure and fluid velocity can be calculated.

Duct Blaster Test

The Duct Blaster Test is an industry standard calibrated-fan pressurization test; it was used as a basis for comparison of each other technique. This test requires the use of the duct blaster, a monometer, a vane anemometer, registry tape, duct tape, and painter's tape. Additional tools and supplies, such as trash bags and cardboard stock may be helpful in blocking some ducts as well as sealing the register where the duct blaster is attached.

Data from the Duct Blaster test is normally analyzed to determine a total leakage area in the ductwork. However, for this study, to compare the various testing methods, the researchers instead determine the leakage flow as a percent of the total exhaust flow rate.

The step-by-step process for the Duct Blaster Test follows:

1. The average pressure difference across all grilles connected to an exhaust fan must be determined. This is measured with a standard monometer; one monometer tube is inserted directly into the register, the other is left to measure pressure in the room.
2. All grilles connected to an exhaust fan are then blocked using register tape.
3. Next, the average pressure difference across all blocked grilles is measured by poking a small hole in the center of the register tape on each grille and inserting the monometer tube through the hole. The hole is blocked using duct-tape or painters tape before moving on to other grilles.

4. For all subsequent steps in the Duct Blaster testing method the exhaust fan is turned off and the exhaust discharge vent is sealed.
5. The flex end of the Duct Blaster is attached to an unblocked exhaust register – this register is selected so that it is at least 15 feet away from another exhaust register where pressure measurements can be taken.
6. The fan is attached to the free end of the duct blaster. A ring is placed inside the fan to fix the area for flow rate calculations. For depressurization tests, a flow straightener is inserted ahead of the flow ring (towards the duct).
7. One monometer is affixed to the duct blaster, while a second monometer is connected to separate register at least fifteen feet away from the Duct Blaster.
8. All grilles except the Duct Blaster remain blocked for the test.
9. Measurement of the pressure difference across the Duct Blaster fan and pressure difference across the single grill chosen are taken at several different fan speeds. Measurement at a minimum of five fan speeds is sufficient for accurate analysis.

The leakage volume flow rate is determined from the following power law formula:

$$Q_{leak} = K(P_{blocked})^n \qquad 8$$

where $P_{blocked}$ is the average pressure difference across all blocked grilles measured with the exhaust fan running. There is not enough information to solve Equation 8 directly; first it is necessary to determine both the exponent (*n*) and the exponential coefficient (*K*). Both are found from a plot of the natural logarithm of the duct pressure (P_{duct}) as a function of the natural logarithm of the Duct Blaster volume flow (Q_{db}). The exponent (*n*) is equal to the slope of the plotted line, and the coefficient (*K*) is equal to the exponential of the y-intercept. Expressed as equations:

$$n = \frac{d(\ln Q_{db})}{d(\ln P_{duct})} \qquad 9$$

$$K = e^{y-intercept} \qquad 10$$

The leak percentage is then determined as the ratio of Q_{leak} (equation 8) to Q_{normal}, the exhaust discharge flow rate measured during normal system operation.

Flow Difference Test

This test only requires use of the vane anemometer, or other flow measurement device.

The Flow Difference Technique uses a simple mass flow analysis performed by calculating the difference between flow measured through the exhaust fan and the sum of flows measured through all of the exhaust registers.

Expressed as an equation:

$$Q_{Fan} - Q_{Registers} = Q_{leak} \quad 11$$

Pressure Drop Test

This test requires use of the monometer and registry tape.

The Pressure Drop Test was designed to rely on a compilation of data collected through standard testing methods, such as a calibrated-fan pressurization test, to derive the leak percentage of any particular system based only on a few simple pressure measurements. If results for leak percentage from calibrated testing techniques can be confidently expressed as a function of key pressure measurements at registers throughout the system, then pressure measurements alone should be sufficient to derive leakiness empirically.

The Blocked Grille Test

This test requires a monometer, vane anemometer or pitot tube, registry tape, and duct tape.

The blocked grille test is based on a mass flow analysis, determined by measuring flow at the exhaust outlet first with all registers open, then with all registers blocked. The exhaust outlet flow with all registers blocked is clearly a measure of duct leakage, but only under blocked grille conditions. To determine the leak flow rate under normal conditions the ratio of pressures measured across registers under each condition and a power law flow model must be used.

The step-by-step process for the Blocked Grille Test follows:

1. The average pressure difference across all open registers in the system is found using the monometer. The average pressure difference across all grilles connected to an exhaust fan must be determined. This is measured with a standard monometer; one monometer tube is inserted directly into the register, the other is left to measure pressure in the room.
2. The flow rate through the system is calculated by measuring an array of flow velocities at the exhaust outlet, averaging to a single value, and then multiplying by the outlet area.
    a. If a vane anemometer is used for this measurement, a correction factor based on duct outlet shape and grille free face area must be used.

b. If a pitot tube is used to measure flow velocity in a straight, unobstructed section of duct a correction factor need not be used.
c. If the exhaust outlet is exposed to strong or highly variant winds or if the outlet has an unusual shape, such as a mushroom cap, that impedes accurate flow measurements, it may be necessary to construct an artificial plenum to direct flow through a measureable geometry. If such a plenum exerts significant back pressure on the system the flow measurements must be corrected, by equation 14, based on pressure measurements at each open register under normal operating conditions and while the artificial plenum is in place.

3. All of the registers are then blocked using register tape.
4. Next, the average pressure difference across all blocked grilles is measured by poking a small hole in the center of the register tape on each grille and inserting the monometer tube through the hole. The hole is blocked using duct-tape or painters tape before moving on to other grilles.
5. With all grilles blocked, the flow at the exhaust outlet is measured using the same process as step 2.

The leak flow and leakage percentage are then determined from the following equations;

$$Q_{leak\ normal} = Q_{leak\ blocked} \left(\frac{P_{normal}}{P_{blocked}}\right)^{0.6} \qquad 12$$

where the value of the exponent, 0.6, has previously been shown to be representative of power law relationships for flow through irregularly shaped pathways. The leak percentage is then calculated as:

$$Leak\ Percentage = \frac{Q_{leak\ normal}}{Q_{normal}} \qquad 13$$

If an artificial plenum is used at the exhaust outlet to direct flow through a geometry that allows for accurate measurements, the flow rate measured must be corrected to account for additional back pressure exerted by the plenum arrangement in order to derive the exhaust outlet flow under normal operating conditions. The same power law formula as equation 12 is used, except with a different exponent:

$$Q_{normal} = Q_{plenum} \left(\frac{P_{normal}}{P_{plenum}}\right)^{0.5} \qquad 14$$

Additionally, correction factors for vane anemometer readings taken at open duct outlets and at grilles should be used to account for the flow expansion at the outlet and for effects of grill shape and free face area. These correction factors were determined through laboratory experiments by measuring flow at the outlet of a duct fed by a calibrated-fan. The factors were calculated by the following equation:

$$n = \frac{Q_{calibrated}}{V_{anemometer}\, A_{outlet}} \qquad 15$$

where Aoutlet is the area of the outlet measured by its outside dimensions, regardless of the shape or free face area of the grill. For open square ducts the correction factor was determined to be n=0.85. For vane anemometer measurements on the outside face of a grille the factor was n=0.65 and more-or-less independent of the angle of louvers on the grille. Anemometer readings at each type of duct exit were multiplied by this correction factor to determine actual flow rates.

Cost Effectiveness Analysis

This task used standard economic analysis to determine the cost effectiveness of sealing leaky exhaust ducts, and calculated the savings for multiple scenarios of climate zone, exhaust flow, and exhaust leakiness. The analysis calculated annual cost savings, return on investment and payback period as the primary metrics of interest.

California Code Change Proposal

This task has not been completed, but future action will incorporate the results of this research into a code-change proposal to address exhaust duct leakage in new construction, as well as in alterations.

Project Outcomes

Objective 1

Objective 1: Demonstrate that a simple tool can be used to analyze the savings potential of exhaust duct sealing

Comparison of Simplified Analysis Tool with Detailed Simulations

Simulation of Air Flows in Apartment Buildings

Factorial Analysis

The 6-story prototype building model was simulated in CONTAM 2.4c for a range of different input conditions to describe the main effects and interactions between factors of interest. $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$, the ratio of change in air infiltration to the change in exhaust flow, was the metric calculated and analyzed for each simulation. The main effects of most of factors studied are intuitively understood, but comparing everything at once through a factorial analysis provides comprehensive clarity and a quantitative comparison of the effects across the range of values studied.

The results of this effort are presented together in Figure 2. The vertical axis on each plot represents $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$, the horizontal axis is common for each column of plots and is labeled at the bottom of each. The values presented are averages corresponding to the conditions defined in each plot. For example, data for the blue line in the upper left plot are averages for all the simulations varying floor condition and grille condition at wind speed = 0 *mph* at each wind direction.

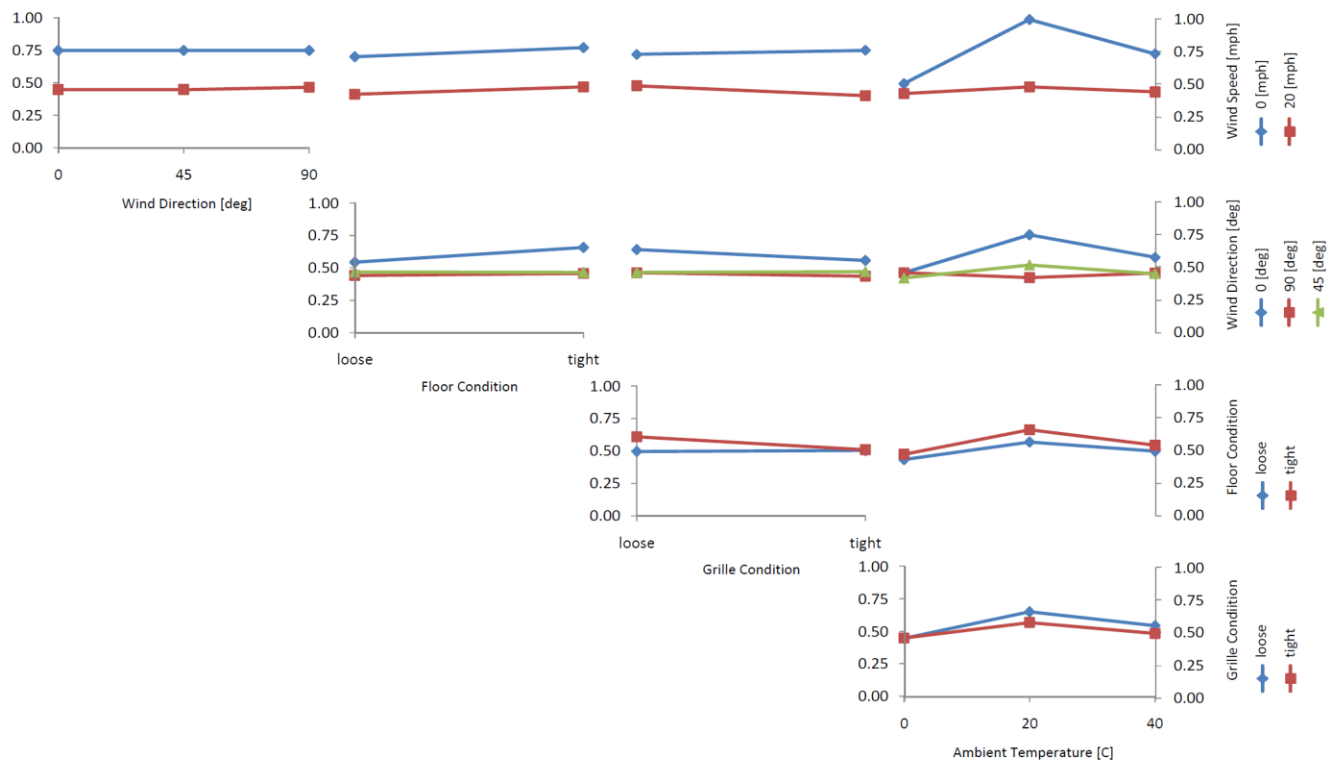

Figure 2: Interaction Plot for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$

Through this analysis one can make several observations about the relationship between $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ and each variable, as well as about the combined effects of any two variables:

- When ambient temperature and indoor temperature are equal (20 ℃ for these simulations), and there is little or no wind, $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ approaches 1. Since neither wind pressure nor stack pressure are active, exhaust pressure is the only mechanism driving air movement in the building and any change in exhaust flow will be matched by an equal change in infiltration flow.

- Wind speed has the greatest impact on the response in $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ for the ranges of variables studied. Change from zero wind speed to 20 *mph* changes $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ by approximately 0.25, though this affect is minimized when temperatures are very cold. This occurs because during heating periods, wind pressure and stack pressure tend to counteract one another. Stack pressure increases proportional to height and in proportion to the indoor-ambient temperature difference, while wind pressure increases as approximately height $^{0.25}$ depending on local terrain conditions. In the cold season the two independent pressure profiles oppose one another and, when cold enough the net pressures can sum to zero.
- Wind direction has more of an effect when floor conditions are tight or when grille conditions are loose. Wind direction affects the net wind driven pressure, and flow through loose grilles is more sensitive to changes in environmental mechanisms than are tight grilles.
- Wind direction has negligible effect when ambient temperatures are cold, again because the stack pressure distribution tends to counteract wind pressure, so perturbation in net wind pressure associated with directional shifts and building geometry does not greatly impact the total pressures driving infiltration flow.
- Wind direction affects infiltration most significantly when indoor temperature is near ambient. In this case, since stack pressure is negligible, small changes in net wind pressure associated with direction are a more significant portion of the total driving pressure. Infiltration flow scales approximately with $\Delta P^{0.6}$ so a small change in pressure when the total driving pressure is small will impact $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ more significantly than the same change when the total pressure is greater.
- Tight and loose floor conditions affect infiltration most when grille conditions are loose. If grill conditions are tight then floor conditions hardly impact infiltration.
- Floor conditions and grille conditions have more of an effect at one building orientation than at another. If the building were round with equally distributed leaks, wind direction wouldn't matter, but since the building geometry is irregular, and since leaks are not evenly distributed, the wind pressure changes as wind direction changes. When wind pressure decreases due to directional effects, changes in less significant factors such as grille and floor conditions have a greater impact on $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$.
- From this factorial analysis, it seems as if when wind speed is high, a change in wind direction has very little effect, but through further investigation, to be discussed in *Project Outcomes* for the *Transient Weather Simulations*, this observation is found to be only a relic of sampling error. At wind speeds of approximately 20 *mph*, $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ can actually range between 0.4 and 0.7, depending on wind direction. At lower speeds the impact is minimal.

Transient Weather Analysis

Factorial analysis develops a rudimentary characterization of the pressures and flows through a building, but only depicts the affects and interactions of a handful of variables, and only at the few design points chosen for evaluation. So, to gain a clearer understanding of the actual energy savings that could be gained by sealing leaky exhaust systems, adjusting fan flow, and avoiding the heating and cooling costs of excess air infiltration, the researchers input transient meteorological conditions into the CONTAM simulations. Using EnergyPlus resources for typical year long weather data, a range of simulations were computed to gauge sensitivity to three different parameters:

- Climate Zone
- Initial exhaust flow rate
- Magnitude of change in exhaust flow rate

The relationship between infiltration flow and changes in exhaust flow varies with meteorological conditions. To gain a better understanding of such relationships, each climate zone was first characterized by statistical analysis of the important meteorological parameters. For example, Figure 3 plots the frequency of wind speed occurrences and the probability that wind speed will ever exceed a particular value, thus it illustrates how regularly certain wind events occur and provides a metric for the comparison of different climate zones. Such information could be especially important to describe the range within a simple model for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ reliably applies. For example, a simple function for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ could take different forms based on the characteristics of wind speed distribution. Likewise for the temperature characteristics of each climate zone; the simple model for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ could be made a function of average temperature or temperature range.

As will be discussed, wind direction tends to have less of an effect on $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ than does wind speed or temperature, but at high wind speeds it can have a significant effect. It's unlikely that a simple model for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ would somehow be made a function of dominant wind direction, but none the less wind direction was analyzed for each climate zone. Figure 4 plots the directional dependent probability that wind events will exceed a given speed.

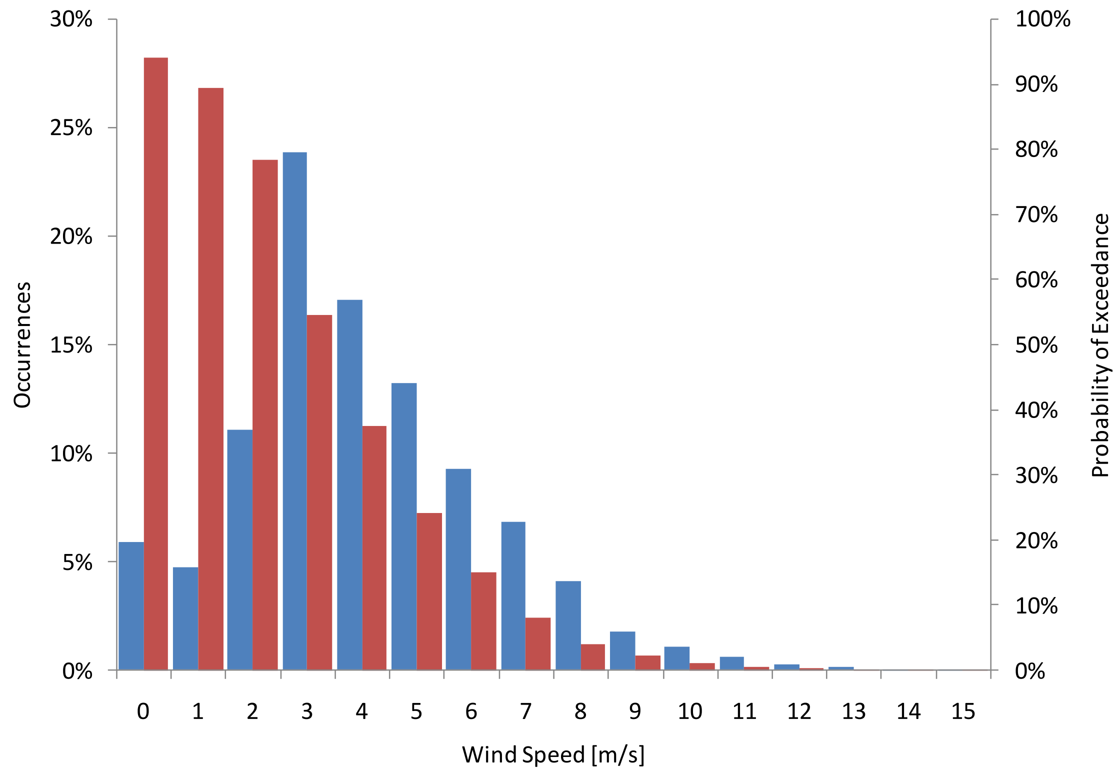

Figure 3: Histogram of wind speed frequency and probability of exceedance, for CA Climate Zone 12 (Sacramento)

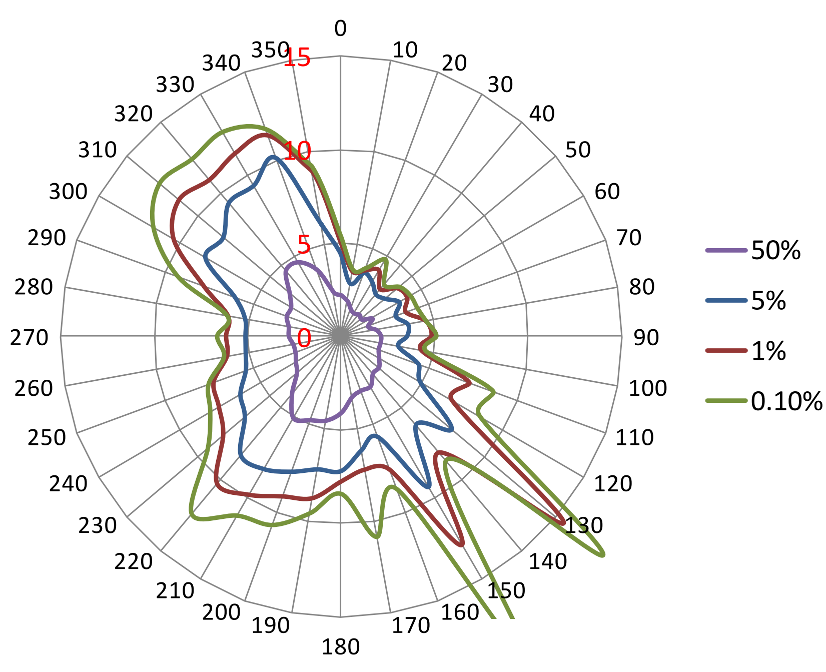

Figure 4: Wind speed probability of exceedance as a function of wind direction, for CA Climate Zone 12 (Sacramento). Radial axis for wind speed in m/s, polar axis for wind direction in deg, North=0°

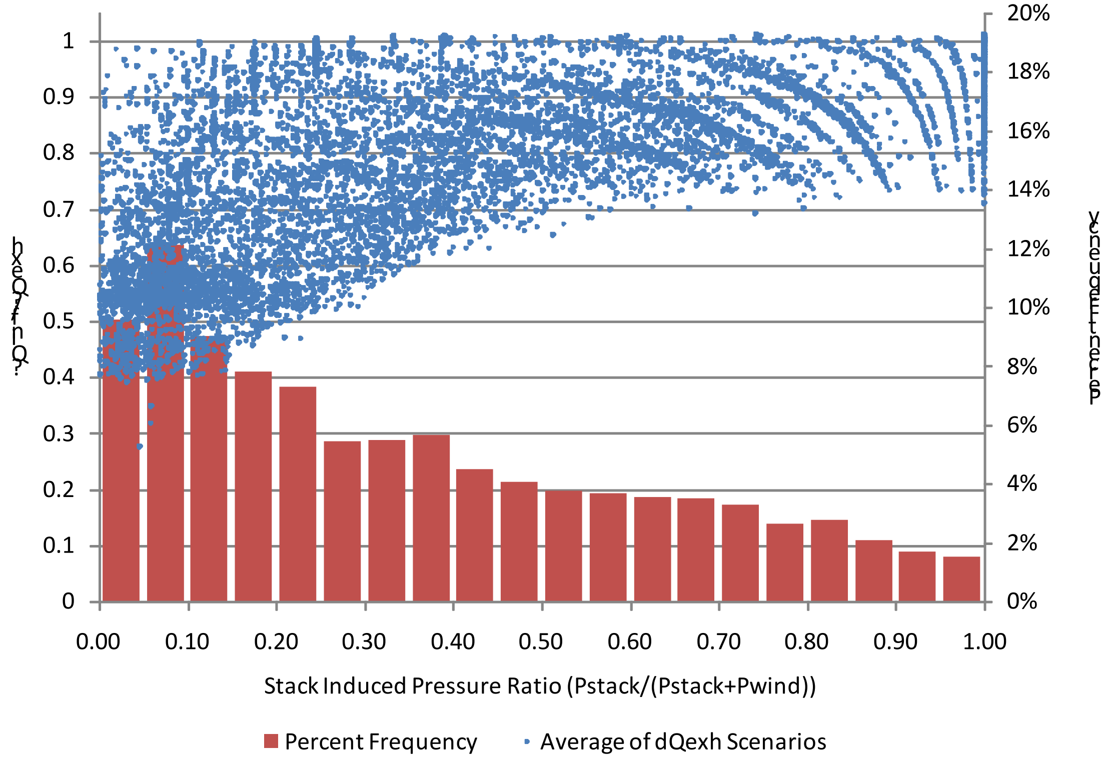

Figure 5: $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ *as a function of stack induced pressure ratio, and the frequency of occurrences, for CA Climate Zone 12 (Sacramento)*

Figure 5 plots the computed values of $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ for every hour in a typical year for CA Climate Zone 12 as a function of the stack induced pressure ratio; the density of occurrences is also described by a histogram for percent frequency of data. The stack induced pressure ratio is a metric developed for this study to compare the role of wind and stack mechanisms at each hour; it is calculated by:

$$R_{stack} = \frac{P_{stack}}{(P_{stack} + P_{wind})} \quad (16)$$

where P_{wind} and P_{stack} are calculated by equations 3 and 4.

The wind induce pressure ratio is the compliment of the stack induced pressure ratio, so $R_{wind} + R_{stack} = 1.0$:

$$R_{wind} = \frac{P_{wind}}{(P_{stack} + P_{wind})}$$ 17

This analysis indicates that when wind pressure is the dominant environmental pressure mechanism, for CA Climate Zone 12, the ratio $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ stays lower on average than when stack pressure is dominant. This is likely because when stack pressure is dominant, total environmentally induced pressure is relatively low, and therefore any change in Q_{exh} is nearly matched by a change in Q_{inf}. To induce the trend from its extreme, a circumstance with zero wind speed and zero indoor to ambient temperature difference, would result in $\frac{\Delta Q_{inf}}{\Delta Q_{exh}} = 1.0$. Figure 6 further illuminates the role of each environmental pressure component; the plot shows the magnitude of the characteristic wind pressure and characteristic stack pressure for every hour in a typical year for CA Climate Zone 12, as a function of the wind induced pressure ratio.

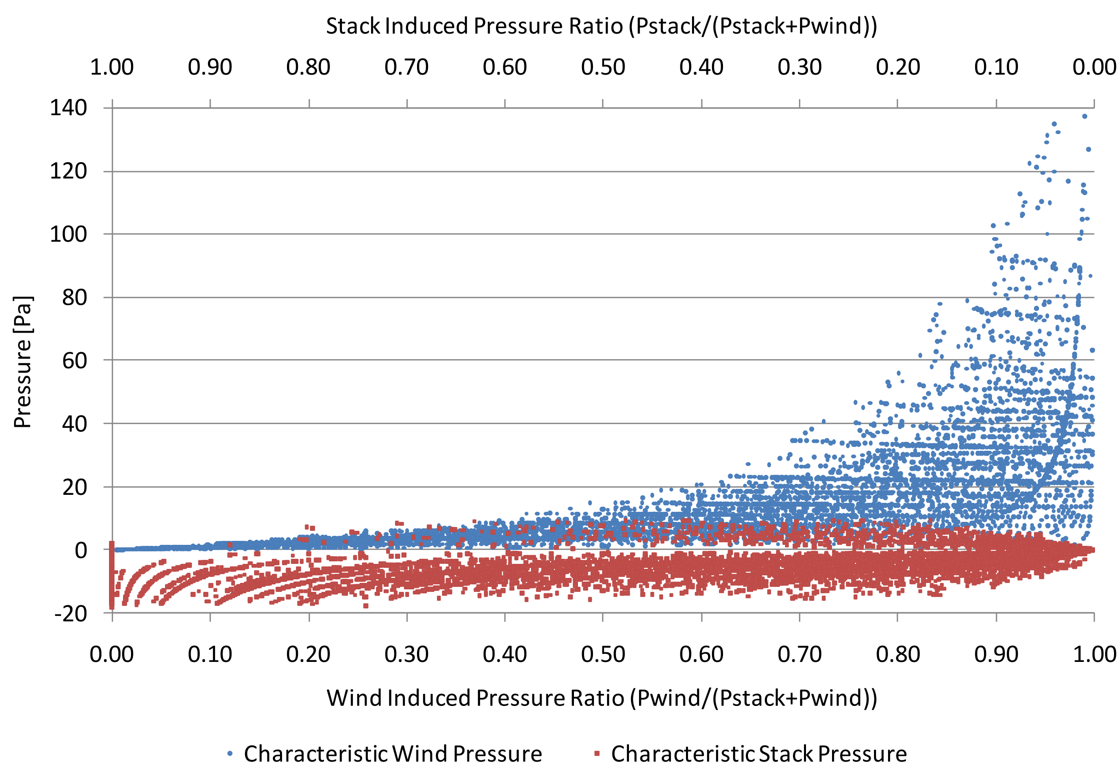

Figure 6: Characteristic wind and stack pressures (defined by equations 3 & 4) as a function of wind and stack induced pressure ratios, for CA Climate Zone 12 (Sacramento)

It is clear that at times wind pressure exerts much more driving force on infiltration flow than does stack pressure. It's only when wind pressure is lower than ~15 *Pa* (corresponding to ~4 *m/s*) that stack is the dominant environmental mechanism. This supports the reasoning for the trend in Figure 5.

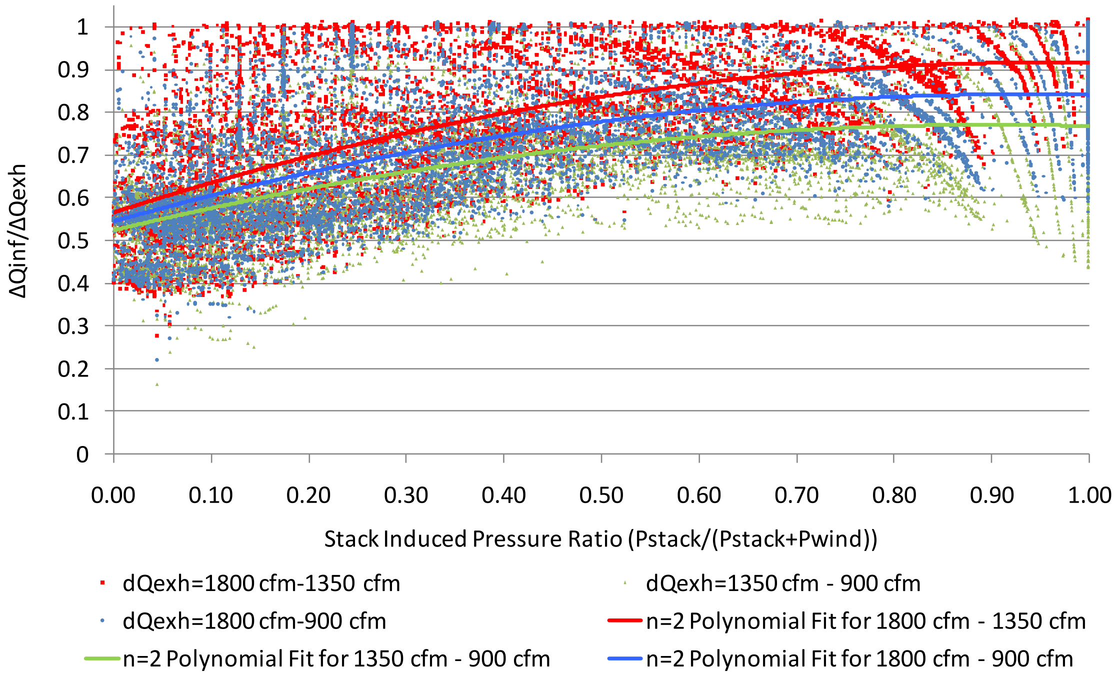

Figure 7: A comparison of $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ *as a function of stack induced pressure ratio for three different* ΔQ_{exh} *scenarios, for CA Climate Zone 12 (Sacramento)*

The transient weather simulations were computed at different exhaust flow rates so that ΔQ_{exh} and ΔQ_{inf} could be calculated by comparing the separate simulations. Figure 7 shows the same as Figure 5 except at different magnitudes of ΔQ_{exh}. The analysis illustrates that the magnitude of $Q_{exh}$and ΔQ_{exh}can result in a significant difference for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$. When stack pressure is dominant, $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ can range from ~0.78 to ~0.92 for the ΔQ_{exh} scenarios plotted here. Note that while the ΔQ_{exh}=1800 *cfm*-1350 *cfm* scenario and the ΔQ_{exh}=1350 *cfm*-900 *cfm* scenario have the same magnitude of ΔQ_{exh}, their results differ significantly.

Figure 5 and Figure 7 show clouds of data from which it is only possible to discern the general effect of one dimension; in this case wind induced pressure ratio. However, if the data is teased apart by relevant independent variables, additional insights emerge.

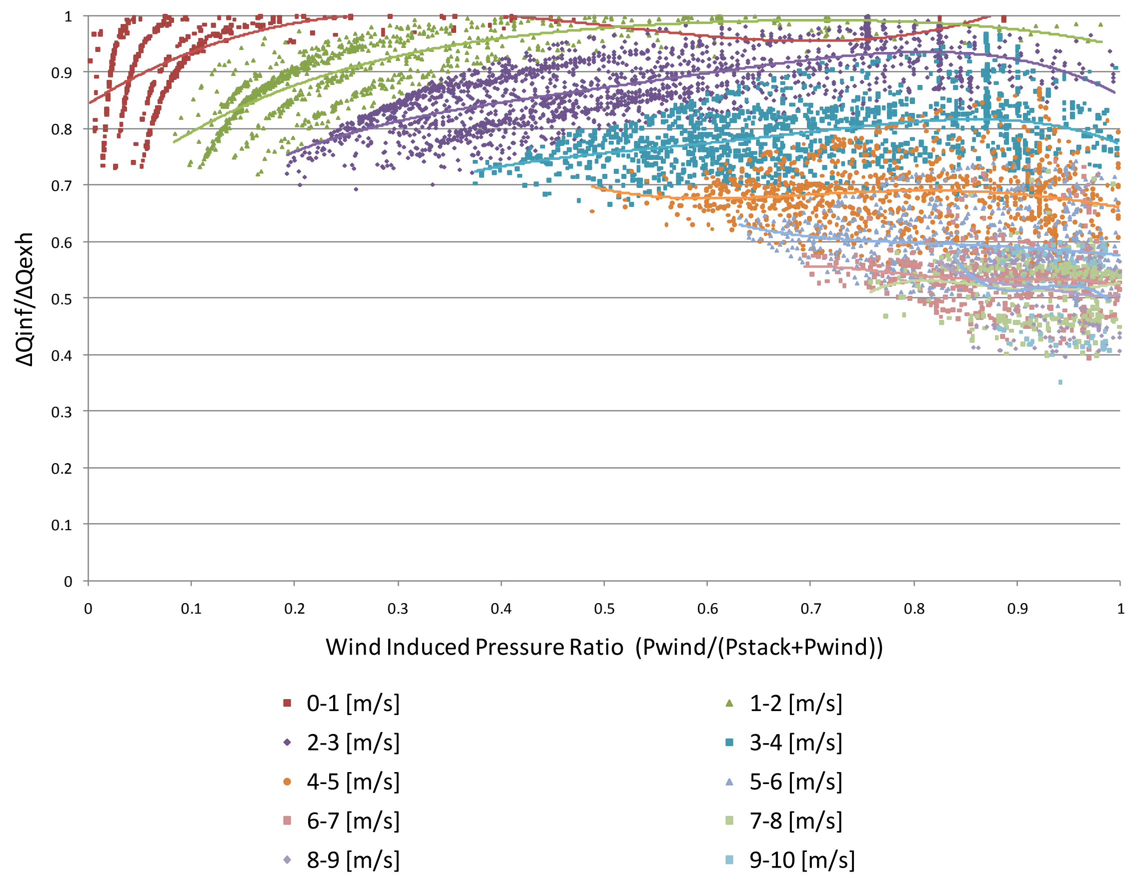

Figure 8: $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ as a function of wind induced pressure ratio and wind speed, for CA Climate Zone 12 (Sacramento)

Figure 8 plots the same data as Figure 5, but breaks out the results for : $\frac{\Delta Q_{\mathrm{inf}}}{\Delta Q_{\mathrm{exh}}}$ across different wind speeds. The analysis illustrates that when wind is the dominant environmental pressure $\frac{\Delta Q_{\mathrm{inf}}}{\Delta Q_{\mathrm{exh}}}$ is very sensitive to wind speed, and remains steady on average across a range of pressure ratios. When wind speed is low, the value $\frac{\Delta Q_{\mathrm{inf}}}{\Delta Q_{\mathrm{exh}}}$ can vary significantly. When wind speed is 7-10 *m/s* $\frac{\Delta Q_{\mathrm{inf}}}{\Delta Q_{\mathrm{exh}}}$ may be as low as ~0.4 and not higher than ~0.6. When wind speed is 0-4 *m/s* $\frac{\Delta Q_{\mathrm{inf}}}{\Delta Q_{\mathrm{exh}}}$ may range from ~0.7 to as much as 1.0. Interestingly, there are also instances when wind speed is relatively low, 1-2 *m/s*, yet wind is still the dominant environmental pressure mechanism. This indicates that the total environmental pressure is very low; accordingly, in these instances $\frac{\Delta Q_{\mathrm{inf}}}{\Delta Q_{\mathrm{exh}}}$ is near unity.

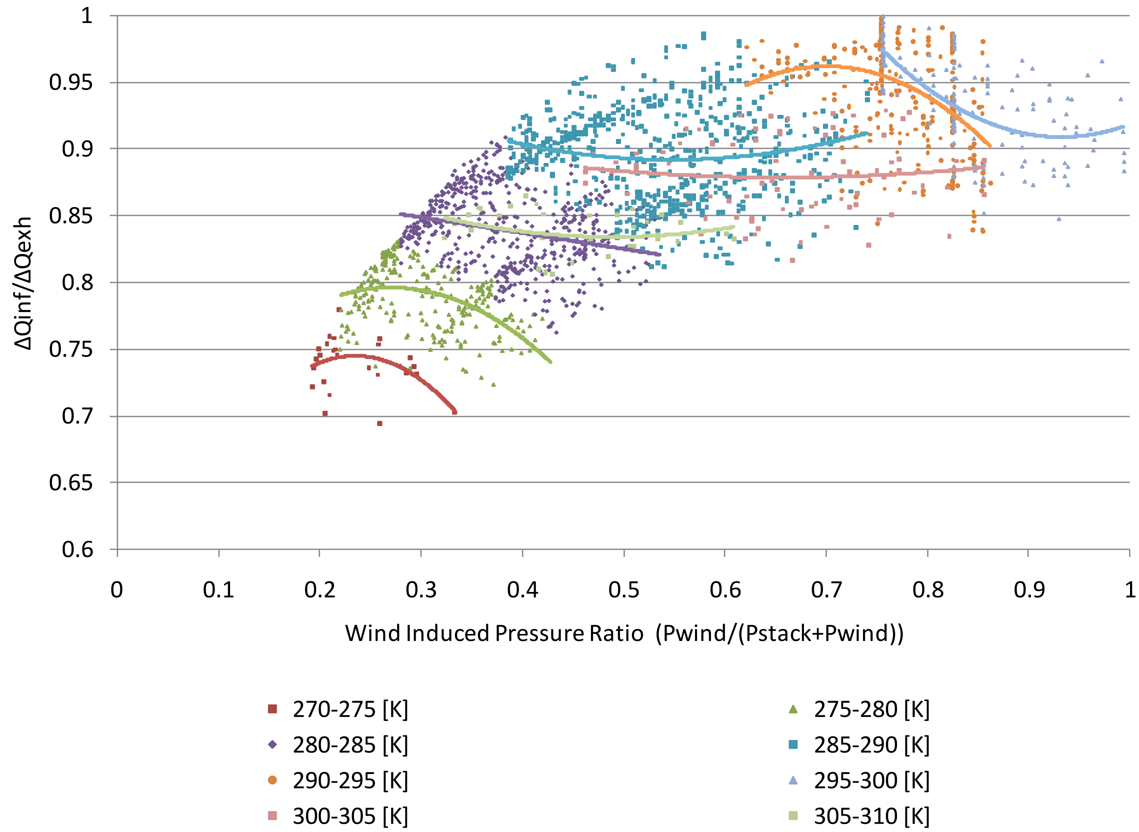

Figure 9: $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ *as a function of wind induced pressure ratio and temperature, for wind speed range 2-3 mph, and for CA Climate Zone 12 (Sacramento)*

Figure 9 plots a segment of the data from Figure 8 for wind speeds between 2 and 3 *mph* and breaks the response apart by ambient temperature. From this analysis it can be concluded that, for CA Climate Zone 12, most of the change in $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ for a particular wind speed is related to temperature. However, even within the constraints of a particular wind speed and temperature $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ can vary by as much as ~0.2. Ostensibly, this is related to the effects of wind direction.

It is expected that within the bands in Figure 8 defined by higher wind speeds, temperature has less effect on $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$, compared to the effects seen in Figure 9, although it does change the pressure ratio. The range of $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ equal to ~0.4-0.6 for wind speed ~7-10 *m/s* can more conclusively be attributed to wind direction effects by analysis of Figure 10.

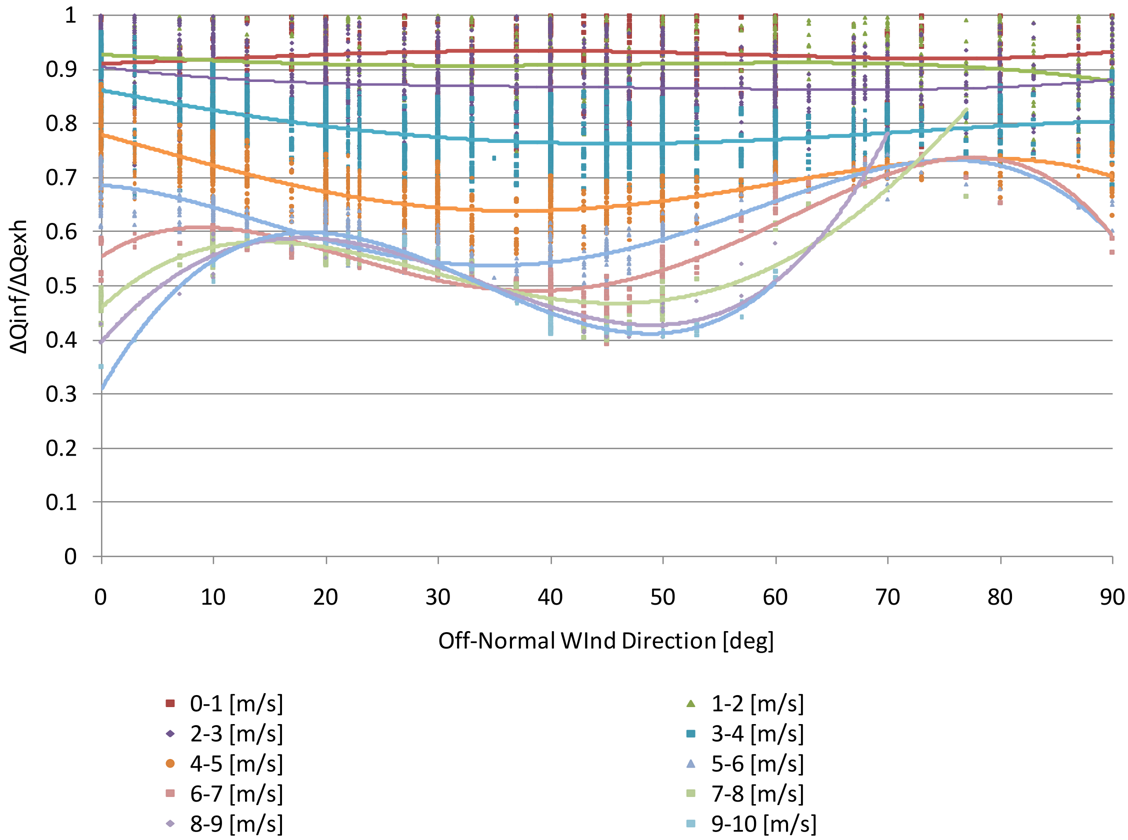

Figure 10: $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ *as a function of off-normal wind direction and wind speed, for California Climate Zone 12 (Sacramento)*

This plot illustrates the magnitude of impact that wind direction has on $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$; it charts $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ computed for every hour of the year against the corresponding off-normal wind direction. Off-normal wind direction is a parameter used for this analysis to reduce the compass direction based on symmetry of the prototype building model. If North is defined the normal wind direction, since the model is symmetric across its E-W and N-S axis, 180° can be reduced to 0°, 135° can be reduced to 45°, and 275° can be reduced to 85° off-normal. The figure illustrates that at higher wind speeds $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ can vary significantly based on wind direction. At 9-10 *m/s* $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ ranges from ~0.45 at 0° to ~0.6 at 20°. Looking again at Figure 8 it is clear that when wind speed is high, and thus wind induced pressure ratio tends toward 1.0, wind direction can impact $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ as much or more than temperature.

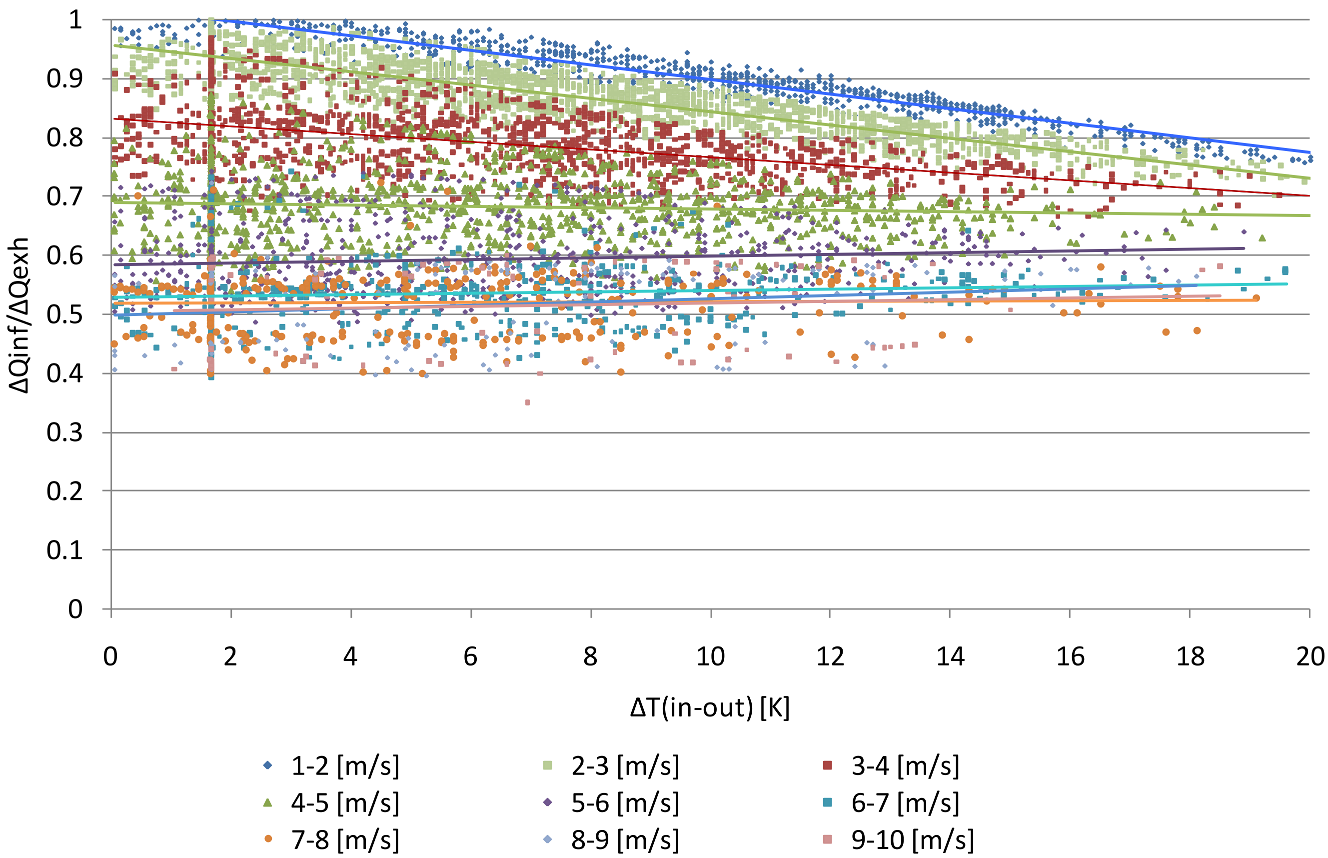

Figure 11: $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ *as a function of indoor-ambient temperature difference and wind speed*

Figure 11 shows that for any given wind speed $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ is linearly related to the indoor versus outdoor temperature difference. Expectedly, an increase in stack pressure has less and less effect on $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ as wind speed increases, but at low wind speeds a change of 20 $^{\circ}C$ can drive $\frac{\Delta \mathrm{Q_{inf}}}{\Delta \mathrm{Q_{exh}}}$ from ~1.0 down to about ~0.75.

Of course, while the relationship between $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ and driving climatic variables is relevant, the thrust of this exercise was to develop a simplified model for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ that would be representative of impacts to infiltration flow on average over the course of a typical year. The original hope was to compute $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ for every day in a year then use a straight forward average annual value as a constant factor for further calculation; although such a model would be imprecise on an hourly basis it would predict appropriately on the whole. Figure 12 shows the error between $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ calculated on an hourly basis and a simple average for the entire year in CA Climate Zone 12; the value is plotted against the stack induced pressure ratio. The error often ranges to ~0.35 and tends to be worse in general near the extreme meteorological conditions.

Although the average is a perfectly valid way to predict the annual average impacts on energy savings for a certain climate zone, it may not apply reasonably in regions with distinctly different meteorological characteristics. Moreover, as illustrated in Figure 7 the exhaust flow rate, Q_{exh}, , and the magnitude of change in exhaust flow, ΔQ_{exh}, , both appreciably impacts the result for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$. Subsequently, the simple model, as discussed in the next section, accounts for these factors.

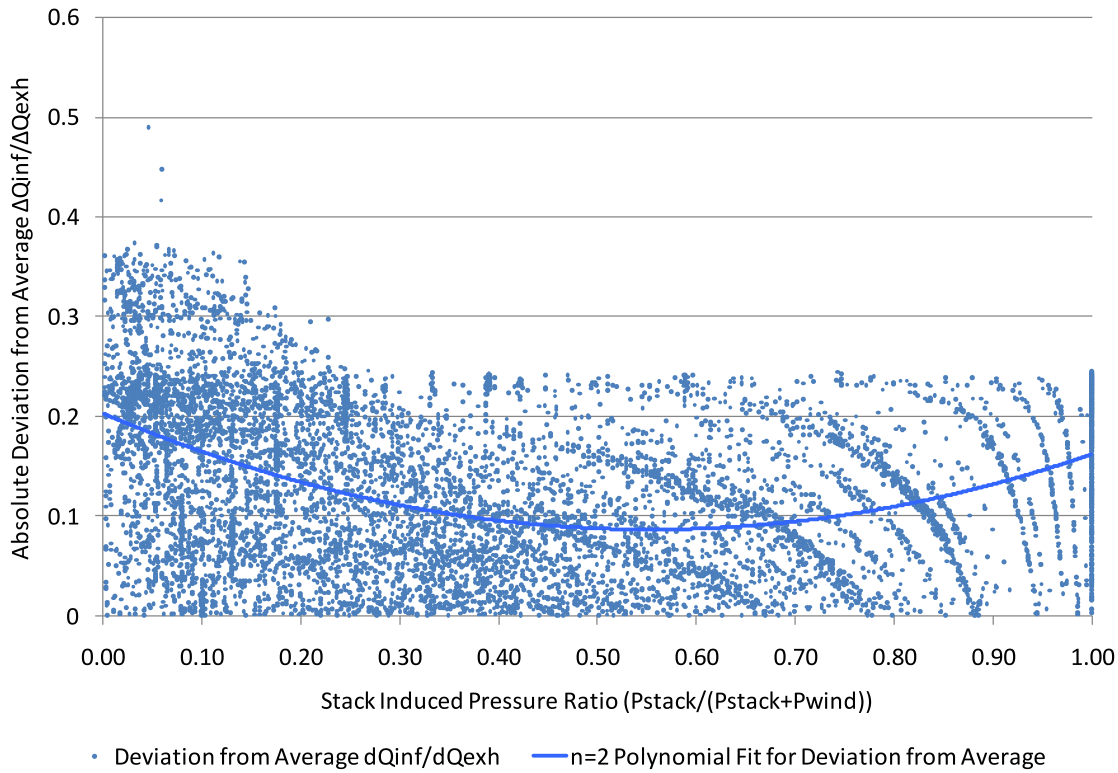

Figure 12: Absolute deviation from the annual average $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ *as a function of stack induced pressure ratio, for CA Climate Zone 12 (Sacramento)*

Simplified Model for Energy Savings from Exhaust

The simple model for energy savings to be gained from sealing exhaust leaks begins with a simplified function for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$, then follows with a straightforward calculation of thermal energy savings and fan power savings, as defined by Equation 6 and Equation 7.

To develop a simplified function for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ that accounts for all appropriate variables the research began with complex zone pressure and link flow simulations in CONTAM to compute the annual average value of $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ for a range of initial exhaust flow rates (Q_{exh}) for three different magnitudes of exhaust flow change (ΔQ_{exh}), and for four different climate zones. For comparison California Climate Zones 2, 12, and 15, and US Climate Zone 1, corresponding to Santa Rosa, Sacramento, Palm Springs, and Juneau Alaska respectively, were used. Juneau Alaska was chosen merely for the sake of contrasting results with an extreme climate zone. Figure 13 plots the results for all of these simulations against Q_{exh}, for each magnitude of ΔQ_{exh} and for each climate zone.

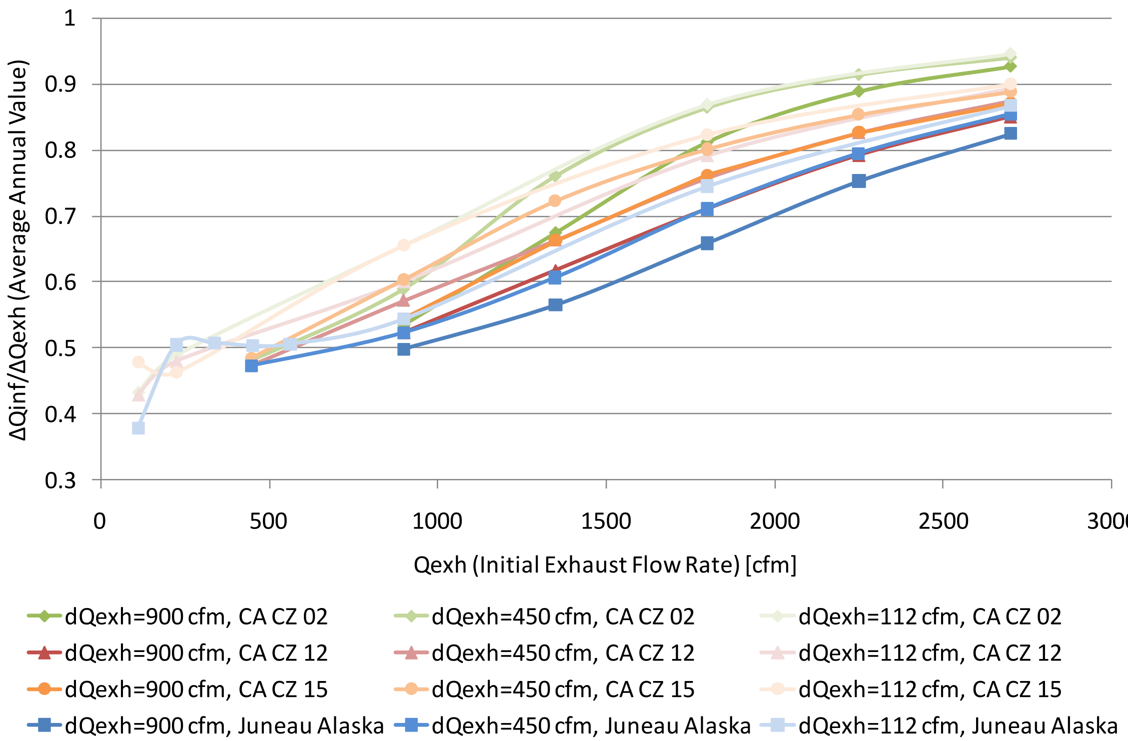

Figure 13: Annual average values for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ as a function of Q_{exh} for different magnitudes of ΔQ_{exh} in different climate zones

Clearly a single constant value is inadequate to accurately estimate $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ for all circumstances in all climate zones. Even if the results from Juneau are dismissed, $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ ranges from ~0.45 to ~0.95. Further, a single linear fit, or even a polynomial function of Q_{exh} could grossly misjudge the value, since for a particular value Q_{exh}, , $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ can vary by up to ~0.2.

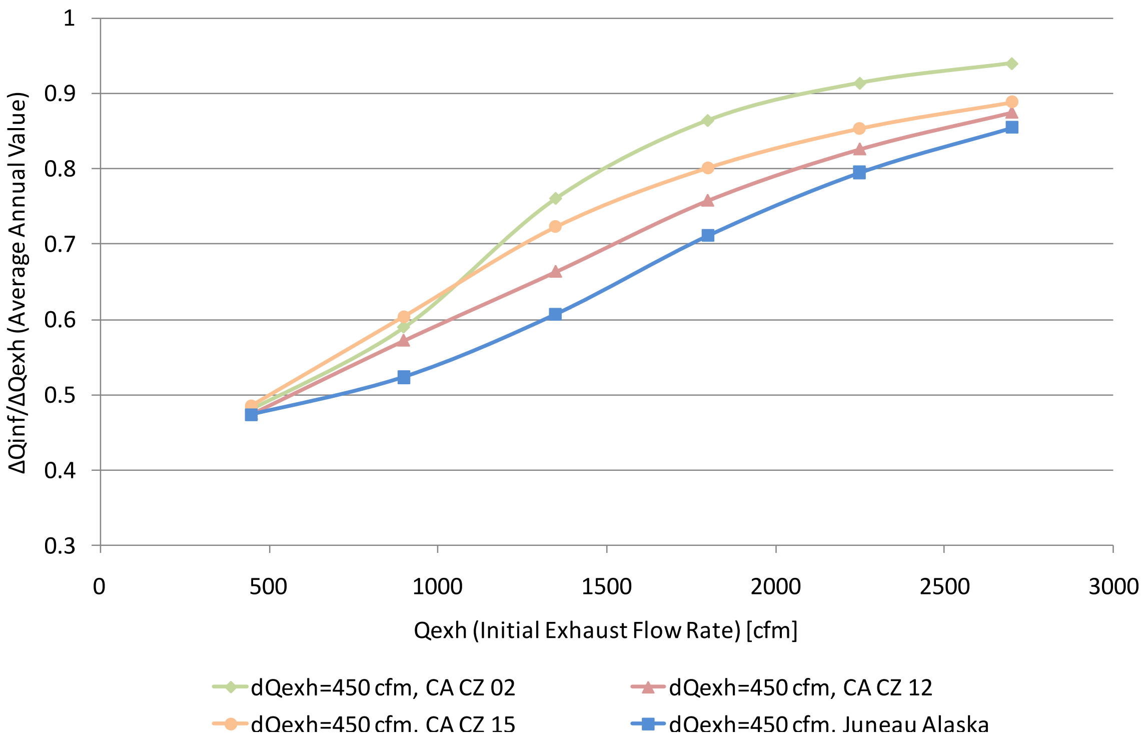

Figure 14: Annual average values for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ *as a function of* Q_{exh} *for* ΔQ_{exh}*=450cfm in different climate zones*

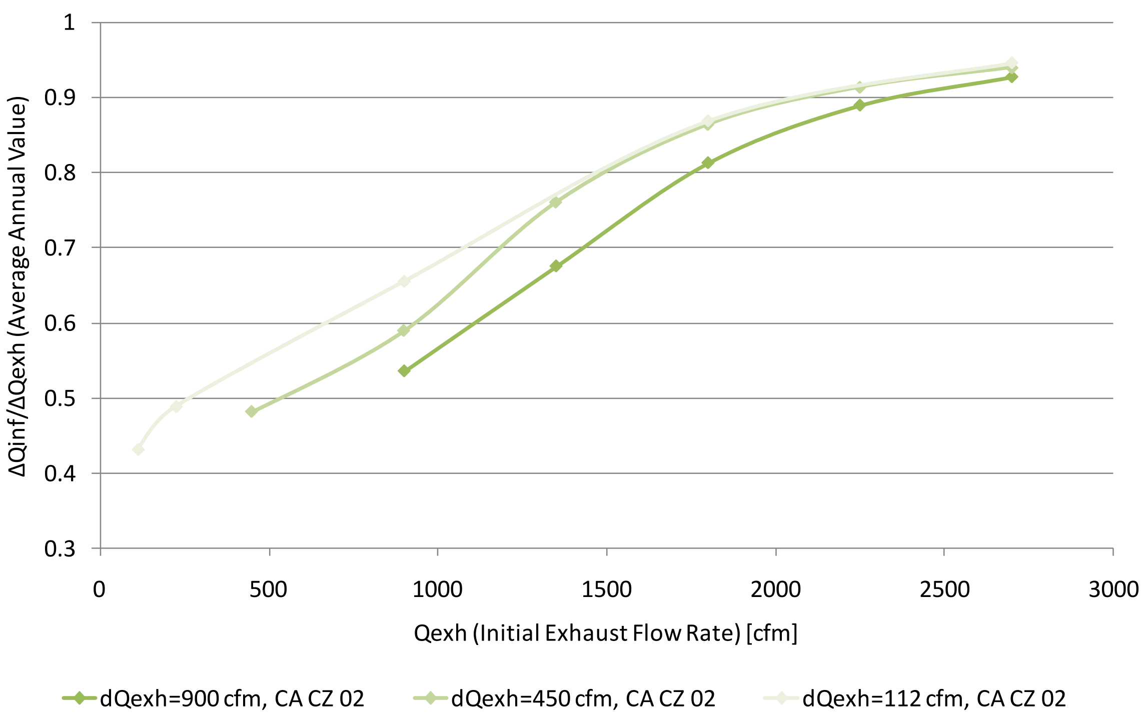

Figure 15: Annual average values for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ *as a function of* Q_{exh} *for different magnitudes of* ΔQ_{exh} *in CA Climate Zone 02 (Santa Rosa)*

Even for a single magnitude of ΔQ_{exh} , as plotted in Figure 14, the difference in $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ between climate zones is appreciable. The value of ΔQ_{exh} also significantly impacts $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$, as shown in Figure 15 for CA Climate Zone 02.

However, while all of the circumstances simulated and compared are possible, they are not all probable. As will be covered in *Discussion of Results from Leakage Measurements*, while the leak percentage in exhaust systems is often quite large, it generally never accounts for more than 40% of the exhaust flow. Therefore, the researchers can dismiss simulation results for which the fractional change in exhaust flow, $\frac{\Delta Q_{exh}}{Q_{exh}}$, is greater than 0.4. Likewise, results with $\frac{\Delta Q_{exh}}{Q_{exh}}$ values below ~0.1 can also be dismissed, since systems in this range may not warrant exhaust sealing. Table 2 tabulates the fractional change in exhaust flow, for each pair of Q_{exh} and ΔQ_{exh} simulated. The values for fractional change in exhaust flow correspond to the leakiness of ducts that would be sealed and the probable circumstances are highlighted in red.

ΔQexh % Change	Qexh initial: *2700*	*2250*	*1800*	*1350*	*900*	*450*	*225*	*112*	ΔQexh
	0.33	0.40	0.50	0.67	1.00	2.00	4.00	8.04	*900*
	0.17	0.20	0.25	0.33	0.50	1.00	2.00	4.02	*450*
	0.08	0.10	0.13	0.17	0.25	0.50	1.00	2.01	*225*
	0.04	0.05	0.06	0.08	0.12	0.25	0.50	1.00	*112*

Table 2: Percent change in Q_{exh} for each Q_{exh} and ΔQ_{exh}, where the value corresponds to leakiness of exhaust duct. The probable circumstances are highlighted in red.

Figure 16 plots $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ as a function of Q_{exh} for all scenarios considered narrowed down to probable circumstances for duct sealing projects – the probable cases are shown as red. Fortunately, this judicious selection for the likely range of circumstances allows the researchers to simplify the model for estimation of $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$.

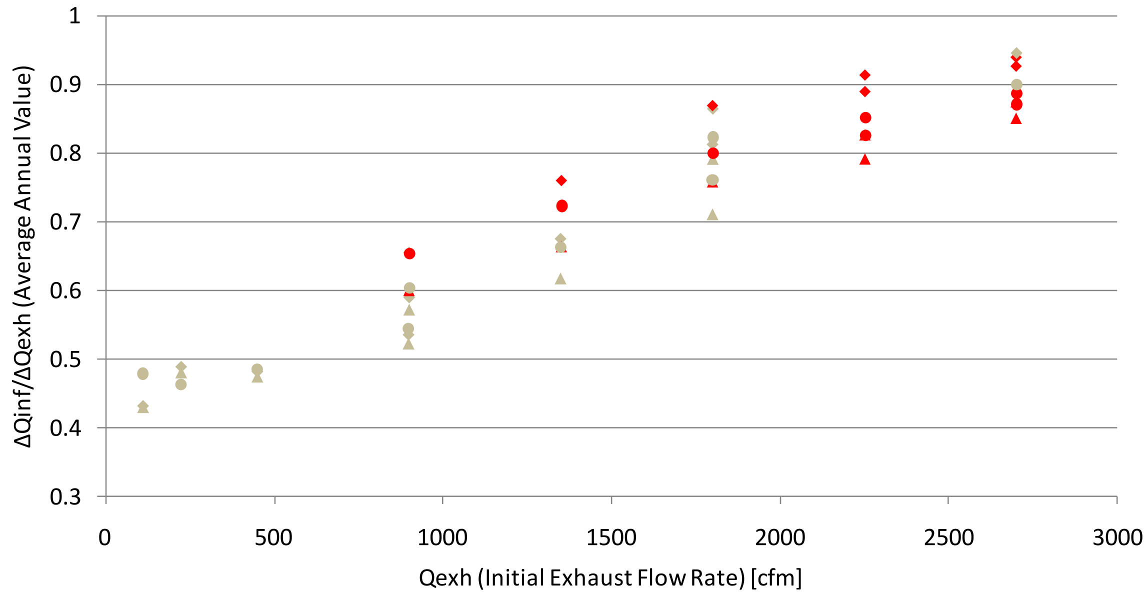

Figure 16: Annual average values for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ as a function of Q_{exh} for different magnitudes of ΔQ_{exh} in different California Climate Zones, highlighted points represent probable circumstances

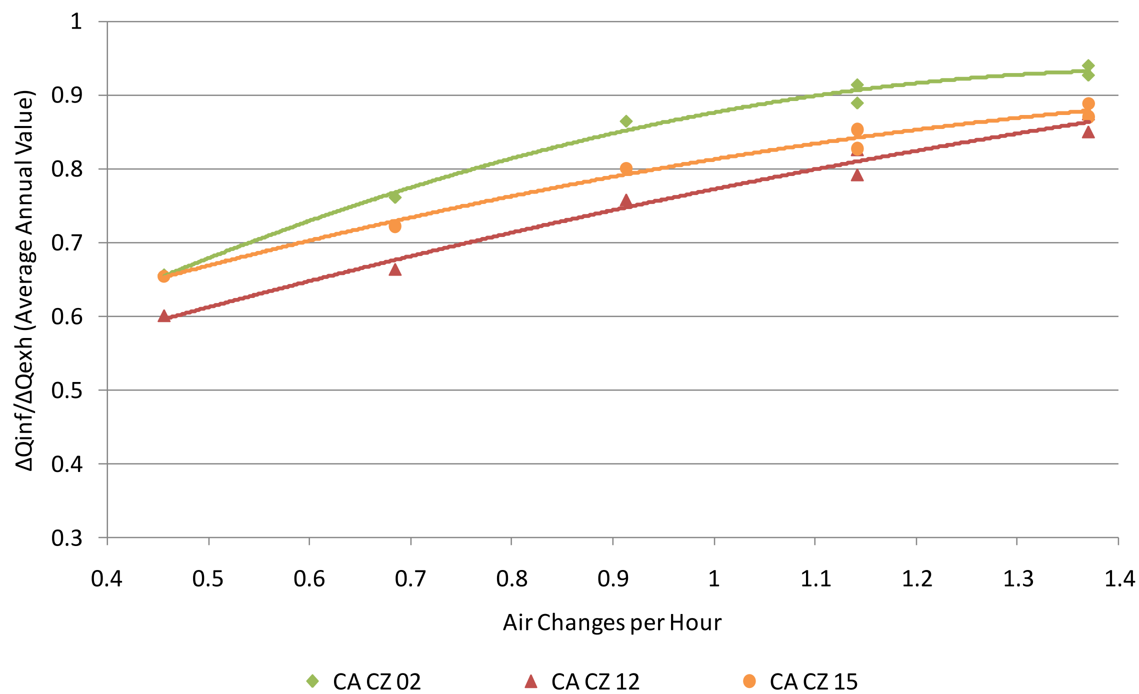

Figure 17: Simple model to estimate the annual average value of $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ as a function of ACH and CA Climate Zone

Figure 17 plots the annual average value of $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ for each probable exhaust flow change scenario, as a function of hourly air changes (ACH), for each CA Climate Zone simulated. To be clear, ACH is used here a metric to reduce the exhaust fan volume flow rate to a transferrable parameter that can be applied to any building. It is calculated as a ratio of the exhaust flow rate to building volume and converted to units of *hours*$^{-1}$:

$$ACH = \frac{Q_{exh}}{V_{building}} \quad (18)$$

where:

Q_{exh} = Exhaust fan flow rate prior to duct sealing

$V_{building}$ = Building volume

With the improbable scenarios removed from the equation a simple trend for each climate zone is apparent, and the relationship becomes nearly independent of the magnitude of change in exhaust flow. A second order polynomial fit to the data returns R^2 values of 0.99, 0.99, and 0.98 for CA Climate Zones 02, 15, and 12 respectively.

Thus, a simplified model for the ratio of change in infiltration flow to a reduction in exhaust flow need only be dependent on ACH and climate zone. The equations for the three CA Climate Zones simulated here are presented below:

$$\frac{\Delta Q_{inf}}{\Delta Q_{exh}} = f(ACH, CZ) \quad (19)$$

for CA CZ 02 → $\frac{\Delta Q_{inf}}{\Delta Q_{exh}} = -0.2809\, ACH^2 + 0.8174\, ACH + 0.3397$

for CA CZ 12 → $\frac{\Delta Q_{inf}}{\Delta Q_{exh}} = -0.1267\, ACH^2 + 0.4784\, ACH + 0.4612$

for CA CZ 15 → $\frac{\Delta Q_{inf}}{\Delta Q_{exh}} = -0.058\, ACH^2 + 0.4498\, ACH + 0.4085$

It's likely that this simple model could be made independent of climate zone by analyzing the results across additional variables that characterize the wind speed and temperature distribution in each climate zone, as discussed in *Project Outcomes* for *Transient Weather Analysis*. This is desirable since it would reduce the model for $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ to a single function. However, it would also complicate the function, which would probably become a partial differential equation, and would require specific knowledge about each climate zone to compute. Though this analysis only presents functions for three climate zones, further modeling is under way to develop functions for all 16 California Climate Zones. It's expected that only 4 or 5 separate equations will be needed to adequately describe $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ in all 16 California Climate Zones.

Objectives 2 and 3

Objective 2: Confirm that exhaust duct leakage can be determined cost-effectively
Objective 3: Gather additional field data on leakage levels in exhaust duct systems, particularly for recently constructed buildings

Field Test of Leakage Measurement Techniques

This study has shown that the new methods examined, which are less intrusive, less expensive, and easier to perform than the current industry standard calibrated fan pressurization test, produce comparable results reliably and consistently.

Discussion of Leakage Measurement Techniques

Flow Difference Test

Although this is the simplest and quickest test it is not sufficiently consistent with the standard calibrated-fan pressurization technique. Results of field testing showed that this technique was vulnerable to unpredictable errors. For example, if an exhaust register were to be partially or completely blocked with dust, which is not uncommon in older buildings, this test would produce a false reading, and would incorrectly indicate a high level of leakage.

Pressure Drop Test

For the Pressure Drop Tests, the researchers measured the pressure difference across grilles under three sets of conditions:

1. Normal operation
2. One grille blocked at a time
3. All grilles blocked at once

The hope was that from these measurements a pattern might emerge indicative of whether or not a system is leaky enough to merit sealing. Unfortunately, the pressure measurements proved to be a poor gauge of leakage for a number of reasons:

1. All the patterns looked about the same, including the one tight system that was measured with this method

2. All of the systems had about the same leakage, so developing a correlation between measured pressures and leakage was impossible
3. In the test with all grilles blocked a drop in pressure with distance from the fan could indicate leakage, however by the time you block them all, you might as well measure flow at the exhaust fan outlet to calculate a more accurate measure of leakage by the Blocked Grille Test.

The Pressure Drop technique was discontinued; therefore results are not compared to other methods in summary tables and charts.

Blocked Grille Test
This was found to be the simplest test that produced results that are reliably consistent with the Duct-Blaster test. This test uses the following simple method (explained in greater detail in the Methods Section):

1. The flow through the exhaust system is measured with all of the grilles opened and closed
2. A correction factor is used to relate the exhaust flow at blocked grille pressures to normal operating pressures
3. The difference between the normal operating flow and corrected blocked grille flow is thus the leakage flow rate through the system, from which a percent leakage can be computed.

Discussion of Results from Leakage Measurements

Technique	Description	Average absolute difference in % leak compared to standard	Average percent difference in leak % compared to standard	Remarks
Duct Blaster	Turn off exhaust fan, block exhaust outlet vent, block all registers, connect calibrated fan to system, measure flow, compare to normal operation	0	0%	Industry Standard
Pressure Drop	Compare pressure difference across each register to pressure differences for systems with known leak percentage	NA	NA	Invalidated
Vane Anemometer	Compare difference between exhaust outlet flow and register inlet flow to determine leak percentage	2.33%	9.22%	Validated
Blocked Grille	Measure flow at exhaust outlet and pressure difference across each register with grilles open and blocked	4.28%	20.80%	Validated

Table 3: Summary table for results of each leakage measurement technique compared to the industry standard calibrated fan pressurization test

Figure 18 compares results of the Duct Blaster, Flow Difference, and Blocked Grille test for determining percent leakage in several different buildings. Note that the Flow Difference technique was discontinued after Dormitory 3. Initially, results for the Blocked Grille test did not match the Duct Blaster test within a reasonable margin of error; however, as the Blocked Grille technique was refined and tuned the researchers were able to match results to within 1-2%. These refinements are discussed further in the *Project Approach*, but included the use of artificial plenums for mushroom caps and large face area grilles, as well as empirical correction factors developed to properly measure volume flow through grille louvers and out open duct ends.

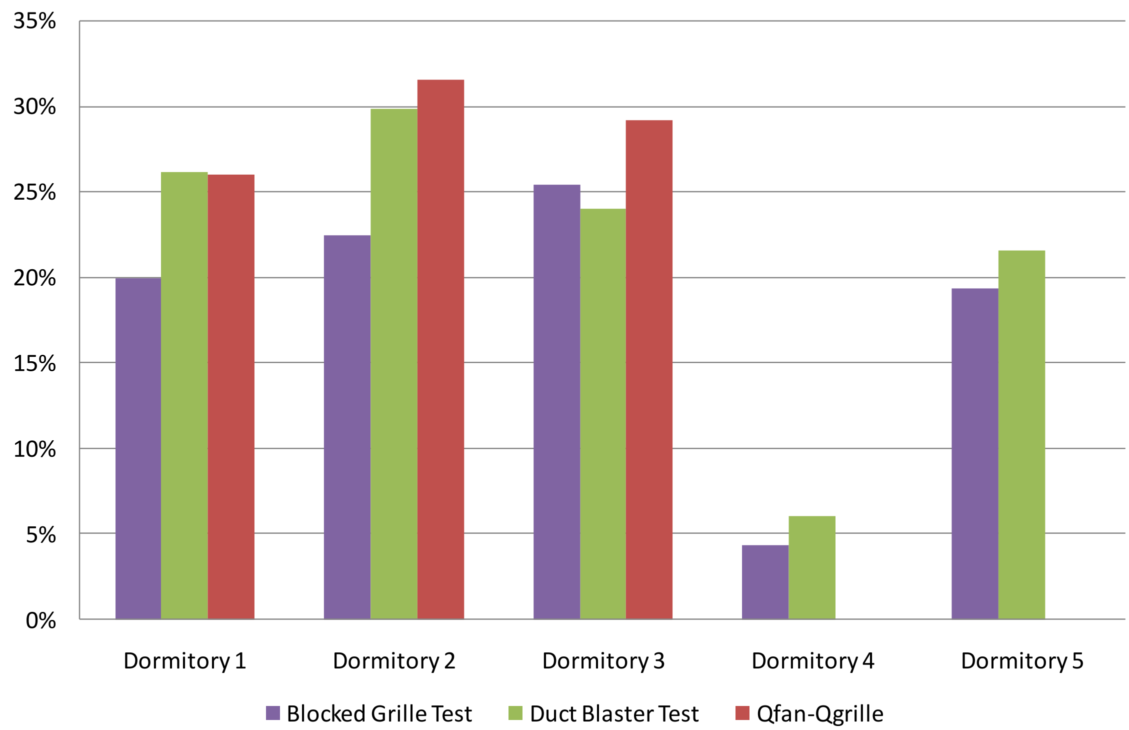

Figure 18: Comparison of simplified exhaust system leakage measurement techniques

Once the Blocked Grille test was well refined to consistently match the Duct Blaster test, field testing focused on measuring several additional systems using the Blocked Grille test only. The results for percent leakage for all systems tested are plotted against building age in Figure 19. The hypothesis was that older buildings would leak more than newer buildings, or buildings with new renovated exhaust systems. However, while most newer exhaust systems leak less than 10%, within the range expected, some newer buildings have substantial leaks near 20%. One 7 year old building measured 31% leakage, but the results were dismissed based on measurement uncertainties. Additionally, some older systems seem to perform within the range of what is expected for newer buildings.

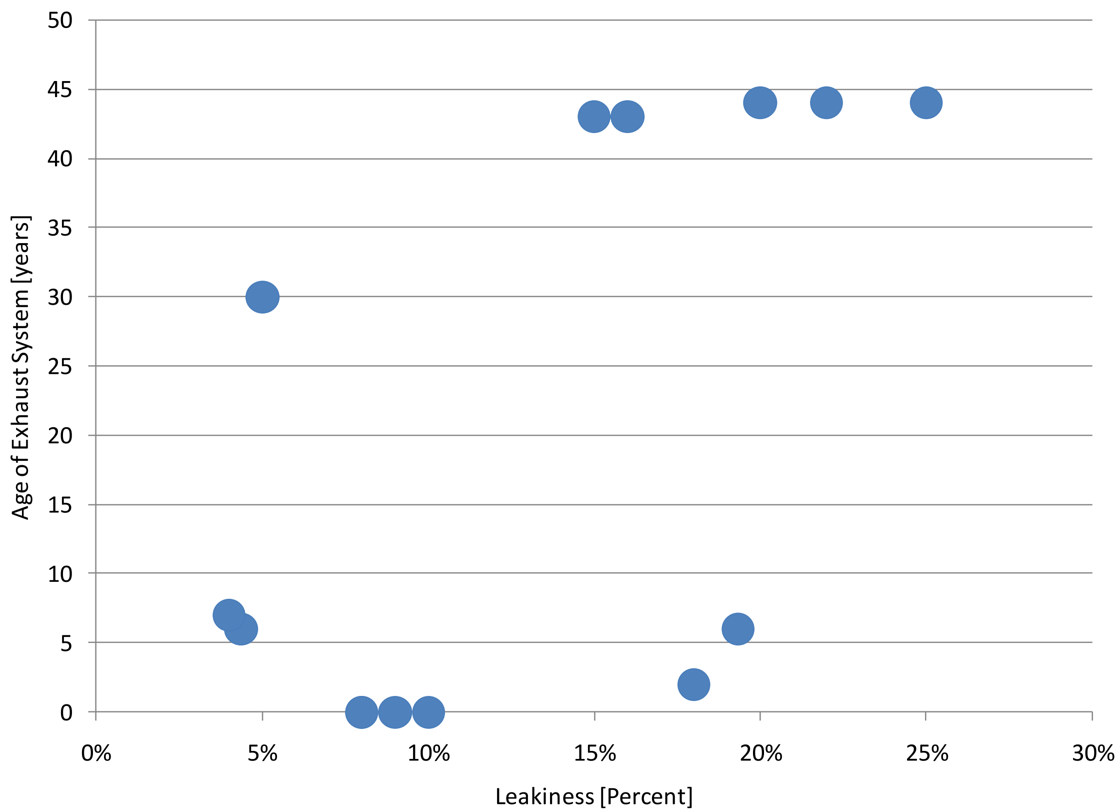

Figure 19: Comparison of leakiness and building age for all systems tested

The amount of data is not sufficient to describe a relationship conclusively, but the results indicate that while leakage increases for older buildings, newer buildings are not necessarily leak free.

Based on the test results, it can concluded that the blocked grille tests is a viable alternative to the Duct Blaster test for determining the leakage flow in exhaust systems. The test appears to be limited at this time to buildings with simple exhaust systems, vertical risers with branching ductwork leading to registers and no filters or heat exchangers. It is easier, less costly, quicker, and less intrusive than the calibrated fan pressurization test; and it produces reliably similar results.

Objectives 4, 5, and 6

Objective 4: Compile "best-estimate" leakage flow and cost data
Objective 5: Quantify the savings that can be achieved by sealing various levels of exhaust duct leakage in California buildings.
Objective 6: Calculate the cost effectiveness of exhaust duct sealing in different applications

Cost Effectiveness Analysis

The cost effectiveness analysis conducted for this study is computed for a range of different hourly air change rates, initial degrees of leakiness, and for two California Climate Zones. Differences as a result of climate zone are attributable to differences in the ratio $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ which varies with ACH and climate as described by Figure 17 and Equation 19. The cost of duct sealing was assumed to be $0.20 *per square foot* of space served by a fan, and leaks were assumed to be sealed by 85%, based upon data from Carrier-Aeroseal (Aeroseal 2009). Electricity for cooling and fan power was assumed to cost $0.12 *per kWh*, natural gas for heating was assumed to cost $1 *per therm.* The results for the payback period and return on investment for exhaust duct sealing in two different climate zones and multiple degrees of leakiness are presented in Figure 20 and Figure 21.

Expectedly, higher levels of leakiness sealed, and higher initial air change rates result in quicker payback and better ROI. For exhaust systems with higher air flow rates, such buildings with ACH near or above ~0.9, it would be just as cost effective to seal a relatively tight system, ~10% leakage, as it would to seal a leakier system at a lower flow rate. This analysis also indicates that the effects of climate zone are muted for economic value as compared to the importance of ACH and intial leakiness.

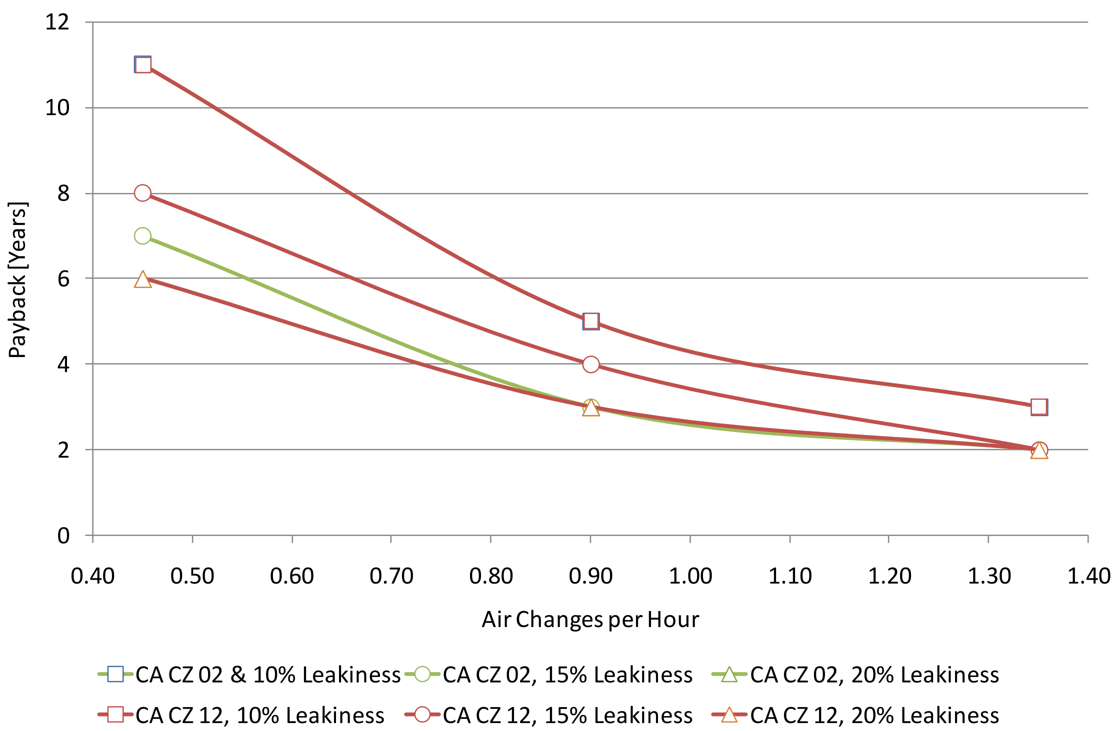

Figure 20: Return on Investment for exhaust duct sealing as a function of ACH, for two climate zones(Sacramento & Santa Rosa), and three degrees of leakiness (10%,15%, & 20%)

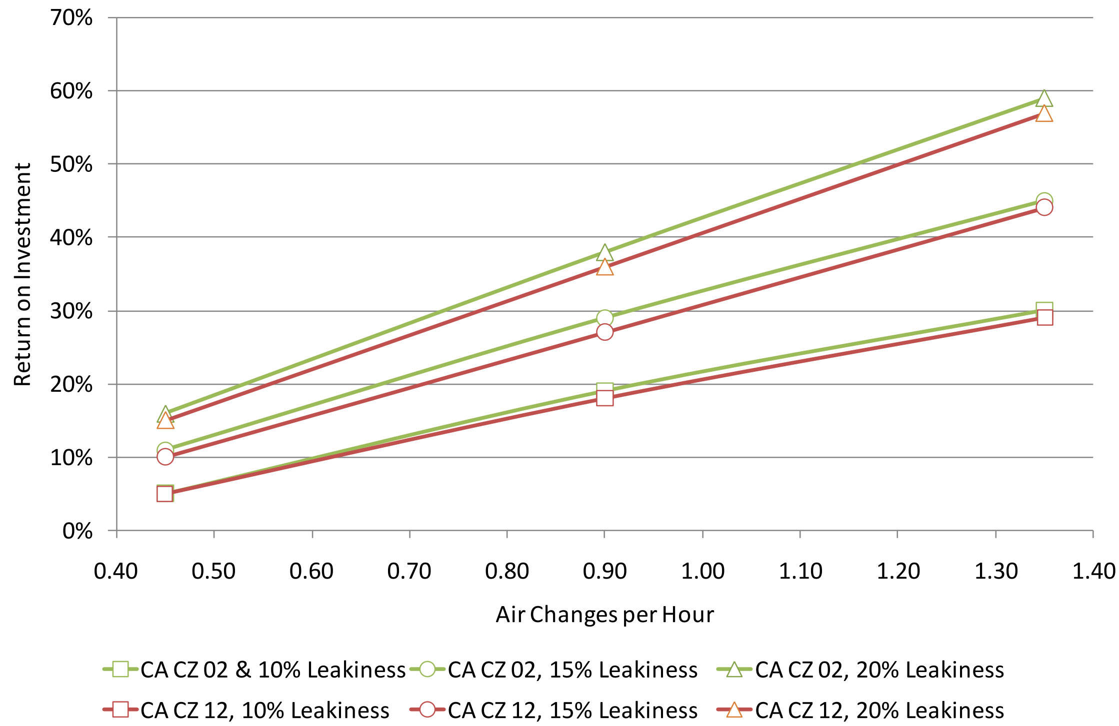

Figure 21: Return on Investment for exhaust duct sealing as a function of ACH, for two climate zones(Sacramento & Santa Rosa), and three degrees of leakiness (10%,15%, & 20%)

Objective 7

Objective 7: Deliver a code change proposal to the California Energy Commission related to exhaust duct leakage

California Code Change Proposal

This objective has not been completed, since an official code-change proposal has yet to be filed, but future action will incorporate the results of objectives 1-6 into a code-change proposal to address exhaust duct leakage in new construction, as well as in alterations. The key changes to be suggested are summarized in the recommendations section of this report.

Conclusions

Several techniques for auditing the leakiness of exhaust systems were tested and compared to the current industry standard method in order to identify a simplified approach that is quicker, less intrusive, and less costly than the calibrated-fan pressurization test. The Blocked-Grille test, which compares pressure and flow measurements in normal conditions and while the exhaust registers are all blocked, was proven as a reliable strategy. After refinement, the method was applied to test exhaust systems in several different hotels and dormitories throughout California to test the technique in different circumstance and to get an indication of leakiness for a range of different buildings. Though the data collected does not provide a conclusive characterization of the building stock, it does seem that while older buildings are leakier on average, the newness of a building does not guarantee low leakage. The integrity of exhaust systems is likely more a factor of construction quality.

The findings of this research confirm expectations that sealing leaky exhaust systems could save 20% of heating and cooling energy costs, and up to 50% of fan energy costs in exhaust driven buildings such as hotels and dormitories. These values are an upper end of potential savings estimated for a building with ~25% leakage and a relatively high ACH of ~1.2. In comparison, for a building with ~15% leakage and ACH of ~ 0.7 , heating and cooling energy savings would be closer to 8% and fan energy savings would be near 30%. For the six-story prototype building model with an exhaust flow change from 1350 *cfm* to 900 *cfm*, which corresponds to sealing a system with 30% leakiness, analysis estimates a heating and cooling load reduction of 11.2 *MWh/year*, not accounting for the inefficiencies of heating and cooling devices.

Another major insight from this research is a clear characterization of the relationship between infiltration flow and changes in exhaust flow. While it was hypothesized that a single constant value might be adequate to estimate $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ for all probable circumstances, transient weather modeling illustrated that the relationship can actually change considerably based on a number of different conditions. However, a simple set of second order polynomial functions, based only on ACH for each climate zone, was developed to estimate the average annual value of $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ to an R^2 of about 0.99.

These findings illustrate the importance of sealing exhaust systems, as the energy and monetary implications of exhaust leaks are a significant. The recommendations section of this report outlines the basis for proposed changes to State of California Building Energy Efficiency Codes. The anticipated benefits of such code changes to the State of California, in terms of reducing energy expenditures during a time of economic crisis, reducing the consumption of natural resources, and reducing the state’s environmental impact, are substantial.

Recommendations

Based on the results of this research the researchers recommend a number of actions for investment in building efficiency measures, for the focus of utility Energy Efficiency programs, for building energy efficiency standards, and for future research and demonstration in this area.

Foremostly, since field measurements indicate that even new buildings can have significant leaks in the exhaust system, California Building Energy Efficiency Standards ought to be revised to ensure the integrity of exhaust ducts in new construction. Further, code concerning building renovations should be amended to include exhaust duct sealing for systems which measure beyond 10% leakiness, and for some less leaky systems if exhaust flow rates are particularly high, such as in laboratories or hospitals. Title 24 Section 144 (k) provides prescriptive requirements for the sealing of leakage in air distribution systems; this section should be expanded to include requirements for sealing exhaust systems as well.

Appendix NA2 of the 2008 California Building Energy Efficiency Standards outlines specifications for leakage diagnostic test procedures for supply air systems; this section should be expanded to include exhaust systems, and the test procedures should be amended based on the simpler more cost effective techniques which were developed though this study. The Blocked Grille test produced reliable and reasonably accurate results compared to a current industry standard calibrated fan pressurization test. These procedures should also be included in utility programs related to energy audits for buildings with exhaust driven infiltration.

Moreover, in the realm of research, field testing should be continued and expanded to better characterize the leakiness in existing building stock and to develop a more solid understanding of the cause of leaks, including age, design, and construction quality. Modeling should be continued to develop a complete set of simplified functions for the ratio $\frac{\Delta Q_{inf}}{\Delta Q_{exh}}$ to represent all California Climate Zones.

Lastly, the researchers recommend that the theoretical results for energy savings presented in this study be validated through a pre and post retrofit demonstration and monitoring project in multiple hotel or dormitory buildings.

Public Benefits to California

Nearly any building with a central exhaust system could gain measureable energy savings by sealing exhaust ducts to avoid the fan energy used to move excess air. For negative pressure buildings with exhaust driven infiltration, an even greater amount of energy can be saved by avoiding the costs of heating and cooling excess infiltration air. In certain cases, such as those modeled through this study, more than 20% of annual heating and cooling costs could be avoided by sealing exhaust systems. Were exhaust duct sealing adopted as a Title 24 requirement, at least 50 percent of California's commercial building stock would benefit from energy and cost savings of the retrofit energy efficiency measure. Based on indications from this research about the distribution of exhaust performance, and drawing from information about energy use in California's commercial building stock (Itron 2006) and information about the carbon dioxide emissions from California electricity and natural gas (CAT 2007), sealing exhaust ductwork statewide could avoid approximately 2 percent of California commercial electricity consumption, 3 percent of California commercial building natural gas consumption, and avoid 677,000 metric tons of carbon dioxide equivalent greenhouse gas emissions. The impact will be greatest in buildings with exhaust induced building ventilation where leaks draw air from conditioned space, and in building sectors that rely on high exhaust flow rates.

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California Energy Commission Buildings Energy Research Grant (BERG) Program **PROJECT DEVELOPMENT STATUS**	**Questionnaire**

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Please Identify yourself, and your project: **PI Name** Modera, **Grant** # 54918A/06-06B	
Overall Status	
Questions	**Comments:**
1) Do you consider that this research project proved the feasibility of your concept?	*Yes, the research team validated simplified measurement techniques against industry standard*
2) Do you intend to continue this development effort towards commercialization?	*Yes*
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	*No obstacles prevent demonstration*
4) Have you defined a development path from where you are to product demonstration?	*Yes*
5) How many years are required to complete product development and demonstration?	*Zero*
6) How much money is required to complete engineering development and demonstration?	*$25,000*
7) Do you have an engineering requirements specification for your potential product?	*No*
Marketing	
8) What market does your concept serve?	*Residential, commercial, industrial. Any buildings with rooftop exhaust systems.*
9) What is the market need?	*A significant majority of exhaust systems have leaks that are well worth sealing, both in terms of benefits to the public, as well as benefits to private financial interests.*
10) Have you surveyed potential customers for interest in your product?	*No*
11) Have you performed a market analysis that takes external factors into consideration?	*No*
12) Have you identified any regulatory, institutional or legal barriers to product acceptance?	*Yes. Adoption of such technologies often requires they be included in building standards.*
13) What is the size of the potential market in California for your proposed technology?	*The researchers estimate that 85 % of existing buildings in California could benefit from exhaust duct sealing.*

14) Have you clearly identified the technology that can be patented?	*Not Applicable*
15) Have you performed a patent search?	*Not Applicable*
16) Have you applied for patents?	*Not Applicable*
17) Have you secured any patents?	*Not Applicable*
18) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	*No*
Commercialization Path	
19) Can your organization commercialize your product without partnering with another organization?	*No, logical partners would be HVAC manufacturers with cost effective leak sealing technologies, such as Carrier-Aeroseal, as well as investor owned utilities, energy efficiency auditors, and building energy consultants*
20) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	*Yes*
21) Have you developed a commercialization plan?	*No*
22) What are the commercialization risks?	*There are challenges in overcoming common misconceptions about the energy and cost implications of exhaust leakage*
Financial Plan	
23) If you plan to continue development of your concept, do you have a plan for the required funding?	*Yes*
24) Have you identified funding requirements for each of the development and commercialization phases?	*No*
25) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	*No, but we've submitted research proposals to California Energy Commission for follow-on funding in this vein*
26) What are the go/no-go milestones in your commercialization plan?	*The biggest go/no-go milestone for the tools developed in this project is the adoption of recommended changes to Title 24*
27) How would you assess the financial risk of bringing this product/service to the market?	*The products available for aerosol duct sealing are commercially available. The success of these products in market would be significantly improved by changes to Title 24. The diagnostic methods developed trough this research will seriously reduce the cost and complexity of duct leakage measurements*
28) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	*No*

Public Benefits	
29) What sectors will receive the greatest benefits as a result of your concept?	*All non-residential building sectors, electric utilities, environmental interests, and all citizens through lowered societal costs and reduced electricity rates.*
30) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	*Sealing exhaust systems with 25% leakage could reduce fan power by 50% and reduce heating and cooling costs by 20%. Most systems measured in this study leak at least 10%, and many leak more than 20%. The energy savings have positive implications to both economic and environmental interests.*
31) Does the proposed technology reduce emissions from power generation?	*Yes*
32) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	*Probably not, the research is focused on diagnostic techniques and methods for estimating energy savings*
Competitive Analysis	
33) What are the comparative advantages of your product (compared to your competition) and how relevant are they to your customers?	*The techniques and methods developed allow for simplified estimates of energy savings from exhaust sealing and reduces the need for energy modeling*
34) What are the comparative disadvantages of your product (compared to your competition) and how relevant are they to your customers?	*The techniques developed are somewhat less accurate than typical methods*
Development Assistance	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
35) If selected, would you be interested in receiving development assistance?	*Yes; assistance in market assessment would be helpful*