DUCTOLOGY – Part 2

Does Your Ventilation System Make the Grade?

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FOREWORD

Ductology – Part 1 provided basic relations for designing economically optimized duct systems. An economically optimized duct network is one that should minimize a homeowner's lifetime cost. How can one determine if an installed duct system performs in a manner consistent with the characteristics of an economically optimized ventilation system? Ductology – Part 2 develops a foundation for assessing the performance of ventilation ductwork.

The main body of this report is reasonably brief and is intended to allow readers of all backgrounds to understand the concepts behind the ventilation duct performance and duct leakage tests. The "C value" analyses developed for duct performance and duct leakage is extended for characterizing house sealing (blower door) and house infiltration. Unifying duct performance, duct leakage, house sealing, and house infiltration allows one to determine the relative significance of these important factors that impact our health, comfort and energy usage.

Appendices with more extensive details are included for those readers who wish additional background. The appendices include experimental data and mathematical derivations used to develop and validate the duct performance test, duct leakage test, and house performance model.

The author apologizes for the dry nature of this material. Ventilation ducts are essential elements of a healthy home, but unfortunately, for many, it is not that interesting of a topic.

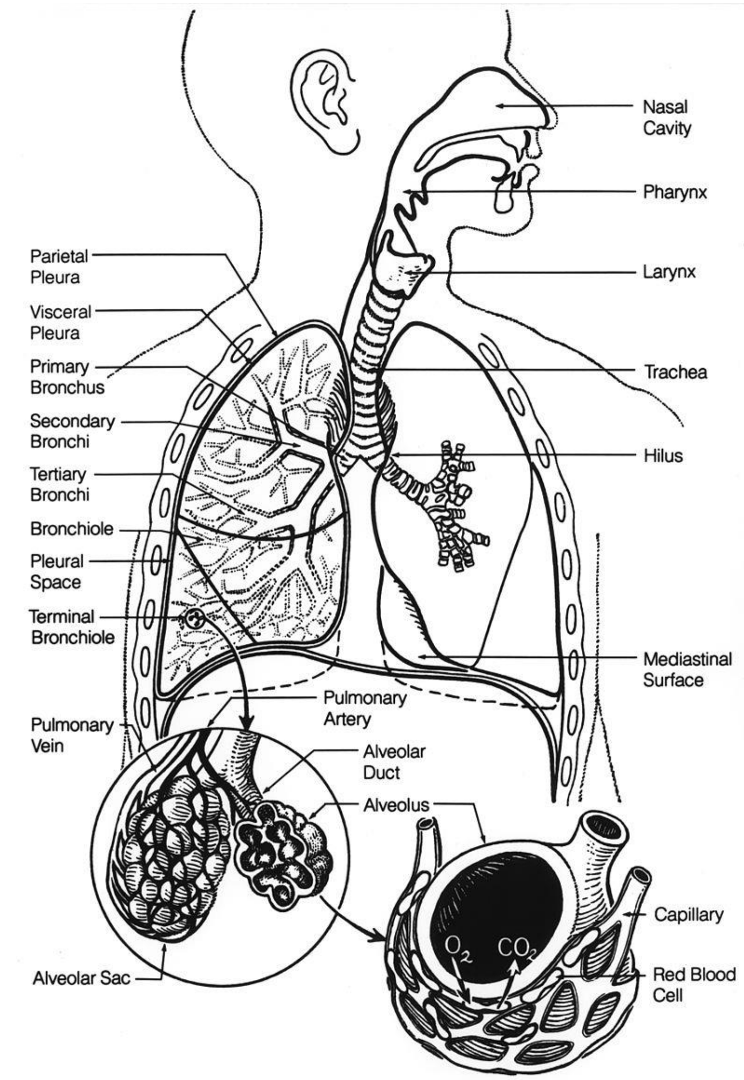
Executive Summary

Ductology – Part 2 develops procedures for assessing the performance of an installed duct network in terms of its air flow and air leakage. Several key ideas and results are included in this report:

1) Single duct lengths and whole duct networks can be described by a single parameter we call a "C value".
2) The C value for a duct relates a duct network's air flow to the duct network's pressure drop.
    a. C value relations are developed with units commonly used in the U.S. (air flow units in "cfm", or cubic feet per minute, and pressure units of "inches H_2O")
    b. Ventilation ducts are good when C values are 1000 or greater, and not good when C values are less than 500
    c. Duct leakage should have C values that are 5% or less than duct performance C values, with duct leakage C value less than 50 desired for the average home
3) Test procedures for "rough-in" duct performance and duct leakage tests are described
4) The duct performance analysis is extended to house infiltration and house blower door tests to unify and provide a rationale basis assessing house infiltration characteristics
    a. Blower door test results are converted to a C value in an identical manner as used for duct performance and duct leakage
    b. A mechanistic model is developed for relating a blower door C value to a wind driven infiltration C value as $C_{Wind} = C_D^{0.57} \times C_{Blower}/2^{1.57} = 0.34 \times C_D^{0.57} \times C_{Blower}$
        i. C_D is a building drag coefficient with an expected value of 0.3 to 0.7 (0.5 typical value)
        ii. The model produces results consistent with the K-P model's rule-of-thumb that normal pressure (4Pa) infiltration is 1/20 of blower door (50Pa) air flow
5) A 2000sqft home with a ventilation duct performance C value of 1000 and a duct leakage C value of 50 would have:
    a. 10cfm of uncontrolled leakage for 200cfm of ventilation air flow
    b. If the house has a blower door test value of 6ACH at 50Pa, the wind driven infiltration C value is approximately 1000, indicating that a wind dynamic pressure equal to duct ventilation pressure will result in an infiltration rate equal to the ventilation duct air flow
    c. If the house has a blower door test value of 0.6ACH at 50Pa, the wind driven infiltration C value is approximately 100, indicating that a wind dynamic pressure equal to duct ventilation pressure will result in an infiltration rate equal to 10% of the ventilation duct air flow

Introduction:

The human respiration system is an exquisite ventilation system that efficiently moves air through the nasal cavity, larynx, pharynx, trachea, bronchial tubes and into the lungs. We go into distress when any part of the respiratory system is not functioning properly. Our health is similarly stressed when any section of our home's ventilation system is improperly designed or poorly installed.



Respiratory System; National Cancer Institute

Part 2 of Ductology focuses on the performance of ventilation ductwork. We describe two "rough-in" tests that should be performed on installed duct systems *before* ducts are hidden behind wallboard and ceilings. The cost and heartache associated with inadequate ducting after finishing touches have been applied to a home are immense. And the cost of living with a poor ventilation system is even greater in terms of impact on home occupant health and lifetime operational cost for excessive blower power.

The ventilation system performance test we present is straightforward to implement and interpret. Ventilation ductwork that scores above 1000 are good. Ductwork scoring below 500, not so great.

A second, related test is presented for assessing duct system leakage. Duct leakage, in accordance with ASHRAE duct design principles, should be 5% or less of a duct system's design air flow rate. The duct leakage performance test scores of 50 or less are desired for attaining 5% or less leakage.

Blower door testing of homes is now commonplace, and the ventilation test protocols we describe are ones that should similarly be conducted on every home. In fact, the same equipment used for blower door testing and duct leakage testing can be used for this test procedure.

We also consider house infiltration. The cracks, fissures, and passageways that leak air into and out of a house are duct-like, and can be modeled in a similar manner as a ventilation system. We develop a house infiltration model using blower door test results. The house infiltration model shares a common basis with the duct performance and leakage models, which unifies house air flow movement.

In the following sections, we:

1) describe the performance characteristics of a single length of duct using relations previously developed in Ductology – Part 1
2) extend the analysis to any complex duct network consisting of multiple duct branches of assorted sizes, lengths and flow rates, and any other flow modifying fittings and components that are part of the ventilation system
3) suggest a ventilation system performance scale and test procedure for assessing the duct network performance
4) extend the ventilation method for assessing duct leakage
5) present a relation for converting blower door performance data to wind-driven house infiltration model, and discuss the relation between ventilation system air flow and house infiltration air flow

Section 1: Characterizing Ventilation System Performance of a Single Duct

We characterized the performance of a single length of duct using basic relations between air flow and pressure drop in Ductology – Part 1. Appendix A is repeated from Ductology – Part 1 with the basic duct performance and economic cost relations. The relation between air flow and pressure drop in a length of duct is determined as:

$$Q = C \times DP^{0.57}$$

Where DP = static pressure drop across duct length (“H_2O)

Q = air flow (cfm, cubic feet per minute)

C = duct system coefficient

“C” is not an arbitrary factor of unknown origin. The C value contains factors such as air viscosity, air density, duct length, duct diameter, and unit conversion factors that form relations between air flow rate and pressure drop in a duct. Likewise, the pressure drop exponent, “0.57”, is a factor derived from basic fluid mechanics relations. We do not want to clutter this main body of this report with an array of equations and analyses, however, and have included appendices that detail our discussions with supporting equations, analyses and experimental data.

The value of C is all we need for characterizing the performance of a duct. Table 1 shows values of C for a single length of duct (C values for duct lengths of 100ft and 50ft) with diameters ranging from 2” to 14”. The value of C is independent of air flow (yes, there are some exceptions, but for ventilation air flows in residences, this is almost always true). Figure 1 is a plot showing how C values vary as duct diameter and duct length change.

Table 1 “C” value for 100ft and 50ft duct lengths with diameters ranging from 2” to 14”.

Duct L(')	Duct D(")	"C"		Duct L(')	Duct D(")	"C"
100	2	19		50	2	29
100	3	58		50	3	86
100	4	126		50	4	187
100	5	231		50	5	342
100	6	378		50	6	561
100	8	824		50	8	1223
100	10	1508		50	10	2239
100	12	2472		50	12	3670
100	14	3754		50	14	5573

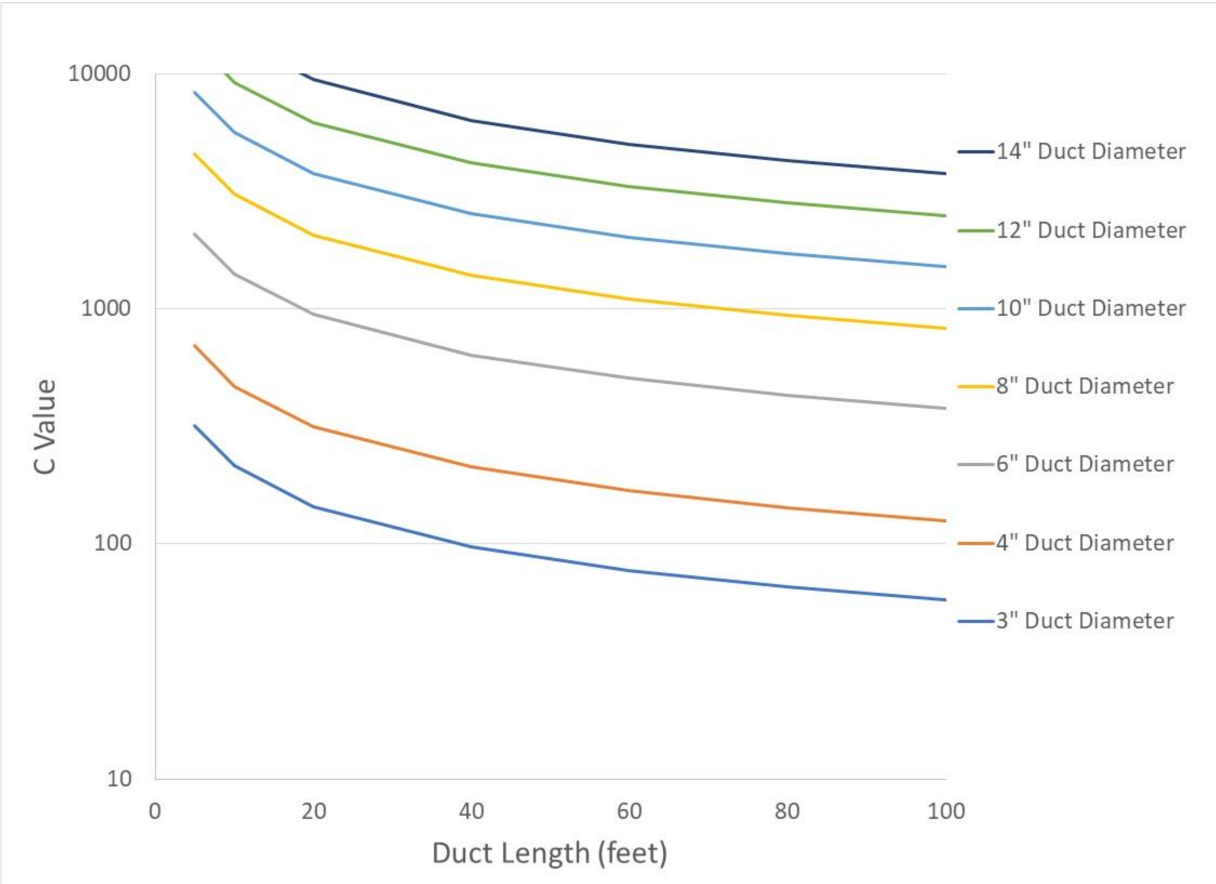


Figure 1 C value variation for different duct diameters and lengths.

Suppose a length of duct has been installed above a ceiling so that we are unable to see the duct. If we attach a fan to the length of duct, and measure the air flow and pressure, we can calculate the C value by using a rearrangement of the previous relation:

$$C = Q / DP^{0.57}$$

Even though the C value is derived from duct length, duct diameter and air properties, the above relation says that we can experimentally determine C by measuring air flow and pressure drop of a duct.

Let's assume that we measure 300cfm air flow with a pressure of 0.2"H_2O. Using the above relation, we find a "C" value of 750. Table 1 shows us that the hidden duct has the characteristics of a 100ft long duct with a diameter of 7" to 8", or perhaps, a 50ft long duct with a diameter of 6" to 7". Although we do not know the specific length and diameter of the duct, the C value gives us everything we need for characterizing duct performance. For any air flow, we know what the pressure drop will be, and for any given pressure drop, we know the air flow. With the additional duct performance relations in Appendix A, we can determine the fan power and the annual energy cost to blow air through the unknown duct.

Section 2: Characterization of Multi-Branched Duct Systems

Determining air flow and pressure drop throughout a multi-branched network of ducts is complicated and tedious as one equalizes pressures while preserving mass flow balances throughout a ventilation system. Any change of a duct fitting, length of duct, or adjustment of a diffuser is propagated throughout the ventilation system. We recommend The Energy Vanguard's 4-part series for those who would like to delve deeper into ventilation system design.

Fortunately, we can characterize the performance of a duct network in an incredibly simple manner! You do not have to be skilled in ventilation system design to conduct the test, nor do you need to have an engineering degree to interpret test results.

The same relation used in the previous section for characterizing a single length of duct can be used to characterize a complex, multi-branched ventilation system. Let's repeat this……a single C value also characterizes the performance of any multi-branched, complex duct network!

From the example in the previous section, we determined a "C" value of 750 for an unknown duct with a measured air flow of 300cfm and a pressure 0.2"H_2O. With that result, we were able to state that the duct acted like a 100ft long duct with 7" to 8" diameter, or alternatively, it could be described as a 50ft long, 6" to 7" diameter duct. The hidden duct, rather than being a single length of duct, could also have been a complex duct network with branches upon branches upon branches of ducts. Regardless of ventilation system complexity, one can define a single "C" value that characterizes the flow and pressure characteristics of the entire duct network.

For those readers interested in digging deeper, Appendix B contains an analysis of a branched duct network showing how a single "C" value can be derived. Our goal in this section, however, is to show how to use this single, simple parameter. Heat flow through a house wall, or a window frame assembly can be described by a single, overall "U" coefficient. Our "C" value is analogous to an overall U value, and is also a "conductance" parameter. In an opposite manner, a high C value for a duct network is good while a low U value for a house or window is good.

Appendix C provides experimental validation for the characterization of multi-branched duct systems with a single C value. Results from two duct experiments are included in Appendix C. Build Equinox conducted a series of duct configuration tests at ventilation levels typical of residential fresh air ventilation systems. A second series of multi-branched duct system experiments was conducted by personnel at the Lawrence Berkeley National Laboratory (LBNL). The LBNL tests were conducted in large ducts (14-16" diameter branches) with air flow rates more typical of house central comfort conditioning systems (500 to 1500cfm). The experimental results in Appendix C demonstrate the validity of characterizing complex duct work over a broad range of air flow and duct pressures with a single characteristic C value.

Section 3: Ventilation System Performance Scale and Performance Test

We formulate a duct system performance scale that provides us with a straightforward way to judge whether an installed duct system is performing in a reasonable manner. If it performs better than the design specifications, great. If it performs worse, one needs to determine the reasons for its lack of performance.

So, what value of C is a good value, and what value of C is not so good? Figure 2 is repeated from Ductology – Part 1 (Figure 3) in which a plot of optimal duct diameter versus air flow are plotted. Assuming that residential ventilation systems are designed for a minimum air flow of 150cfm, with 300cfm as a reasonable upper fresh air ventilation air flow level, a single duct system should have a diameter of 8" to 12" for 150 to 300cfm of air flow. Notice that Figure 2 indicates that economically optimized ducts have relatively constant 300-400feet per minute air velocities. On a simple basis, if one uses 350fpm velocity for residential duct design, the resulting duct diameters will be close to the diameters obtained for an economically optimized duct.

From Table 1, we see that an 8 inch duct would have a C value ranging from 800 to 1200 for duct lengths between 100feet and 50 feet, similar to duct system lengths in residences. For a 12 inch diameter duct, C values in Table 1 range from 2500 to 3700 for duct lengths between 100feet and 50feet. Remembering that these C values can also represent more complex multi-branched duct systems, we can also state that an economically optimized duct system capable of efficient flow of 150cfm would be expected to be in the 500 to 1000 C value range. An economically optimized duct system capable of flows up to 300cfm should be expected to have a C value exceeding 1000. Duct systems with C values less than 500 are more restrictive, with excessive fan power required for operating at airflow above 150cfm.

Appendix E is a test procedure for determining the performance of a duct network. Included with the test procedure are Figures 3 and 4. The test procedure consists of blowing air through a duct system at an arbitrary, but reasonable, flow rate. The C value from the test can either be calculated directly or selected from Figure 3 by using the performance air flow rate and pressure measurements. C values above 1000 are good for residential ventilation systems, while C values below 500 are not good. Figure 4 is a graphic showing "good", "ok", and "poor" duct system performance regions.

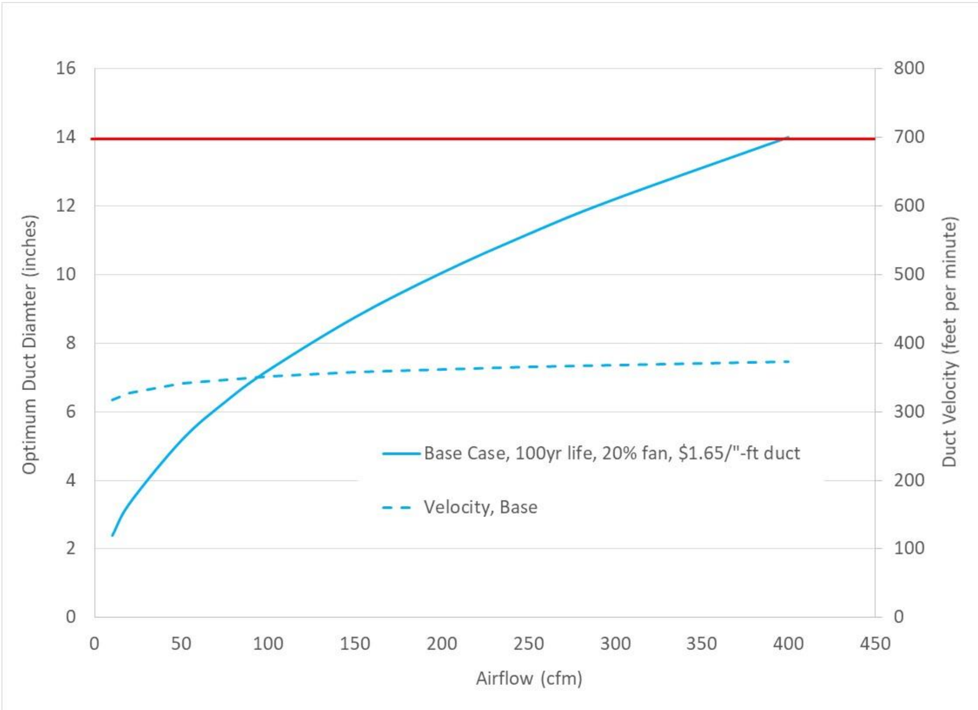


Figure 2 Economically optimized duct diameter and associated duct velocity as a function of air flow (same as Figure 3 in Ductology – Part 1).

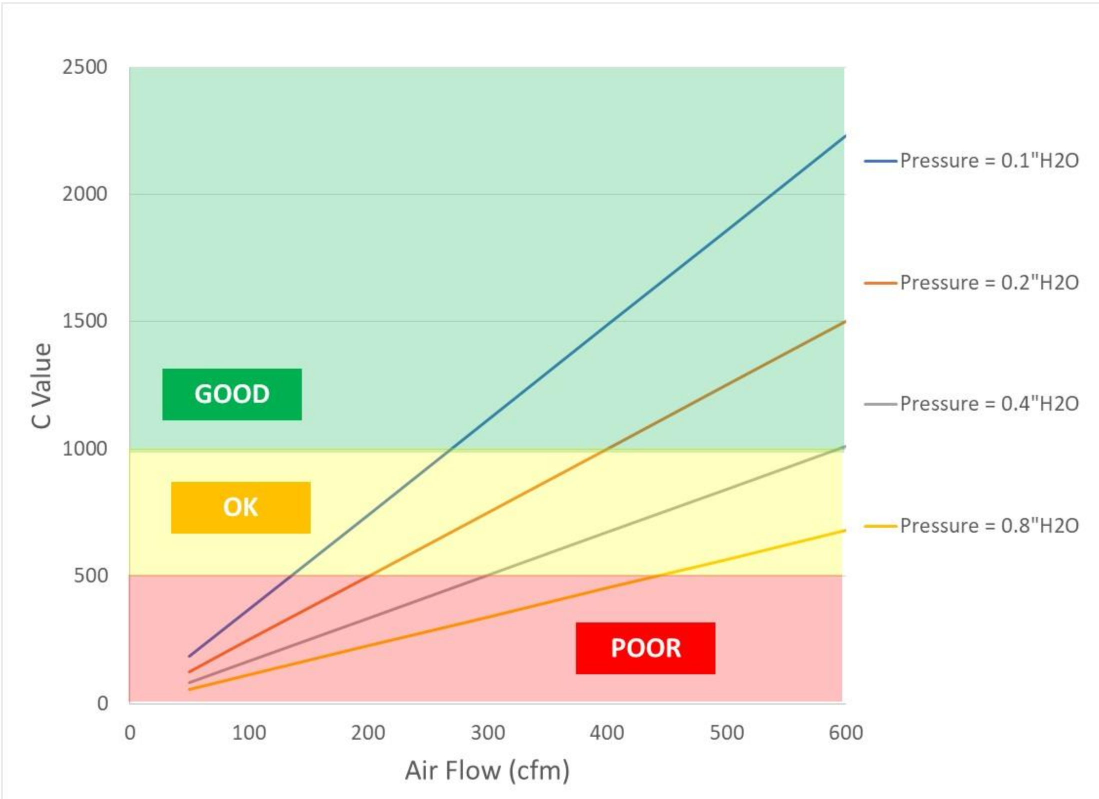


Figure 3 C values as a function of air flow and pressure.

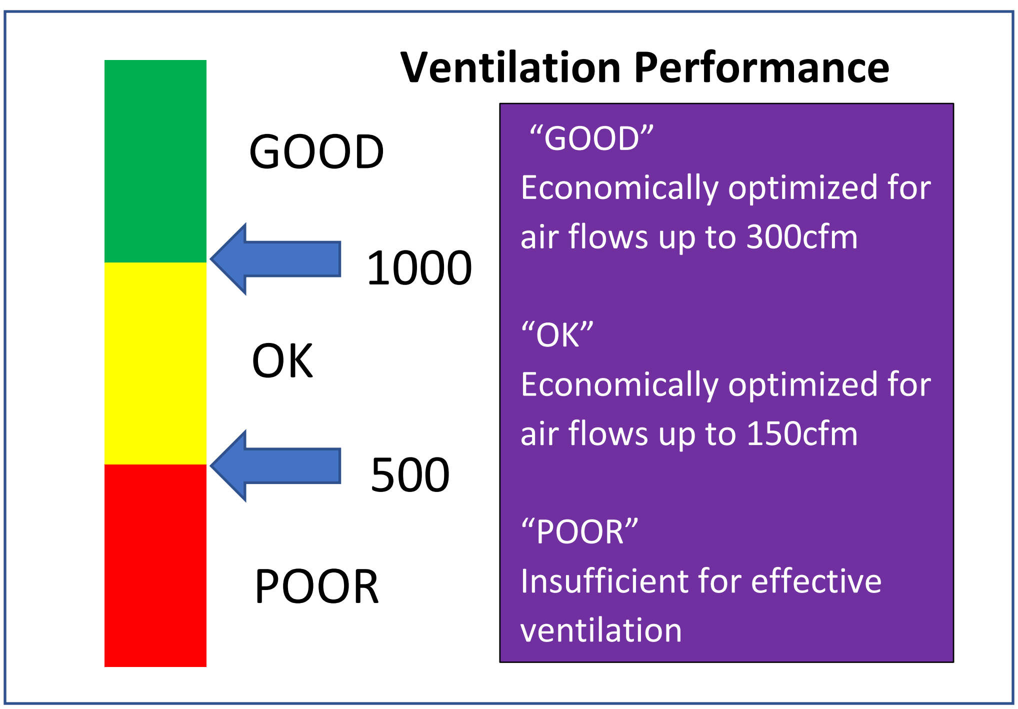


Figure 4 Duct system performance chart.

Section 4: Characterizing Ventilation System Leakage

How much leakage in a home's plumbing system is reasonable? Of course, we want zero leakage! So why do we tolerate high duct leakage levels? Today's IECC (International Energy Conservation Code) allowable duct system leakage of 3cfm per 100sqft is very leaky. And, excusing ductwork kept within a home's thermal envelope from meeting any duct leakage requirement makes no sense. The purpose of ducting is to move air from one region to another. Any leakage is extra air flow that one pays to move, and impacts the economic efficiency of a home's operation as well. Leaked air reduces the supply of fresh air where it is needed most, and reduces the exhaust of air from contaminated regions. The cost of blowing air through a ventilation system can easily exceed the energy cost of a home's roof and walls.

We agree with ASHRAE (Chapter 21, Section 6.1, Fundamentals 2017) that duct leakage should be less than 5%, regardless of whether ductwork is inside, outside or both. Our C value test procedure provides a convenient test method for determining whether duct leakage is less than 5%.

Duct leakage is important to characterize for several reasons:

1) Duct leakage in unconditioned spaces can be a significant energy load
2) Duct leakage in conditioned spaces reduces the ability to deliver fresh air and remove stale air effectively from all regions of a house
3) Duct leakage results in excess fan power
4) Duct leakage can cause water condensation, resulting in health problems and building deterioration
5) Duct leakage reduces the ability to meet local exhaust levels in bathrooms and kitchen
6) Duct leakage is an indicator of duct installation quality

We are going to look at duct leakage differently than the more traditional view, with a goal of providing a metric for determining the amount of air leakage relative to the amount of air delivered (or returned) from the intended spaces in a house. Duct leakage per floor area of a house makes no sense.

The traditional duct leakage view is also important because most building codes are based on the IECC requirements. Our duct leakage metric uses the results of the traditional test, so no extra field work is required. We will review the traditional duct leakage test and then discuss our recommended analysis method.

Two traditional duct leakage tests are the "total" duct leakage test and the "external" duct leakage test. Total duct leakage is determined by sealing all duct inlets and outlets except for one that is used for connecting a variable speed fan with air flow and pressure measurement. Some windows and/or doors are opened to equalize pressure between the inside of the house and outside. The fan speed is adjusted until the duct pressure reaches a desired level, usually 25Pa (0.1"H_2O). The air flow leakage measured is divided by the house floor area. Because the house interior and exterior are at common pressures, the total duct leakage consists of air leaks between the duct and the house interior and exterior.

The second test for external duct leakage identifies the amount of duct leakage to the exterior. The basic idea is that air leakage to the interior is not as significant because of a lowered energy impact, however, leakage inside a home should also be kept very low. In order to determine external duct leakage, a blower door is used to pressurize a home to 25Pa (0.1"H_2O) above the outside ambient pressure. The duct leakage blower is operated at 25Pa (0.1"H_20) as before. Now, the interior house pressure is equalized to the duct pressure, which minimizes the amount of air leaking between the duct and the house. The following videos provide nice duct leakage test explanations.

1) Southface youtube video
2) Building Performance Group video
3) The Energy Conservatory video

Note that video 3) found 86cfm of total duct leakage with 25Pa duct pressure. Video 2) measured 17cfm external leakage to the outside of a 2200sqft home.

The 2015 IECC duct leakage requirement is 3cfm per 100sqft or less for "Rough in" with "no air handler". Testing at rough in is important so problems can be addressed before ducts are sealed in walls, ceilings and chases. A problem with the IECC metric is that it does not specify the leakage in relation to the air flowing through the duct. For example, a duct system in a 2000sqft home can have up to 60cfm leakage. For ventilation systems carrying 150cfm to 300cfm, this is a lot!

Figure 5 The number 1 orifice has a C value of 300, orifice 2 has a C value of 150 and orifice 3 has a C value of 75.

Defining a duct leakage C value related duct leakage to duct air flow in a straightforward manner. We would like to have no more than 5% duct leakage. Video 3, for example, measured 86cfm duct leakage at 25Pa (0.1"H_2O) in a house duct system. The leakage C value, using our relation between air flow and pressure drop, is therefore:

$$C_{leak} = 86\text{cfm}/(0.1\text{"}H_2O)^{0.57} = 320$$

Duct leakage can occur anywhere along the length of a duct system, and the actual leakage depends on the location of the leaks. If most duct leakage is near a fan's outlet where duct pressure is highest, more air leaks from the duct system than in a situation in which most leaks are near duct outlets where duct pressure is lower. If the leakage is predominately near the mid-region of the duct system, air leakage will be driven by some intermediate pressure difference between the duct and its exterior.

As a conservative approach and to simplify assessment of duct leakage, we assume duct air leakage is driven by the same duct pressure as that driving the air flow through the duct. Therefore, the ratio of the leakage C value to the duct performance C value is the ratio of duct air leakage to duct air flow. The ratio of the leakage C value to duct performance C value should be 0.05 or less to ensure that duct leakage is no greater than 5% of the duct airflow. For the C_{leak} value of 320, the duct performance C value should be greater than 6400, which is unreasonably high for residential ventilation systems. Instead, the duct leakage in this house should be reduced to a lower level.

Our duct performance scale views C values of 1000 or greater as measures of good duct design for ventilation air flows up to 300cfm. Duct leakage of 5% or less requires a duct leakage C value of 50 or less. In a manner similar to sealing a home's envelope to reach high performance sealing levels of 1ACH at 50Pa or less, all duct runs should be carefully sealed. When sealing ducts, be sure to use "no VOC" duct sealants!

Appendix F summarizes the duct leakage test. The duct leakage test should be used in conjunction with the duct performance test summarized in Appendix E. The same equipment can be used for both tests. The difference between the two tests is that the performance test is operated with duct branches open and balanced as they would be in actual operation, while the duct leakage test seals all duct inlets and/or outlets.

Section 5: House Leakage and Infiltration

We finish this report by considering house leakage. Our discussions on duct performance and duct leakage are directly related to house leakage. Conceptually, all the leakage paths into and out of a house are no different than a complex duct network between the inside and outside of a house. That is, a stream of air that flows through an electrical receptacle, up a wall cavity, through a ceiling joist cavity, and outside through a soffit is the same as air moving through a series of ducts. Using this viewpoint, we can unify and characterize a home's leakage characteristics with the same C value analysis we have used in the previous sections to describe duct performance and duct leakage. By using this generalized approach, we have a common means for assessing the relative importance of duct airflow, duct leakage and house infiltration. In general, we want excellent duct performance with minimal duct leakage and minimal house infiltration. The ratio of C values provides us with a basis for comparing these three important factors.

On March 12, 1978, forty years ago to the day that this report section is being written, a remarkable meeting occurred in Washington DC that impacts the leakage characteristics of homes built today. ASTM (American Society for Testing and Materials) held a symposium, "Building Air Change Rate and Infiltration Measurements" with the purpose of assessing available technologies for measuring building leakage, and for the symposium attendees to begin a discussion of determining a test method for characterizing residential air leakage. Attendees included the Professor Charles "Chuck" Sepsy (Ty's graduate school advisor at The Ohio State University, and past ASHRAE President), Professor Victor Goldschmidt from Purdue University, and a young Max Sherman from the Lawrence Berkeley Laboratories (now, Lawrence Berkeley National Laboratory) who has made innumerable contributions to building energy and environmental quality since that time.

The "tightness" of a home's envelope is described in terms of its "air changes per hour" (ACH) when the house is held at a prescribed pressure relative to atmospheric pressure (typically, 50 Pascals or 0.2"H_2O). A well-sealed house has an ACH less than 1 when held at 50Pa (0.2"H_2O), while a reasonably sealed home would be 3ACH. Today's conventional homes without significant sealing efforts are in the 6 to 10ACH range, and homes of yesteryear in the 10-plus range.

Appendix G develops models for determining the C value for a blower door test, and for converting the blower door test C value to an infiltration C value. An example included in Appendix G considers a 2000sqft home with 8 ft high ceilings (16,000cuft volume). If the home has a blower door test result of 6ACH at 50Pa (typical of modern construction without excessive effort to seal), it would have a blower door C value of 4000, and a C value of 400 if the blower door test was 0.6ACH at 50Pa (Passive House level). The infiltration C values derived from the blower door test C values are 910 and 91 for the 6ACH and 0.6ACH homes, respectively.

As shown in Appendix G, the infiltration C values allow one to determine the infiltration air flow rate as the wind speed varies. The 6ACH home would have 70cfm infiltration with a 5mph wind while the 0.6ACH home would have 7cfm infiltration. At 25mph wind speed, the 6ACH home has 450cfm of infiltration while the 0.6ACH home has 45cfm of infiltration.

The leaky home often has sufficient infiltration to provide a majority of its fresh air. Our research shows, however, that air quality is often poor in occupied areas of leaky homes because where the leaks are and where people live are often different. One of the important reasons for recirculation is the distribution of fresh air in unoccupied areas of a home.

Sealed homes also vary in infiltration as wind speed varies, and depending on occupancy and wind speed, a significant fraction of fresh air may be supplied by infiltration. Smart ventilation systems assess and deliver the proper amount of fresh air as wind speed and occupancy change, resulting in significant savings of energy in addition to actively ensuring excellent air quality under all conditions.

Finally, note that the infiltration C value unifies our house leakage characteristic with our ventilation duct system's characteristics. For example, if we have a well-designed ventilation duct with a C value of 1000 and a duct leakage C value of 50, we can compare this directly to a home's infiltration. From the Appendix G example, a 2000sqft leaky home with blower door performance of 6ACH at 50 Pa has an infiltration C value of 910. In effect, this home moves air through its leaks as easily as air is moved through the ductwork. The 0.6ACH sealed home, however, with an infiltration C value of 91, is much more restrictive than the ductwork, and similar to the duct leakage C value. When one has a house infiltration C value much lower than the ductwork C value, most of the fresh air will be filtered through the fresh air ventilation system.

Appendix A – Duct Relations

The results discussed in this article are based on standard duct friction relations. We have massaged these functions into convenient units for residential duct design, which should allow interested users to easily incorporate into a spreadsheet format.

Pressure Drop:

$$DP = (1.532\times10^{-3} \times L \times Q^{1.75})/ D^{4.75}$$

Where DP = static pressure drop across duct length ("H_2O)

L = duct length (feet)

Q = air flow (cfm, cubic feet per minute)

D = duct diameter (inches)

As an example, an 8 inch diameter duct with 300cfm of air flowing through 100 feet of duct will have a pressure drop of 0.17"H_2O. You can verify this result by checking the duct friction chart at the Engineering Toolbox.

Airflow:

If you would like to determine airflow for a given pressure drop, the reciprocal of the previous relation is:

$$Q = 40.6 \times (DP/L)^{0.57} \times D^{2.71}$$

Using the previous example, 100 feet of 8 inch diameter duct with 0.17"H_2O pressure drop has 300cfm flow.

Power:

The power required to move air through a length of duct of a specified diameter is equal to the airflow rate times the pressure drop (P = Q x DP). The expression below includes unit conversions and fan efficiency to determine the fan power in terms of Watts.

$$P = 1.8\times10^{-4} \times L \times Q^{2.75} / (\eta \times D^{4.75})$$

Where P = electrical power (Watts)

η = fan-motor efficiency (fraction)

L = duct length (feet)

Q = air flow (cfm, cubic feet per minute)

D = duct diameter (inches)

For fans with airflow less than 400cfm, a good fan-motor efficiency is 0.2 (20%). Recent ASHRAE research indicates that R&D efforts could double small fan-motor efficiencies in the future ("Path to 50+% Efficient Fans For Unitary Applications", S. Kavanaugh, D. O'Neal, ASHRAE Journal, Dec, 2017).

From the previous example, and assuming a fan-motor efficiency of 0.2, the electrical power required to have 300cfm flow through an 8 inch diameter, 100ft long duct is 30Watts. The impact of reducing duct diameter from 8 inches to 6 inches results in an increase of fan power to 118Watts! In the days of incandescent lighting, 118Watts may not sound large, but in today's high performance homes, continuous operation of an electrical load with 118W is 1030kWh of electrical energy usage per year, or enough energy to drive today's Electric Vehicles 3000 to 4000 miles! Also note how the duct system impacts a fan's airflow per power (cfm/W) condition. The 8 inch diameter duct results in 10cfm/W performance compared to a 6 inch diameter duct with only 2.5cfm/W, assuming the fan's efficiency is the same.

Duct Installation Cost:

The following is a model for installed duct cost:

$$I = (\alpha \times D^2 + \beta \times D + \gamma) \times L$$

Where I = duct installation cost per length ($/ft)

D = duct diameter (inches)

L = duct length (ft)

α = duct cost per diameter squared per length ($/ft-in^2) ~ 0.0216$/ft-in^2

β = duct cost per diameter per length ($/ft-in) ~ 1.65$/ft-in

γ = duct cost per length ($/ft) ~15.5$/ft

For ducts smaller than 12 inches in diameter, the higher order term (α) can be neglected. With the duct installation cost factors assumed above, the relation for duct installation cost is:

$$I = (\$1.65/\text{ft-in} \times D + \$15.50/\text{ft}) \times L$$

Installation cost for a 100ft long, 8 inch diameter duct would be $2870.

Of course, this duct installation cost relation will be different based on local wage rates and material costs. These factors can be determined from quotations received from local contractors. One should request installation costs for two different duct diameters. For example, suppose a home will have 75ft of duct length, and the installation quote for 8 inch diameter duct is $2500 and the quote for 10 inch diameter duct is $3000.

The β factor for duct installation would be determined as:

$$\beta = (\$3000 – \$2500)/((10\text{in} – 8\text{in})\text{x}75\text{ft}) = \$3.33/\text{ft-in}$$

and the γ factor would be:

$$\gamma = (\$3000/75ft) – (\$3.33/ft\text{-}in) \times 10in = \$6.7/ft$$

The β factor is important for determining the optimal duct diameter, discussed later.

Lifetime Energy Cost:

The lifetime energy cost for operation of a fan for blowing air through a length of duct is:

$$E = 1.8x10^{-7} \times L \times Q^{2.75} \times t \times U / (\eta \times D^{4.75})$$

Where E = lifetime energy cost ($)

L = duct length (ft)

Q = air flow (cfm)

t = duct lifetime (years; eg, 100 years)

U = utility energy cost ($/kWh; eg, $0.12/kWh)

η = fan-motor efficiency (eg, 0.2)

D = duct diameter (inches)

Life Cycle Cost (LCC) Relation:

The LCC based on the previous duct relations, and assuming negligible time variation of money (ie, no interest, escalation or inflation) is the sum of lifetime duct operation cost and duct installation cost.

$$LCC = E + I$$

Where LCC = life cycle cost ($)

E = lifetime energy cost ($)

I = duct installation cost ($)

Optimum Duct Diameter:

An expression for the most economical duct diameter can be derived from the LCC relation. The optimum diameter is the one that minimizes the LCC relation, that is, minimizes the sum of lifetime energy cost and installation cost.

$$D_{opt} = [(8.55x10^{-7} \times Q^{2.75} \times t \times U)/(\eta \times \beta)]^{0.174}$$

Where D_{opt} = optimum duct diameter (inches)

Q = air flow (cfm)

t = duct lifetime (years)

U = utility energy cost ($/kWh)

η = fan-motor efficiency

β = duct installation cost parameter ($/ft-in)

Appendix B – Derivation of Ventilation Network “C” Value

Figure B-1 shows an example duct network consisting of 5 duct sections. Duct 1 is the main trunk supplying air from the fan to the rest of the duct branches. A flow meter and pressure sensor are placed at the outlet of the fan. Each section of the duct can be characterized with the air flow versus pressure drop relation listed in Appendix A.

We show that an assemblage of ducts can be grouped together to find a network “C” value that describes the flow resistance of the entire duct network. Air flow is divided among the duct branches as shown below. The manner in which the duct network is “balanced” may be through diffusers or grills at the end of each branch, or perhaps with dampers placed within each branch, or the network may be naturally balanced to achieve desired flow distribution. Our goal is to show that the C values for each duct section can be combined into an overall C value for the network. The combined, or effective C value for the duct network is similar to the process for calculating an overall “R” value for heat flow resistance through multi-material layered walls and to the effective electrical resistance (“Thévenin equivalent”) of an electrical network.

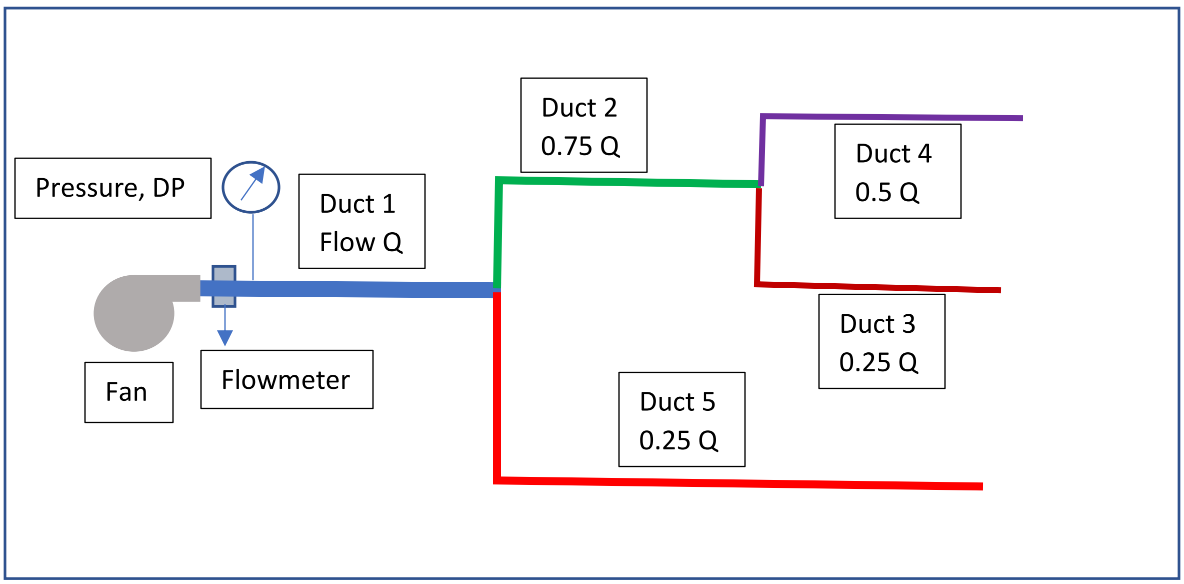


Figure B-1 Example branched duct network.

Altering our air flow versus pressure equation to determine pressure from flow will simplify the analysis. From our air flow versus pressure equation:

$$Q = C \times DP^{0.57}$$

We rearrange as:

$$DP = K \times Q^{1.75}$$

The constant, K, is related to the constant, C, as:

$$K = 1/C^{1.75}$$

For those familiar with duct fitting loss coefficients (eg, tees, elbows, reducers, etc), K is essentially the same proportionality constant between pressure drop and the flow's kinetic energy.

The overall duct pressure drop, DP, measured at the fan exit is the sum of all pressure drops through each duct pathway to atmospheric pressure. For the duct system shown in Figure B-1, there are three duct pathways from the fan to atmospheric pressure (ignoring leakage paths, which we assume to be negligible as they should be in reality).

Path 1: $DP = DP_1 + DP_2 + DP_4$

Path 2: $DP = DP_1 + DP_2 + DP_3$

Path 3: $DP = DP_1 + DP_5$

Where, DP = static pressure measured at fan exit

And, DP_1, DP_2, DP_3, DP_4 and DP_5 are pressure drops for duct sections 1, 2, 3, 4, and 5, respectively

Figure B-1 shows the flow rates for each branch relative to the duct system total flow. The pressure versus flow rate relations can be substituted into the pressure pathway relations to determine an overall duct network relation between system pressure drop and flow rate. For Path 1 (ducts 1, 2, and 4), we find:

$$DP = K_1 \text{ x } Q_1^{1.75} + K_2 \text{ x } Q_2^{1.75} + K_4 \text{ x } Q_4^{1.75}$$

Substituting the total air flow into the pressure relation using the air flow fractions for each duct yields:

$$DP = K_1 \text{ x } Q^{1.75} + K_2 \text{ x } 0.75^{1.75}\, Q^{1.75} + K_4 \text{ x } 0.5^{1.75}\, Q^{1.75}$$

Or, $$DP = (K_1 + K_2 \text{ x } 0.75^{1.75} + K_4 \text{ x } 0.5^{1.75}) \text{ x } Q^{1.75}$$

The term within the parentheses is a constant that we can label "K_{Tot}", representing the flow characteristics of the entire flow network.

$$DP = K_{Tot} \text{ x } Q^{1.75}$$

Note that the other duct pathways are also related to the same total K constant as:

$K_{Tot} = K_1 + K_2 \text{ x } 0.75^{1.75} + K_4 \text{ x } 0.5^{1.75}$ for duct Path 1

$K_{Tot} = K_1 + K_2 \text{ x } 0.75^{1.75} + K_3 \text{ x } 0.25^{1.75}$ for duct Path 2

$K_{Tot} = K_1 + K_5 \text{ x } 0.25^{1.75}$ for duct Path 3

We convert to the flow versus pressure drop relation with the duct flow coefficient, C_{Tot}. Rearranging the above pressure versus flow relation with K_{Tot}:

$$Q = C_{Tot} \text{ x } DP^{0.57}$$

Where $C_{Tot} = 1/ K_{Tot}^{0.57}$

The main takeaways from this analysis are:

1) Any duct network, no many how complex, can be represented with a simple expression between overall air flow rate and system pressure drop
2) Physical parameters (duct length, duct diameter, and fluid properties such as viscosity and density) are the factors in the C value that relates air flow rate and system pressure drop
    a. Although C is fundamentally composed of physical parameters, we can use air flow and pressure drop to experimentally determine the C value of a duct network
3) Quality installation is essential and every bit as important as designing a properly optimized duct system. Poorly connected duct transitions that create flow obstructions (think of a parachute facing into the air flow) and substitutions of improper ducting (ie, small diameter) into a system can have drastic effects on flow performance

Are there exceptions to the above analyses? Yes! But thankfully, exceptions are not so significant for air flow conditions typical of residential ventilation systems. Our ventilation systems tend to have relatively low velocities due to both economic reasons (see Ductology – Part 1) and noise.

Appendix C Experimental Validation of Ventilation Network C Value and Relative Air Flow Balancing

In this appendix, we show that the C value characterizing a ventilation system can be determined with a simple experimental procedure. Two sets of test data are presented. The first set of test data was collected at Build Equinox laboratory in Urbana, Illinois. The second set of test data is from experiments conducted at Lawrence Berkeley National Laboratory as part of a study on measuring branched air flow rates (Walker, Iain; Stratton, J. Chris; LBNL, 2014 "Evaluation of Air Flow Measurement Methods for Residential HVAC Returns for New Instrument Standards", California Energy Commission, CEC-500-2015-079).

The C value for a duct network over a range of air flow rates remains constant as long as the physical characteristics of the duct network are unchanged. Changing the opening of a damper, diffuser or grill causes a physical change of the duct network, which will result in a change of C. The experimental results presented in this appendix demonstrate both effects. Variations in types of fan and fan speed do not change the C value, while changes to the duct system impact the C value.

A second important characteristic of duct networks that follows from the invariance of the C value is the insensitivity of relative flow distribution among a duct network's branches. That is, a branch with 25% of the total duct network air flow at one fan speed will also have 25% of the air flow at other fan speeds. This is a very important characteristic. Therefore, one can balance a duct network at any flow rate and conduct the duct performance test at any flow rate. The LBNL test data provides excellent experimental validation of this concept.

Figure 1 shows a schematic of the ventilation duct system for tests conducted at Build Equinox's laboratory. A 6 inch diameter duct, approximately 40 feet long, with 5 tees and 2 elbows was assembled. Figure 2 shows a photo of the test setup. The test duct sits on top of the building's HVAC distribution duct. One tee was connected to two elbows and a flexduct section for connection to a fan. A pressure monitoring tap was installed after the fan, and a flow measurement station was mounted on the inlet side of the fan. Two fan sizes (Panasonic FV20 and FV30, nominal 200cfm and 300cfm air flow fans, respectively) were connected to the duct test system. Two sets of data were collected for each fan with four duct configurations.

Figure 2 also shows a photo with four duct caps used to cover various duct openings. As described in the Figure 2 photo, configuration "B" consisted of 0/2/3/C/3/1, which relates to the duct cap orifice area ("C" indicates no hole in the duct cap).

Table C-1 contains the "C" values for each of the four duct test configurations for each fan. Note that the low flow (fan FV20) and high flow (fan FV30) vary by as much as 50 to 70% in pressure and 25% in flow rate. The intent of this demonstration is to show how one can conduct such as test in the field. The variation in C values for the two fan tests is less than +/-5% for all flow configurations, which is very good for a "field" test.

Duct configuration "D" was the most restrictive with a "C" coefficient of 450-460, a level that is lower than desired. Configuration "A" was the most open of the duct systems with a "C" coefficient of 800, which is reasonable for residential ventilation systems.

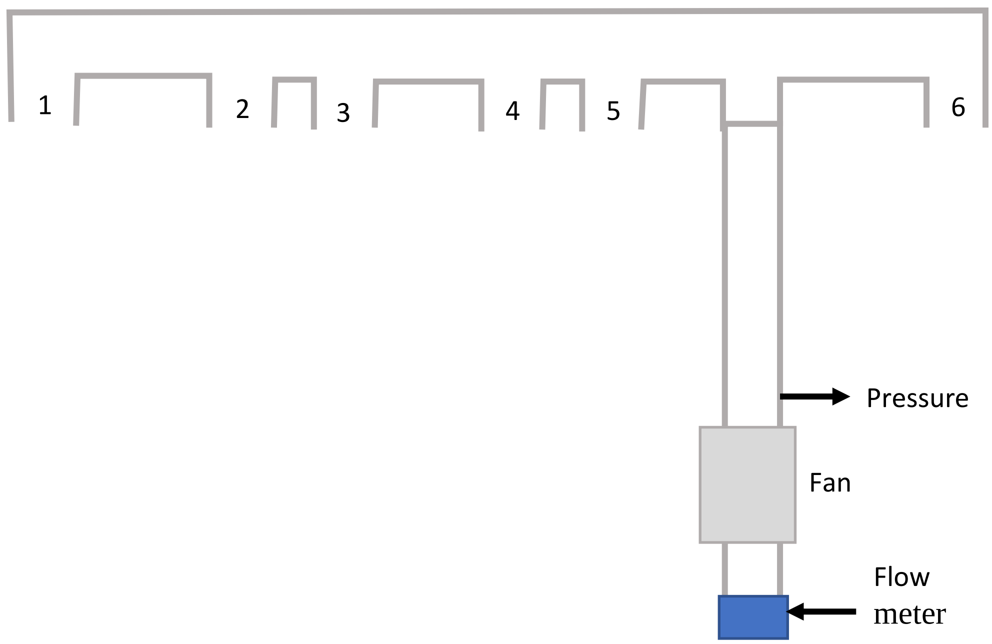


Figure 1 Schematic of 6 inch diameter duct system with 6 outlets. Two fans (Panasonic FV20 and FV30 models) were used to alter the supply air flow and system pressure.

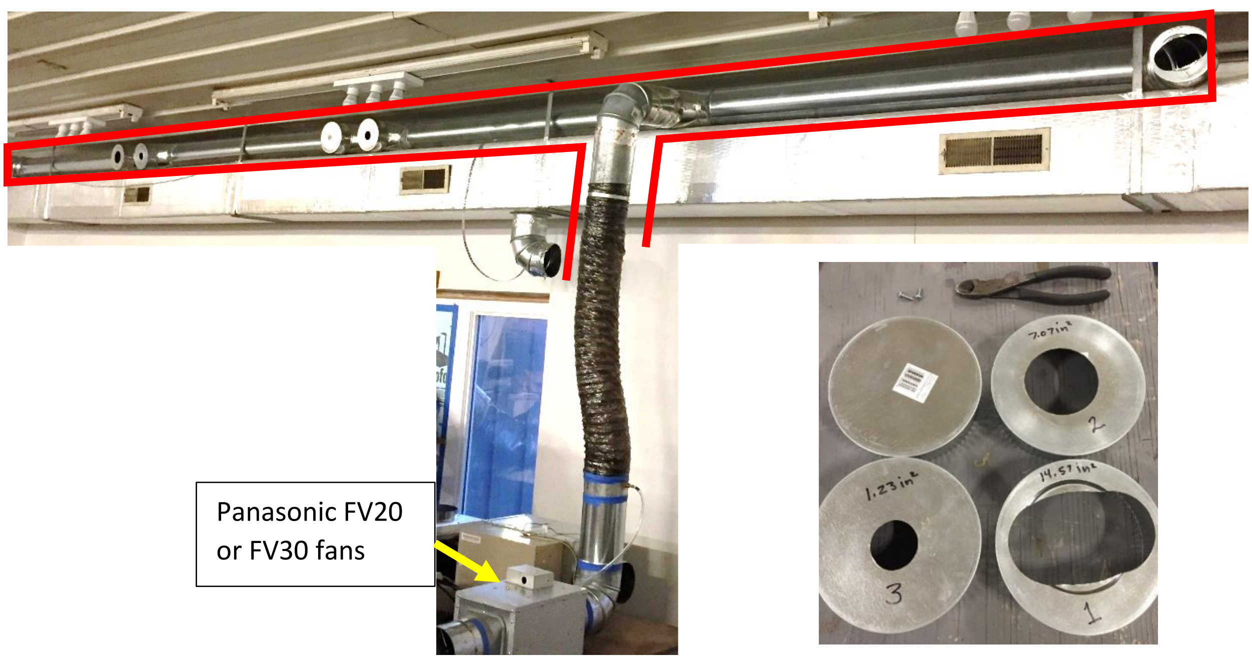


Figure 2 Photos showing the ventilation test setup (outlined in red) and the 3 orifice covers and cover cap. Test configuration “B” (0/2/3/C/3/1) listed in Table 2 is shown. The duct below the test duct is part of the building’s geothermal heat pump duct supply.

Table C-1 Test data from a 6 inch diameter duct ventilation system at Build Equinox laboratory. The six duct openings were configured with one of four orifices or covered as listed. The test configurations (A, B, C, D) were tested with two different fans (Panasonic FV20 and FV30 models).

		Orifices, Locations 1-6								
Config	Fan	1	2	3	4	5	6	Flow(cfm)	"H2O	C
A	FV20	0	0	0	0	0	0	315	0.18	837
B	FV20	0	2	3	C	3	1	306	0.22	725
C	FV20	2	2	3	C	3	1	297	0.24	670
D	FV20	2	2	3	C	3	C	267	0.39	457
A	FV30	0	0	0	0	0	0	386	0.3	767
B	FV30	0	2	3	C	3	1	379	0.35	689
C	FV30	2	2	3	C	3	1	369	0.4	622
D	FV30	2	2	3	C	3	C	331	0.58	452

Orifices: 0 = 28.3in^2, 1 = 14.6in^2, 2 = 7.1in^2, 3 = 1.2in^2, C = closed cap

Researchers at Lawrence Berkeley National Laboratory conducted an extensive set of multi-branched duct tests that were used to assess air flow measurement instruments (see reference listed at bottom of Table C-2). Data from their tests are applicable for validating our duct performance test procedure. The LBNL duct system consisted of three duct branches that were connected at a single junction (plenum). A main duct trunk connected a fan to the plenum. Two types of fan designated “BPM” and “PSC” were alternately connected to the supply duct and operated in high and low air speed modes. Six duct configurations were tested, with the duct system variations caused by opening/closing of dampers in duct branches A, B, and/or C.

Ducts A and B in the LBNL tests were 16 inch diameter, and duct C was 14 inch diameter. A test designation of “0”, “1”, or “2” is listed in Table C-2 to indicate duct branch damper opening. A closed duct section is “0”, part way open is designated as “1”, and full open is “2”. Air flow rates ranged from 500cfm to 1400cfm, extending the range of air flow used in the Build Equinox tests.

Each duct configuration produced four data points (two fans, two fan speeds). As in the Build Equinox duct tests, the four data points should not vary significantly in “C” value because the physical duct characteristics were not changed. For example, Test 1 listed in Figure C-2 had flow rates ranging from 539cfm to 1394cfm with duct system pressures varying from 0.057”H_2O to 0.378”H_2O. Despite the wide variation of air flow and pressure, the “C” coefficient had an average variation of less than 5%, with the lowest flow and pressure levels having a maximum deviation of 9% from the average C value. Notice than the C variation from 2428 to 2770 is not significant. For our purpose of “grading” the duct, we can see that the relatively large size of the LBNL duct tests is significantly greater than our “1000” level for good duct performance.

Table C-3, using the LBNL duct test data, shows another very important characteristic of duct network flows. The fraction of total duct air flow through a duct branch is relatively constant as the overall duct air flow rate is varied. The fraction of total duct network air flow through branches A, B, and C are shown in the last 3 columns, and exhibit very constant flow fractions over wide air flow rate variations. This is an important characteristic to keep in mind when balancing duct distributions.

Table C-2 Branch ventilation system test data from LBNL report[1].

Test 1	Branch/Ratio		A/1	B/2	C/3	Total		Ceff	Error
	Pressure	(Pa)	cfm	cfm	cfm	cfm	"H2O		
BPM	Lo	-14.1	91	172	276	539	0.057	2770	0.091
	Hi	-89.5	233	445	703	1381	0.359	2475	0.025
PSC	Lo	-51	170	326	510	1006	0.205	2484	0.022
	Hi	-94.1	233	447	714	1394	0.378	2428	0.044
							average=	2539	0.045
Test 2	Branch/Ratio		A/1	B/1	C/2				
	Pressure	(Pa)							
BPM	Lo	-13.4	129	129	263	521	0.054	2756	0.089
	Hi	-86.4	333	333	666	1332	0.347	2436	0.038
PSC	Lo	-49.8	253	252	501	1006	0.200	2518	0.005
	Hi	-92.9	347	345	685	1377	0.373	2416	0.046
							average=	2531	0.044
Test 3	Branch/Ratio		A/1	B/1	C/1				
	Pressure	(Pa)							
BPM	Lo	-14.1	174	172	174	520	0.057	2672	0.073
	Hi	-89.1	450	443	445	1338	0.358	2404	0.035
PSC	Lo	-50.6	337	333	334	1004	0.203	2490	0.000
	Hi	-94.7	465	458	459	1382	0.380	2398	0.037
							average=	2491	0.036
Test 4	Branch/Ratio		A/0	B/1	C/1				
	Pressure	(Pa)							
BPM	Lo	-20.4		250	256	506	0.082	2106	0.067
	Hi	-76.2		486	502	988	0.306	1941	0.017
PSC	Lo	-73.3		478	487	965	0.294	1938	0.018
	Hi	-92.2		536	548	1084	0.370	1910	0.032
							average=	1974	0.034
Test 5	Branch/Ratio		A/0	B/1	C/2				
	Pressure	(Pa)							
BPM	Lo	-18.5		177	349	526	0.074	2315	0.062
	Hi	-59.5		322	639	961	0.239	2173	0.003
PSC	Lo	-64.3		316	667	983	0.258	2127	0.024
	Hi	-80.4		351	752	1103	0.323	2101	0.036
							average=	2179	0.031
Test 6	Branch/Ratio		A/1	B/0	C/0				
	Pressure	(Pa)							
BPM	Lo	-17.1	531			531	0.069	2444	0.051
	Hi	-28.1	683			683	0.113	2369	0.019
PSC	Lo	-59.7	1010			1010	0.240	2280	0.019
	Hi	-76.4	1125			1125	0.307	2206	0.051
							average=	2325	0.035

[1]Walker, Iain; Stratton, J. Chris; LBNL, 2014 "Evaluation of Air Flow Measurement Methods for Residential HVAC Returns for New Instrument Standards", California Energy Commission, CEC-500-2015-079

Table 3 Relative flow balancing of LBNL test data

Test 1	Branch/Ratio		A/1	B/2	C/3	Total	A fract	B fract	C fract
	Pressure	(Pa)	cfm	cfm	cfm	cfm			
BPM	Lo	-14.1	91	172	276	539	0.169	0.319	0.512
	Hi	-89.5	233	445	703	1381	0.169	0.322	0.509
PSC	Lo	-51	170	326	510	1006	0.169	0.324	0.507
	Hi	-94.1	233	447	714	1394	0.167	0.321	0.512
Test 2	Branch/Ratio		A/1	B/1	C/2				
	Pressure	(Pa)							
BPM	Lo	-13.4	129	129	263	521	0.248	0.248	0.505
	Hi	-86.4	333	333	666	1332	0.250	0.250	0.500
PSC	Lo	-49.8	253	252	501	1006	0.251	0.250	0.498
	Hi	-92.9	347	345	685	1377	0.252	0.251	0.497
Test 3	Branch/Ratio		A/1	B/1	C/1				
	Pressure	(Pa)							
BPM	Lo	-14.1	174	172	174	520	0.335	0.331	0.335
	Hi	-89.1	450	443	445	1338	0.336	0.331	0.333
PSC	Lo	-50.6	337	333	334	1004	0.336	0.332	0.333
	Hi	-94.7	465	458	459	1382	0.336	0.331	0.332
Test 4	Branch/Ratio		A/0	B/1	C/1				
	Pressure	(Pa)							
BPM	Lo	-20.4		250	256	506	0.000	0.494	0.506
	Hi	-76.2		486	502	988	0.000	0.492	0.508
PSC	Lo	-73.3		478	487	965	0.000	0.495	0.505
	Hi	-92.2		536	548	1084	0.000	0.494	0.506
Test 5	Branch/Ratio		A/0	B/1	C/2				
	Pressure	(Pa)							
BPM	Lo	-18.5		177	349	526	0.000	0.337	0.663
	Hi	-59.5		322	639	961	0.000	0.335	0.665
PSC	Lo	-64.3		316	667	983	0.000	0.321	0.679
	Hi	-80.4		351	752	1103	0.000	0.318	0.682
Test 6	Branch/Ratio		A/1	B/0	C/0				
	Pressure	(Pa)							
BPM	Lo	-17.1	531			531	1.000	0.000	0.000
	Hi	-28.1	683			683	1.000	0.000	0.000
PSC	Lo	-59.7	1010			1010	1.000	0.000	0.000
	Hi	-76.4	1125			1125	1.000	0.000	0.000

Appendix D – Optimized Multi-Branched Duct System Examples

Two example duct systems are discussed in this appendix. The two duct systems are identical in layout, however, they are economically optimized for two levels of ventilation flow, 150cfm and 300cfm. The goal is to show a realistic duct system design, and to demonstrate that optimized duct systems will have performances that follow the duct performance test scale.

Figure D-1 shows the duct system layout. The duct consists of 11 duct sections of varying lengths. The lengths shown for each duct section is a combined length of actual physical length and effective lengths for duct fittings such as elbows. A fan with pressure and flow measurement are shown connected to the duct. Note that for return ducts, the fan draws air through the duct system. For return duct systems, the pressure reading is negative relative to the surrounding ambient pressure. It is important that the air flow moves through the duct system in the direction it will operate because various structures in the air flow react differently depending on the air flow direction. For example, a cup-like structure in the flow stream has significantly different drag when flow faces into the cup in comparison to blowing over the backside of the cup. That's why weather station cup anemometers spin!

Table D-1 shows duct dimeters based on an economic optimization of each duct section using Figure 2. The optimal duct diameters were selected from Figure 2 based on the desired flow rate for that duct section. The duct section "C" values listed can either be calculated from the specified duct length and duct diameter, or can be selected from Figure D-2 that provides C values for duct diameters ranging from 3" to 12 inches, and duct lengths varying from 5' to 100'. "C" can be calculated from the relations in Appendix A:

$$C = 40.6 \times D^{2.71}/L^{0.57}$$

Where C = C value

D = duct diameter (inches)

L = duct length (feet)

Combining the individual duct section C values into an overall duct system C value is beyond the scope of the present discussion, however, a relatively straightforward computational procedure can be derived that successively combines branches together until the entire duct network is formed into a single C value. The process requires determination of the most flow resistive (lowest C value) branch as duct branches are grouped together. Less resistive branches require some adjustment of flow using either a damper in the branch or by adjusting diffuser openings in low resistance branches.

Table D-1 shows that the 150cfm duct flow system will have an overall C value of 1002 and the 300cfm duct flow system will have an overall C value of 2253. Both C values are good levels, and field measurements should result in measured C values that are within 10 to 20% of these C values. In terms of field tests, we want C values greater than 500. If C values are lower, the reason for low C value should be determined. Note that a low C value does not mean that one cannot operate at higher air flow rates, but indicates that excessive fan power will be required. With the experimentally determined

C value, one can use the relations in Appendix A to determine the fan power and annual fan energy required.

Table D-2 uses the duct installation cost relations in Appendix A for providing some information related to duct system cost. Smaller diameter ducts are dominated by duct length while larger diameter ducts have significant diameter cost related impact. On a practical basis, ducts in the 3” to 6” diameter range do not require significant duct support structure, and the extra material of a 6” diameter duct is not much greater than that of a 3” duct. Larger duct sizes, however, begin requiring more significant duct mounting structures as well as increased duct cost (eg, as duct diameters become large, duct wall thickness increases).

Although duct installation costs will vary as discussed in Ductology – Part 1, the cost estimates provided should be a good reference for many regions. Note that do-it-yourselfers who do not count their labor will have significantly reduced cost if they neglect the value of their labor. In this case, optimal duct diameters would be larger than those in Table D-1 because lower duct cost, in relation to fan energy cost, results in larger ducts. For significantly more expensive duct installation cost, as shown in Ductology – Part 1, doubling of the duct installation cost relative to energy cost does not cause a significant reduction of optimal duct diameters because of the steep rise in lifetime energy cost as duct diameter is reduced. Therefore, even though the optimal duct results for these analyses rely of specific cost relations, the results are not expected to vary significantly with either less expensive or more expensive duct installations.

One final note regarding the duct costs provided in Table D-2. The 140ft duct system length is quite extensive for most homes with less than 4000sqft of floor area. Consider an even larger duct system that is twice the size of the example system (280 ft of duct). With a duct installation cost of $8000, plus the cost of a smart fresh air ventilator (CERV2) of $5000, and the cost of comfort conditioning equipment (eg, 3 tons of distributed heating cooling, such as three 1 ton mini-split heat pumps) assumed at $6000, a total fresh air ventilation and comfort conditioning cost of $19,000 is realized. For a 2000sqft home, the fresh air and comfort conditioning system is a cost of $10 per sqft. Relative to the cost of kitchens, bathrooms, flooring, windows, sitework or other home construction expenses, the cost for a high quality ventilation and comfort conditioning system is modest. It is time to recognize that the importance of fresh air ventilation in homes. Home ventilation systems’ current status as an afterthought needs to be elevated to perhaps the most important consideration of any home’s design.

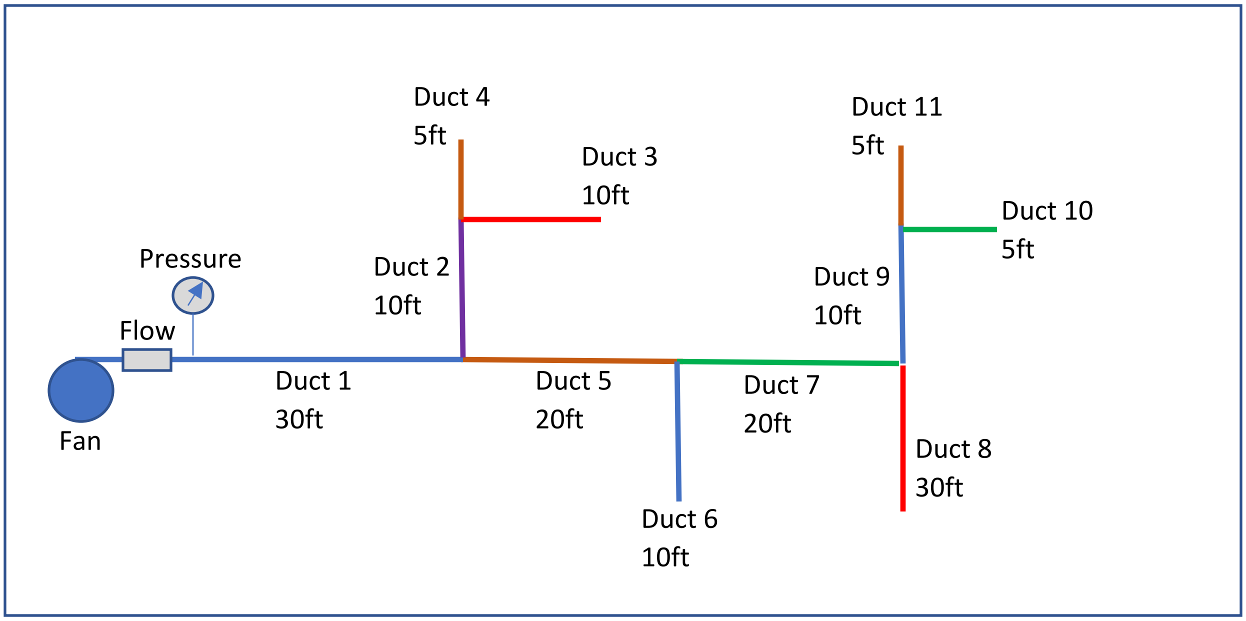


Figure D-1 Example duct system layout.

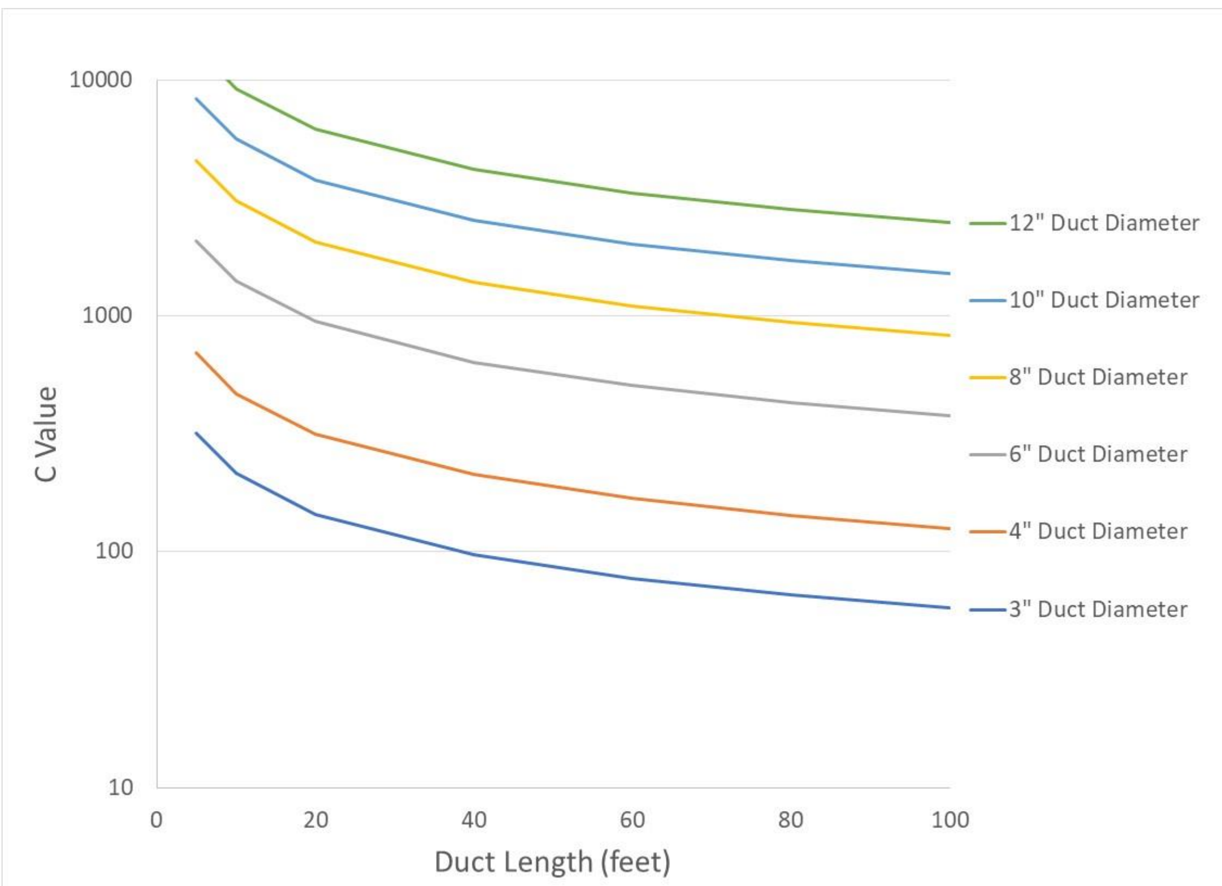


Figure D-2 Relationship between duct C value and duct length and duct diameter.

Table D-1 Economically optimized duct section sizes for duct system shown in Figure D-1

	150 CFM Duct System				300 CFM Duct System		
Duct #	Air Flow (cfm)	Opt Diam (inches)	Duct C Value		Air Flow (cfm)	Opt Diam (inches)	Duct C Value
1	150	9	2252		300	12	4911
2	40	5	857		80	7 (5 ok)	2132
3	20	3	215		40	5	856
4	20	3	319		40	5	1272
5	110	8	2062		220	11	4888
6	60	6 (5 ok)	1404		120	8 (6 ok)	3061
7	50	5	577		100	7	1436
8	25	4	371		50	5	680
9	25	4	468		50	5	857
10	10	3	319		20	4	695
11	15	3	319		30	4	695
Overall	**150**	**NA**	**1002**		**300**	**NA**	**2253**

Table D-2 Duct cost estimates.

	150 CFM Duct System				300 CFM Duct System		
Duct #	Duct Length (ft)	Opt Diam (inches)	Duct Cost ($)		Duct Length (ft)	Opt Diam (inches)	Duct Cost ($)
1	30	9	911		30	12	1059
2	10	5	238		10	7	270
3	10	3	205		10	5	238
4	5	3	102		5	5	119
5	20	8	574		20	11	673
6	10	6	254		10	8	287
7	20	5	475		20	7	541
8	15	4	332		15	5	356
9	10	4	221		10	5	238
10	5	3	102		5	4	111
11	5	3	102		5	4	111
Overall	**140**	**NA**	**3516**		**140**	**NA**	**4003**

Appendix E **Test 1: Duct System Performance**

Build Equinox recommends performing the following "rough-in" duct test on supply and return ventilation ducts prior to installing air handlers or fresh air ventilation units.

The performance test consists of the following steps:

1) Connect fan with air flow measurement and pressure measurement sensors to the duct network (supply or return) to be tested
2) Switch the fan "on", and adjust fan speed (if speed adjustment is available) to desired level
3) Balance registers to desired air flow levels
   a. "Relative" air flow balancing can be used when the performance test air flow is different than design air flow. For example, if test air flow is 400cfm and design air flow is 200cfm, an outlet with a design air flow of 50cfm (25% of 200cfm) should have 100cfm (25% of 400cfm) for the performance test.
   b. Air flow direction for the test should be the same as operational air flow direction. Supply duct systems will have air blown into the supply trunk while return duct systems pull air through the duct network
4) Record fan air flow and duct pressure
   a. If fan speed variation is available, record 2 or 3 air flow and pressure levels

      Calculate the "C" value as: $C = Q / DP^{0.57}$

      Where DP = static pressure drop across duct length ("H_2O)

      Q = air flow (cfm, cubic feet per minute)

      C = duct system coefficient

   b. Note that pressure will be positive (fan discharge pressure) for supply ducts and pressure will be negative (fan inlet pressure) for return ducts. Use the absolute pressure reading (ignore the negative sign for return ducts)
   c. Figure 1 can be used to determine C value directly from air flow (cfm) and duct pressure ("H_2O) measurements
   d. If multiple fan air flow rate tests are conducted, average the C values
5) Figure 2 describes the performance of the duct system.
   a. C values greater than 1000 indicate good air flow performance for systems with ventilation air flow rates up to 300cfm.
   b. C values above 500 are reasonable for ventilation air flows of 150cfm or less.
   c. C values below 500 indicate restricted duct air flow capability with high fan power requirements for residential fresh air ventilation.

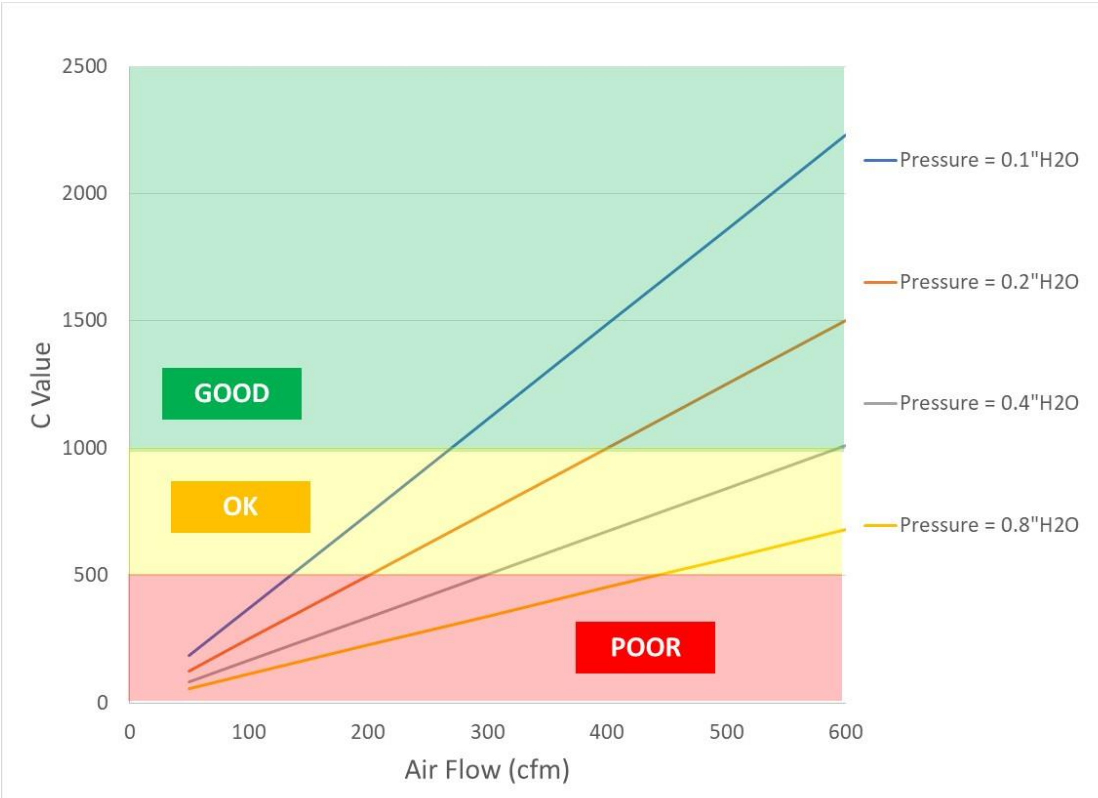


Figure 1 Duct system performance test C value plot based on air flow (cfm) and pressure (“H_2O).

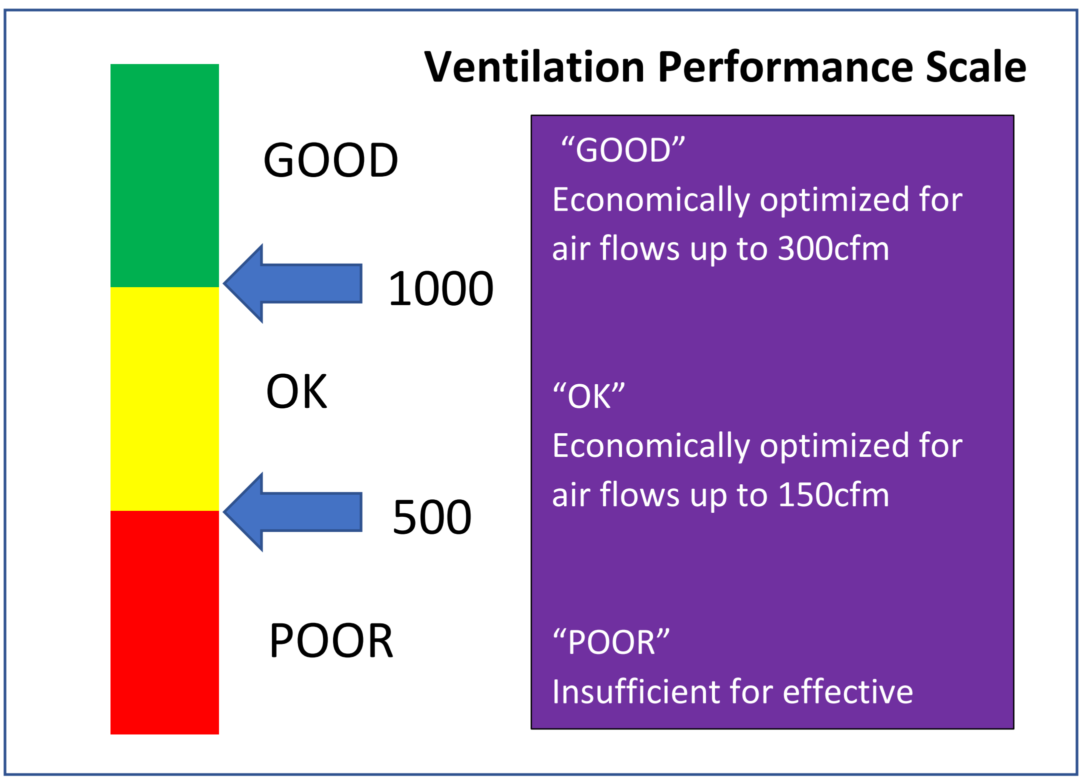


Figure 2 Duct performance test scale.

Appendix F **Test 2: Duct Leakage**

Build Equinox recommends the following rough-in duct *leakage* performance test for supply and return ventilation ducts. The leakage test procedure is the same as the performance test except that all duct outlets/inlets are sealed.

The leakage test consists of the following steps:

1) Tightly seal all duct inlets and outlets.
2) Connect fan with air flow measurement and pressure measurement sensors to the section of duct to be tested
3) Switch fan "on", and adjust fan speed (if speed adjustment is available) to desired level
4) Record fan air flow and duct pressure
    a. If fan speed variation is available, record 2 or 3 air flow and pressure levels

       Calculate the "C" value as: $C = Q / DP^{0.57}$

       Where DP = static pressure drop across duct length ("H_2O)

       Q = air flow (cfm, cubic feet per minute)

       C = duct system coefficient

    b. Note that pressure will be positive (fan discharge pressure) for supply ducts and pressure will be negative (fan inlet pressure) for return ducts. Use the absolute pressure reading (ignore the negative sign for return ducts)
    c. Figure 1 can be used to determine the leakage C value directly from air flow (cfm) and duct pressure ("H_2O) measurements
    d. If multiple fan air flow rate tests are conducted, average the C values
5) Figure 2 describes the leakage of the duct system. C values less than 40 indicate well sealed ducts while C values greater than 60 indicate excessive air leakage.
    a. The ratio of the duct leakage C value to the duct performance C value provides an estimate of the fraction of air leakage to desired duct air flow.
        i. A duct performance C value of 1000 with a duct leakage C value of 50 has an air flow leakage fraction of 50/1000 = 0.05, indicating 5% of the duct air flow is leaked (leakage air into return ducts, or leakage air loss from supply ducts)
        ii. Note that leakage for ducts kept within the thermal envelope of a home are less serious (but still important) than ducts in unconditioned attics, crawl spaces or other spaces

Figure 1 Duct leakage test C value plot based on air flow (cfm) and pressure (“H_2O).

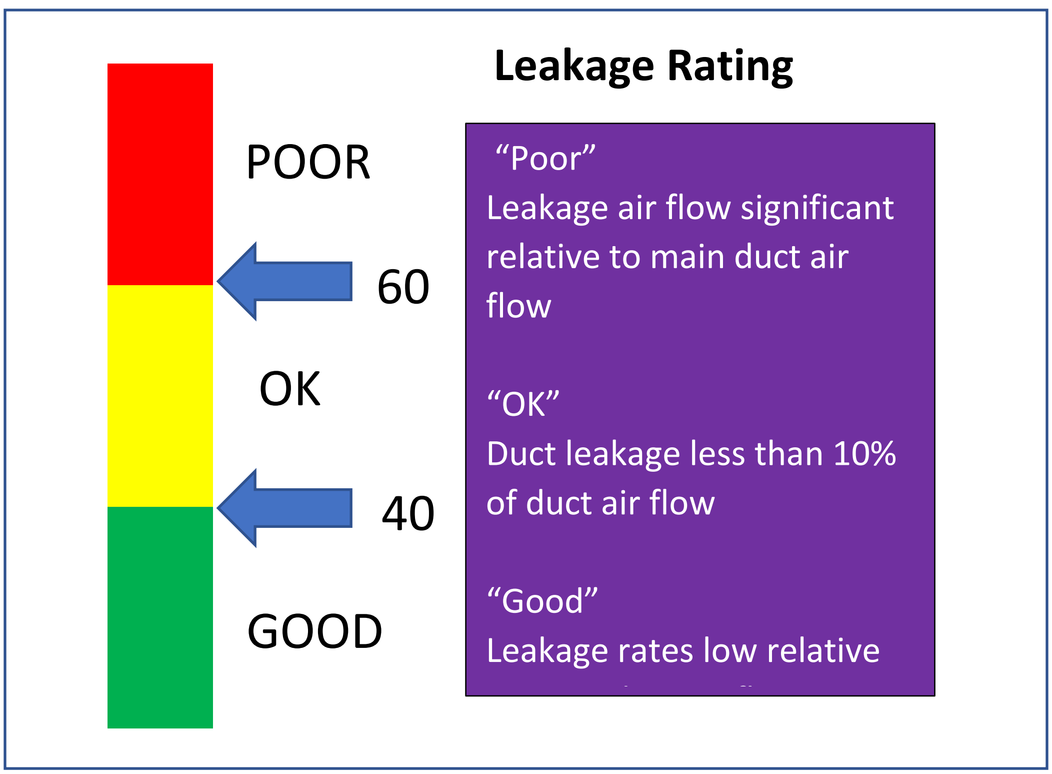


Figure 2 Duct leakage test scale.

Appendix G Modeling Blower Door Air Change Rate and House Infiltration

We develop a simple-to-use, wind-driven infiltration model that allows one to calculate infiltration air exchange rates under varying wind conditions. The model can be extended to include buoyancy (temperature) driven infiltration, however, for the present discussion, we only consider wind driven infiltration. In addition, we develop a relation to link blower door infiltration results with the wind driven infiltration model, and show that the relation is in agreement with the "divide by 20" rule-of-thumb" for converting blower door test results to an average infiltration factor.

Infiltration is a very important factor that affects a home's energy usage and its occupants' health. If infiltration is sufficiently high, although there may be an energy penalty (but not always!), active fresh air ventilation may not be required. If infiltration levels are less than what is required for good indoor air quality, then active fresh air ventilation is required. Two cautionary notes are required regarding infiltrated air:

1) Infiltrated air may not be healthy fresh air if the pathway through a building's leakage paths is filled with mold, vermin and particulates
2) Even when infiltration levels are sufficient for maintaining air quality, the location of air leaks and the location where occupants spend their time may be different, resulting in substandard air quality in occupied areas of a home. Recirculation of house air is essential to move fresh air from unoccupied areas to occupied areas of a home.

Figure G-1 is a schematic of air leakage into a home during a blower door test. For an exhausting blower door setup as shown, all air leakage flows into the house. The blower door holds the house interior at a fixed pressure relative to the outdoor ambient pressure (usually 50Pa or 0.2"H_2O). The air flowing into the house through the leaks can be related to a C value as we have done for a system of ducts. That is, one can consider a system of leakage paths to be the same as a network of ducts. Furthermore, we assume the leakage paths to be made up of two groups that represent "infiltration" and "exfiltration" leakage paths under wind-driven infiltration.

Figure G-2 shows a schematic of the Figure G-1 home during wind-driven infiltration conditions. The home's interior pressure is between high pressure and low pressure regions surrounding the house. The actual pressure distribution around a house is very complex and is dependent on the wind's orientation relative to the house, the house shape, distribution of leakage paths around the house, the size of the leakage paths (large leaks tend to be turbulent air flow while small leaks may be laminar air flow), and surrounding building and terrain features.

For our analyses, we use an integrated approach and lump the complexities together into an overall building drag coefficient that provides us with a model that behaves in a physically realistic manner. We expect real data to be "noisy" based on the complexities described in the previous paragraphs. Figure G-3, showing wind driven infiltration data for two mobile homes, provides some idea of the noisiness of real data. At wind speeds greater than 5mph, infiltration levels at a given windspeed may differ by 0.5 ACH (air changes per hour). Figure G-3 shows infiltration levels of 0.2 ACH and 0.3ACH at low wind speeds for the sheathed and caulked homes caused by temperature differences (16-23C = 29-41F).

Building drag coefficients, C_D, range from 0.5 to 1.5, with 0.5 being used as typical of a drag coefficient for regularly shaped homes. A building drag coefficient of 0.5 is similar to the drag coefficient for fully turbulent flow over a sphere. Note that a drag coefficient of 1 indicates that the energy loss due to drag over an object is equivalent to the wind's kinetic energy over the projected frontal area of a home, analogous to a car's drag coefficient. A drag coefficient of 0.5 indicates that half of the wind's kinetic energy heading toward the projected frontal area of a home is loss. A building with a drag coefficient of 1.5 would be a case in which the building has a "parachute" shaped frontal region that locally reverses some of the wind air flow, causing a kinetic energy loss that is greater than the kinetic energy heading toward the projected frontal area of the building. Note that a building may have a very high drag coefficient when wind heads to an unstreamlined face of the building, and may have a low drag coefficient when the wind blows toward a more streamlined face of the building. That is, infiltration is dependent on wind direction as well as wind speed.

Figure G-4 converts Figure G-3 data from infiltration and wind speed to leakage air flow rate and wind dynamic pressure. The two mobile homes were 65ft by 14ft with an estimated volume of 6500cubic feet. The dynamic pressure of the wind is calculated as:

$$P_{dyn} = \rho \times V_{wind}^2/2$$

Where P_{dyn} = dynamic wind pressure

ρ = air density ($\sim$1.2kg/m^3 $\sim$ 0.074lbm/ft^3)

V_{wind} = wind speed

Figure G-5 is a plot of dynamic pressure as a function of wind speed. Blower door tests are typically operated with 50Pa (0.2"H_2O) pressure difference, which is similar to the dynamic pressure that a 20mph wind can impose on a structure. So-called "Normal" pressure of 4Pa, used to describe the pressure difference driving infiltration under more normal wind conditions, is similar to the dynamic pressure of a 5 to 6mph wind.

Because dynamic pressure is related to the square of wind velocity, increasing wind speed significantly affects infiltration. Goldschmidt, et al, show "instantaneous" infiltration rate data during a storm. Initially, an infiltration rate of 0.54ACH (approximately 60cfm) was measured with winds in the 7 to 10 mph range. During a 10 minute period with 20 to 30 mph winds, infiltration increased to 2.64ACH, or nearly 300cfm of infiltration air flow. Infiltration rapidly adjusts to variations of pressure imposed over a home's exterior.

Our wind infiltration model assumes two regions that define infiltration and exfiltration areas of a house:

1) Infiltration surfaces are in the "upwind" higher pressure area of the home
2) Exfiltration surfaces are in the "downwind" lower pressure area of the home

Our goal for an infiltration model is to be able to predict instantaneous infiltration rates as wind speed varies in a reasonably realistic manner. Ultimately, coupling a wind infiltration model with an occupancy and occupant activity level model allows one to simulate real time ventilation needs.

One might picture the two regions as the front half and back half of a home, however, the situation is more complicated than that on a detailed basis. Deru and Burns (M. Deru, P. Burns, "Infiltration and Natural Ventilation Model for Whole Building Energy Simulation of Residential Buildings", NREL/CP-550-33698, March 2003) provide a good description of the complexities of modeling building surface pressure and infiltration. Sherman's mechanistic model for describing leakage paths, wind speed and wind orientation also captures infiltration details (M. Sherman, "Estimation of Infiltration from Leakage and Climate Indicators", Energy and Buildings, 10 (1987) 81 – 86). Sherman's model has become the basis for ASHRAE's method for determining the annual impact of house air leakage on house energy performance.

For our wind infiltration model, we relate the wind's pressure drag on a house to the wind's dynamic pressure with a building drag coefficient (refer to Figure G-2 for parameters describing the relations):

$$DP_w = C_D \times P_{dyn} = C_D \times \rho \times V_{wind}^2/2$$

Where P_{dyn} = dynamic wind pressure

ρ = air density (~1.2kg/m^3 ~ 0.074lbm/ft^3)

V_{wind} = wind speed

DP_w = wind pressure differential on house

C_D = house drag coefficient assumed to be 0.5

The infiltration region air flow for the house can be described by:

$$Q_I = C_I \times (Pu - Pi)^{0.57}$$

The exfiltration region air flow of the house can be described by:

$$Q_E = C_E \times (Pi - Pd)^{0.57}$$

Where Q_I = infiltration air flow rate

Q_E = exfiltration air flow rate

C_I = infiltration region C value

C_E = exfiltration region C value

Pi = house inside air pressure

Pu = exterior upwind pressure on house

Pd = exterior downwind pressure on house

The infiltration and exfiltration air flow rates are equal, and furthermore, we can combine the infiltration and exfiltration C values together by assuming the infiltration and exfiltration leakage paths to be the same as a series connection of two duct networks. By combining in this manner, we develop a relation with a new C value that relates infiltration and exfiltration to the overall differential wind pressure (DP_w) imposed on the house.

$$Q_I = Q_E = C_w \times DP_w^{0.57}$$

Or, $$Q_I = Q_E = C_w \times (C_D \times P_{dyn})^{0.57}$$

Series connection of two duct networks such as the infiltration leakage pathways and exfiltration leakage pathways result in an overall wind C value:

$$C_w = (C_I \times C_E)/(C_I^{1.75} + C_E^{1.75})^{0.57}$$

If we assume that the leakage characteristics of the upwind (infiltration) and downwind (exfiltration) regions are similar (which also implies that the house inside pressure is midway between the average upwind and downwind pressures imposed on the house), then $C_I = C_E$, resulting in a wind C value of:

$$C_I = C_E = 2^{0.57} \times C_w$$

An overall wind infiltration C value is $C_w \times C_D^{0.57}$. We can experimentally determine the overall infiltration C value by dividing a measured infiltration air flow rate by the wind driven dynamic pressure raised to the 0.57 power:

$$C_{wind} = C_w \times C_D^{0.57} = Q_I/P_{dyn}^{0.57}$$

Figure G-4 from Goldschmidt, et al data has been used to determine a C_{wind} value of 300 for the sheathing board sealed home and a C_{wind} value of 480 for the leakier, conventionally constructed home with caulked seams. As with duct C values, the ratio of these C_{wind} values are ratios of air flow relative to a common pressure difference. For the two mobile homes in Goldschmidt, et al's study, the conventionally constructed home has 60% higher infiltration air flow rates than the sheathing board sealed home.

Finally, we use this modeling strategy to link blower door leakage measurement to infiltration leakage. We assume it is reasonable to state that the same leakage pathways are responsible for both blower door air flow and for infiltration air flow. The primary difference, as shown schematically in Figures G-1 and G-2, is that all air flow through leakage paths are in one direction for the blower door test while half of the air leakage paths flow into the house and half of the air leakage paths flow out of the house. In effect, the infiltration and exfiltration paths operate in a "parallel" manner during a blower door test, and operate in a "series" manner during wind driven leakage.

We define a blower door test C value that relates blower door air flow to the blower door test pressure.

$$C_{Blower} = Q_{Blower}/P_{Blower}^{0.57}$$

For a blower door test, viewing infiltration and exfiltration leakage paths to be acting together as parallel duct networks that combine air flows that move through the blower results in:

$$C_{Blower} = C_I/0.5 = C_E/0.5$$

Therefore, the infiltration and exfiltration C values are:

$$C_I = C_E = Q_{Blower}/(2 \times P_{Blower}^{0.57})$$

Relating the wind coefficient, C_W to the infiltration coefficient, C_I, we find:

$$C_W = Q_{Blower}/(2^{1.57} \times P_{Blower}^{0.57})$$

Using our relation for wind driven infiltration, we obtain the infiltration flow rate as a function of blower door performance test results and wind driven pressure:

$$Q_I = DP_W^{0.57} \times Q_{Blower}/(2^{1.57} \times P_{Blower}^{0.57})$$

Or, $$Q_I = P_{dyn}^{0.57} \times C_D^{0.57} \times Q_{Blower}/(2^{1.57} \times P_{Blower}^{0.57})$$

And, $$Q_I = P_{dyn}^{0.57} \times C_D^{0.57} \times C_{Blower}/2^{1.57}$$

Where $$C_{Wind} = C_D^{0.57} \times C_{Blower}/2^{1.57} = 0.34 \times C_D^{0.57} \times C_{Blower}$$

The final expression is our wind driven C value as a function of building drag coefficient and blower door test C value. This simple, but powerful relation between blower door test results and wind driven infiltration provides us with a means to determine instantaneous trends of infiltration as wind speed changes.

We can check the validity of our result by comparing to the "K-P" (Kronvall-Persily) model, which is derived from regression analysis of blower door test data and infiltration data. The K-P model finds a ratio of infiltration at "normal" conditions (airflow at wind speeds of 5-6mph) to blower door air flow at 50Pa (0.2"H_2O) to be 1/18. The K-P model is often rounded to the rule of thumb 1/20 ratio of infiltration to blower door air flow rate. Sherman's mechanistic model applied to average annual wind conditions at 200 locations around North America found the ratio to vary from 1/15 to 1/30, with 1/18 to 1/20 as a common value.

Our model provides the ratio directly by dividing the infiltration flow rate by the blower door air flow rate:

$$Q_I/Q_{Blower} = P_{dyn}^{0.57} \times C_D^{0.57}/(2^{1.57} \times P_{Blower}^{0.57})$$

Or, $$Q_I/Q_{Blower} = (P_{dyn} \times C_D / P_{Blower})^{0.57}/2^{1.57}$$

$$Q_I/Q_{Blower} = (\rho \times V_{wind}^2 \times C_D / P_{Blower})^{0.57}/2^{2.14}$$

Figure G-6 shows the variation of the blower door to infiltration ratio factor as a function of wind speed and building drag coefficient. For a building with drag coefficient of 0.5, we see that a wind speed of 5 to 6mph results in the rule-of-thumb ratio of 20. Variation of the drag coefficient provides insight into the shape of a building as well as other ameliorating factors (eg, vegetation, fences, etc) that may lower the pressure differential applied to a building. Decreasing a building drag coefficient from 0.5 to 0.3

increases the ratio by 25%, from 20 to 25, which is beneficial. Likewise, a less aerodynamic building shape reduces the ratio, which is undesirable. As wind direction shifts around a home, the building drag coefficient varies, which is part of the effect observed in Figure G-3 data.

Persily (Figure 4, A.K. Persily, "Measurements of Air Infiltration and Airtightness in Passive Solar Homes", Measured Air Leakage of Buildings. ASTM STP 904, H. R. Trechsel and P. L. Lagus, Eds., American Society for Testing and Materials, Philadelphia, 1986, pp.46-60) compares infiltration and blower door test data for 82 homes. On average, the rule-of-thumb ratio of 20 is average for the data, however, scatter in the data is very large with the ratio varying from 8 to 50. The infiltration data was collected by homeowners over a range of unknown wind (and temperature) conditions. Figure G-6 shows that wind variations from 3 to 20mph are sufficient for causing blower door to infiltration air flow rate ratio variations in this range.

We conclude with an example to show how one can use these results in a practical manner. Assume we run a blower door test (50Pa = 0.2"H_2O) on two identical 2000square foot homes with 8ft high ceilings (16,000cubic ft house volume). One home is found to be very well sealed with 0.6ACH at 50Pa (Passive House level) while the other home has 6ACH leakage at 50 Pa (conventional construction without significant sealing effort). The blower door leakage air flow rate for the well sealed home is 160cfm (0.6ACH x 16,000cuft / 60min/hr). The other home has a blower door leakage air flow rate of 1600cfm.

We calculate the blower door C values as:

Sealed Home: C_{Blower} = 160cfm/(0.2"H_2O)$^{0.57}$ = 400

Unsealed Home: C_{Blower} = 160cfm/(0.2"H_2O)$^{0.57}$ = 4000

Assuming a building drag coefficient of 0.5, we determine the wind infiltration C values as:

Sealed Home: C_{Wind} = 400 x $0.5^{0.57}$ / $2^{1.57}$ = 91

Unsealed Home: C_{Wind} = 4000 x $0.5^{0.57}$ / $2^{1.57}$ = 910

We conclude at this point, but recognize that we now have the capability to demonstrate why "smart" ventilation systems are capable of being much more efficient than simple "one-and-done" ventilation systems while more effectively managing indoor air quality. We will save this discussion for another time.

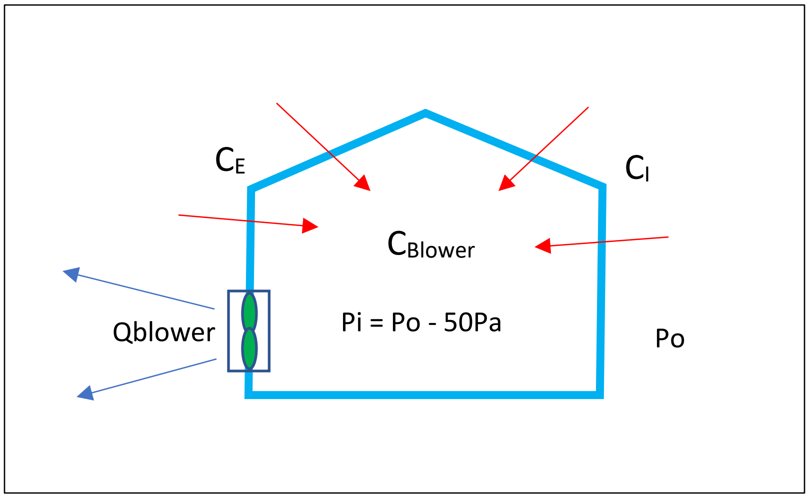


Figure G-1 Schematic of air flowing into a home during blower door testing.

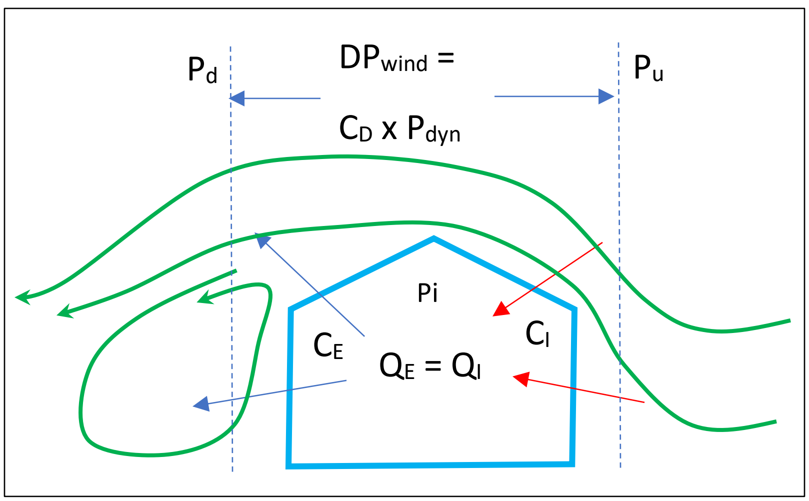


Figure G-2 Schematic of wind driven infiltration and exfiltration.

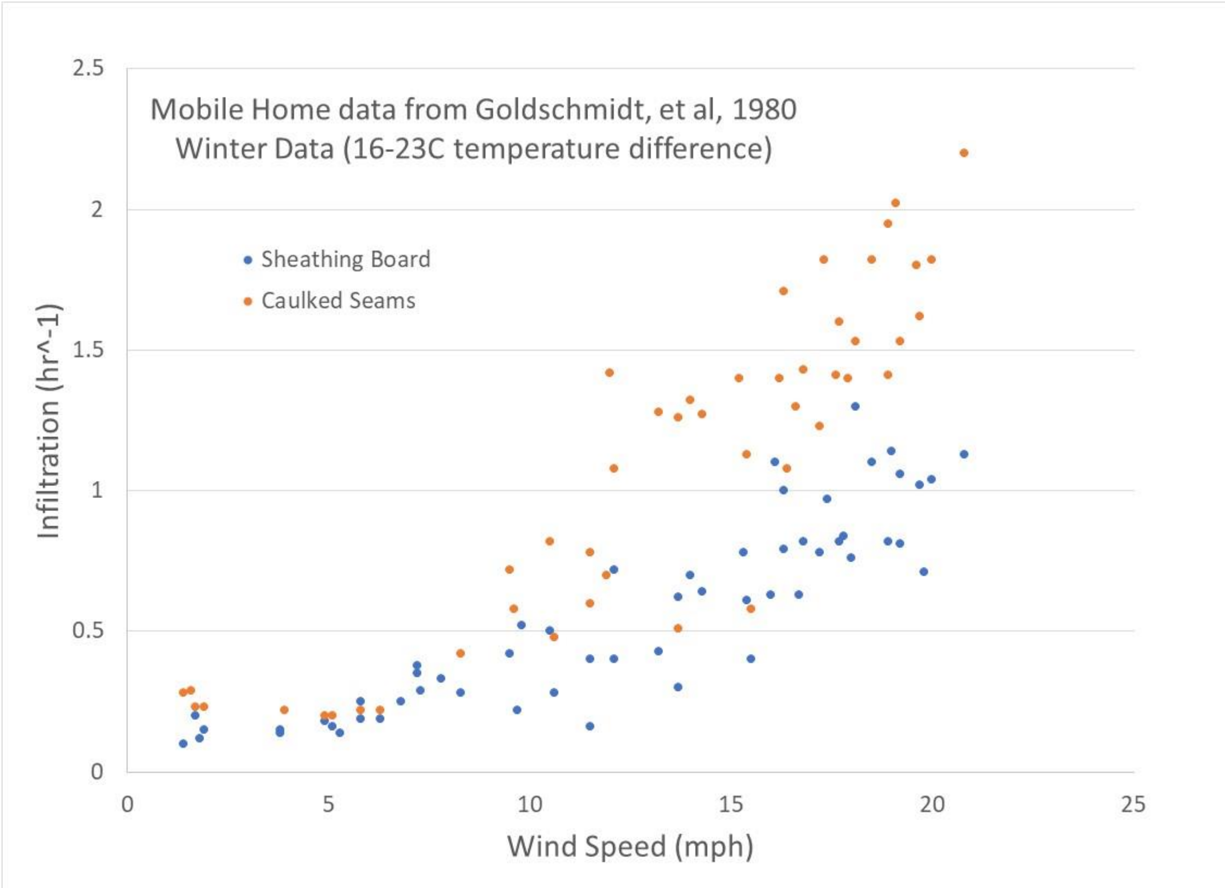


Figure G-3 Infiltration data from two mobile homes (VW Goldschmidt, RG Leonard, JE Ball, and DR Wilhelm, "Wintertime Infiltration Rates in Mobile Homes", p 107, Building Air Change Rates and Infiltration Measurements, Hunt, King, and Trechsel editors, ASTM pub 719, 1980). One is well-sealed with sheathing board while the second one is 1970 era conventional construction that has had seams caulked.

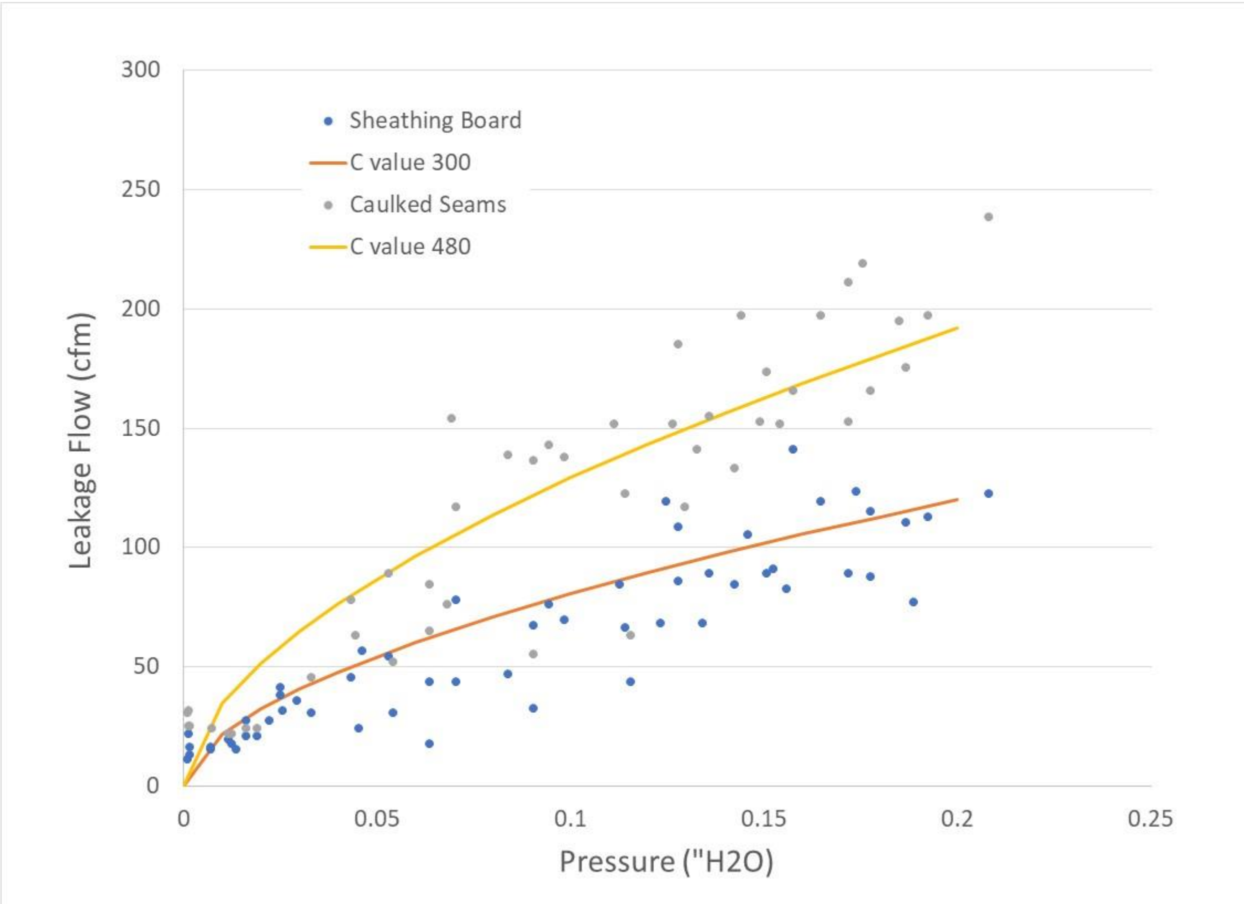


Figure G-4 Figure G-3 data replotted as leakage air flow rate versus wind dynamic pressure. C values for the two mobile homes are shown and resulting air flow curves are plotted.

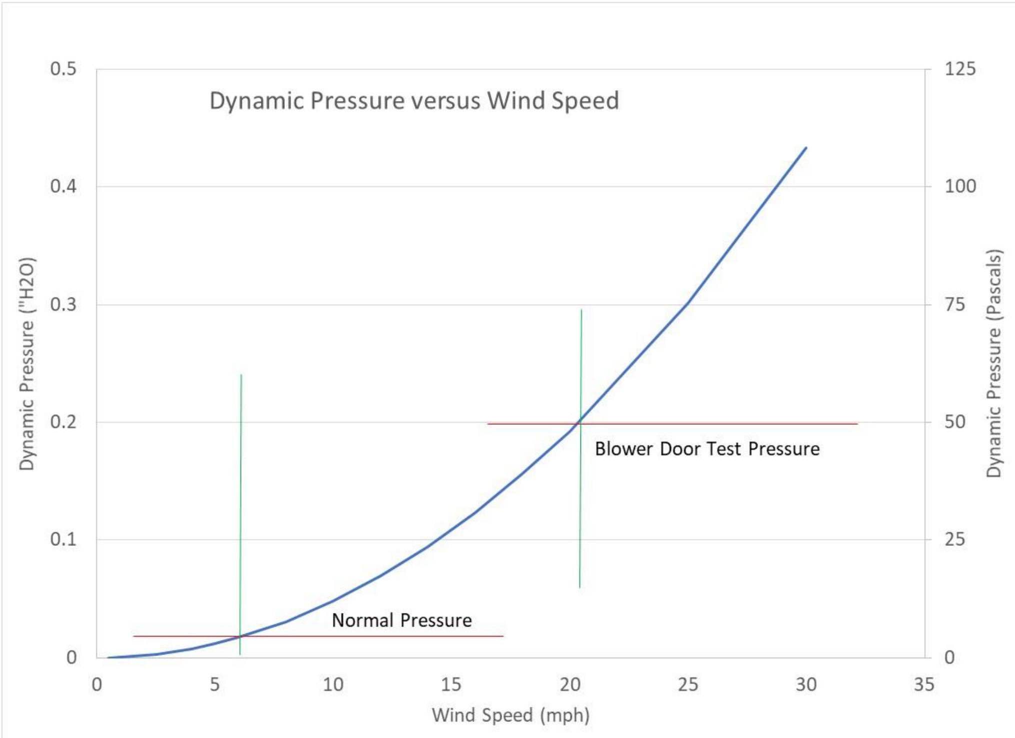


Figure G-5 Plot of dynamic pressure versus wind speed ("H_2O on left axis and Pa on right axis).

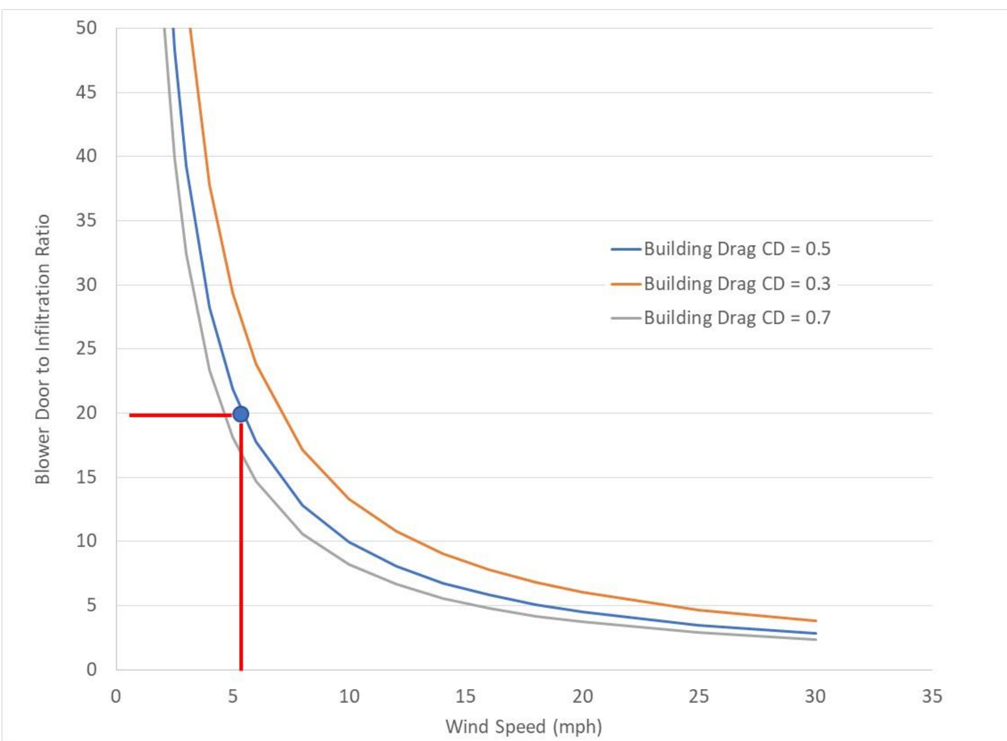


Figure G-6 Plot of Blower Door to Infiltration ratio factor for varying wind speed and building drag coefficients.

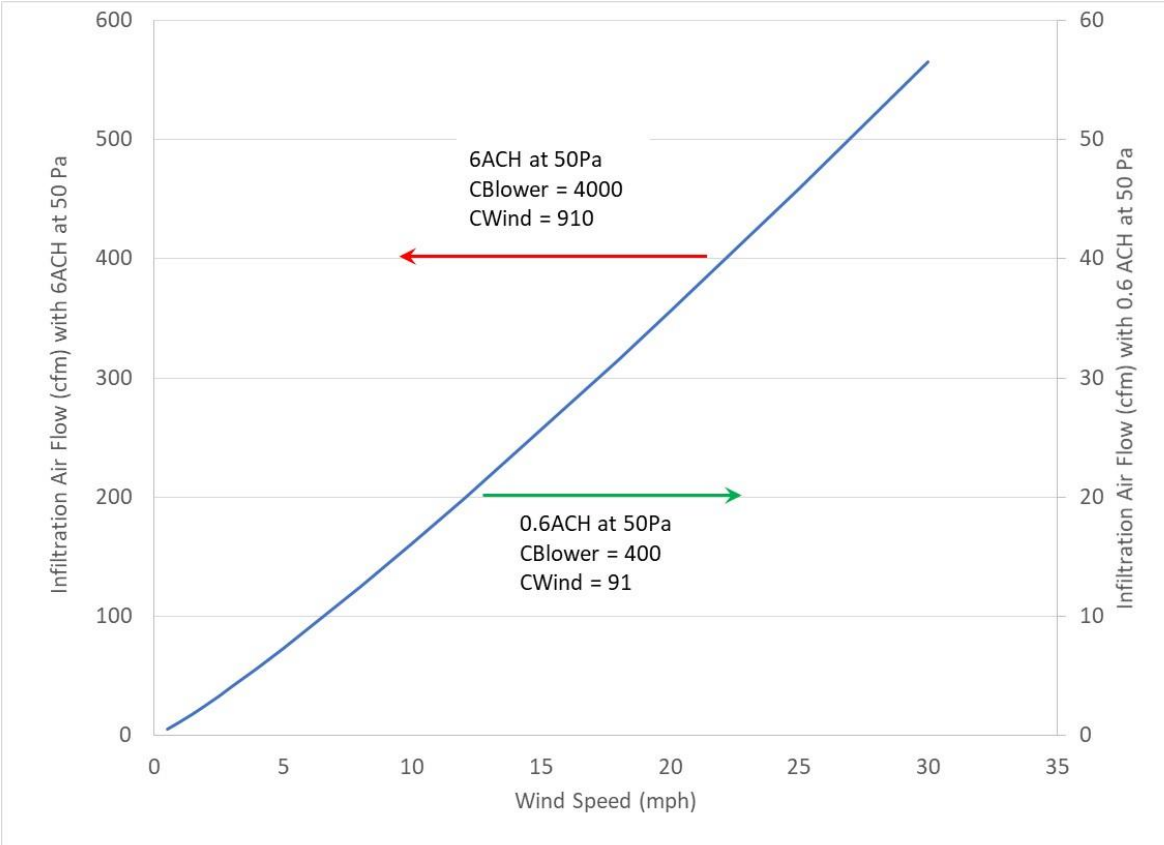


Figure G-7 Infiltration air flow rates for two homes with 16,000cubic ft of volume with one home having 0.6ACH at 50Pa and the other home with 6ACH ay 50Pa blower door test values.