Myron Katz,[1] Norman M. Witriol,[2] and Jinson Erinjeri[3]

The Generalized Subtraction Correction Algorithm for Measuring Duct Leakage Using a Blower Door

REFERENCE: This paper has been submitted for publication to the Journal of Testing and Evaluation, November 2004 issue, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428, and may not be republished, reproduced or distributed elsewhere without the expressed written permission of ASTM International. Editorial review has not been completed and changes may result.

ABSTRACT: The Generalized Subtraction Correction Algorithm (GSCA) improves upon the Modified Subtraction method for determining duct-leakage-to-outside using only a blower door. GSCA utilizes attic pressure both to calculate a generalized Subtraction Correction Factor and to properly identify and assign the correct pressure-difference between the ducts and attic responsible for the calculated duct-leakage flow. This paper also describes the normal procedures that enhance the accuracy of data collection and the subsequent tests on the resulting information for validating the applicability of GSCA to an individual home. GSCA collects associated pressure-coupling data and enhances the reliability of house-leakiness results.

KEYWORDS: Subtraction Correction Factor, duct leakage, attic pressure, house leakiness, energy efficiency, attic-to-home pressure-coupling ratio, automated performance testing equipment, blower door, Duct Blaster™, pressure pan, CFM50, infiltration, energy ratings, air leakage in buildings.

Introduction

The Subtraction Method measures duct-leakage-to-outside (hereinafter referred to as "duct-leakage") by subtracting blower-door induced airflow out of a home during two consecutive tests, the only difference between these two tests being the taping of the duct registers in the second test. Since these measurements involve changes in a variety of environmental parameters, duct-leakage is often underestimated. To correct for these differences [1], Modified Subtraction calculates duct-leakage by multiplying the result of a pure Subtraction Method by a Subtraction Correction Factor (SCF), where $SCF = 50^{0.65} / [50^{0.65} - D^{0.65}]$ and D is the pressure-difference between the ducts and attic when the registers are taped while the home is depressurized to 50 Pa. The larger the interconnection between the ducts and the home, the more pressure-difference there is between the ducts and attic; this increases SCF and therefore the calculated duct-leakage. Modified Subtraction assigns the calculated duct-leakage to 50 Pa.

[1]Energy & Building Science Consultant, Wisznia Associates, AIA, 302 Walnut, New Orleans, La 70118
[2]Department of Physics & Trenchless Technology Center, Louisiana Tech University, Ruston, LA 71272
[3] Department of Industrial Engineering & Trenchless Technology Center, Louisiana Tech University, Ruston, LA 71272

However, Modified Subtraction assumes that the attic pressure does not change when the home is depressurized – an assumption that does not match conditions usually found in practice. This and other practical problems are addressed and included in the derivation of the GSCA.

GSCA principally differs from Modified Subtraction by using the attic pressure to calculate a generalized *SCF* and to assign the resulting duct-leakage to the actual pressure-difference between the ducts and attic. It is important to note that for the same home, GSCA generally calculates a smaller *SCF* than Modified Subtraction, but assigns the resulting duct-leakage to a lower pressure-difference between the duct and the attic. Since the former lowers and the latter raises calculated duct-leakage at a particular pressure, these two errors tend to offset each other. Thus, Modified Subtraction will often provide results close to those given by GSCA. A few examples that illustrate this effect are provided at the end of this paper.

Because GSCA's accuracy heavily depends upon the accuracy of a pair of house-leakiness tests, determination and characterization of house-leakiness are other practical problems addressed and ameliorated in this paper. House-leakiness testing is also discussed here because both objectives, ascertaining duct-leakage and house-leakiness, can be accomplished simultaneously by performing a pair of standard house-leakiness flow measurements via depressurizations of the home at a series of pressures. While the ASTM Standard E779-03, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 136 [2], and the Canadian General Standards Board (CGSB) Standard 149.10-M86 [3] already require that house-leakiness should be tested at a series of pressures, this paper explains how house-leakiness tests taken at a series of pressures also enhance the estimation of duct-leakage. Conversely, since GSCA collects pressure and pressure-coupling data with registers taped and again with registers untaped, and these data are not normally used in a house-leakiness test, GSCA can uncover errors in house-leakiness data collection. Thus, provided herein is a testing technique and system analysis that will improve the determination of the two most important energy-performance tests of a home: house-leakiness and duct-leakage.

In addition, our characterization of house-leakiness contains an enhancement of the standard by introducing a new parameter, the attic-to-home pressure-coupling ratio. This pressure-dependent function can be used to help estimate the proportion of the house-leakiness associated with the home's connection to its attic [4]. Moreover, the attic-to-home pressure-coupling ratio is pivotal to checking the applicability of GSCA.

Although originally derived for the case when ducts are installed in attics, GSCA can be applied to crawlspaces or other semi-exposed locations; in that case, the energy rater should merely measure the pressure of the volume enclosing the ducts instead of the attic.

The comments near the end of this paper discuss the applicability of GSCA in various situations. It should be noted that even GSCA in its present form cannot be applied to a home with two or more independent duct-systems or a single duct-system in more than one independent pressure-volume adjoining a home, for example: in an attic and a crawlspace. It should also be noted that in this derivation, it is assumed that the pressure in the ducts is uniform throughout.

Nomenclature

duct-leakage	=	duct leakage to outside
SCF	=	Subtraction Correction Factor

The following five parameters are unprimed for the measurements with the duct registers untaped, and primed for them taped.

P = outside - inside (house) pressure, Pa
κ = flow-coefficient, $m^3/s\ Pa^{-n}$
n = house-leakiness flow-exponent, unitless
Q = airflow, m^3/s
m = duct-leakage flow-exponent, unitless

The following six terms only appear in the second theorem below:

Q_{oa} = flow from outside to attic
Q_{ad} = flow from attic to ducts
Q_{dh} = flow from ducts to house
P_d = pressure in ducts with respect to outside
P_h = pressure in house with respect to outside
P_a = pressure in attic with respect to outside

P_{D25} = P_D when $P = 25$

Subscripts

D = attic with respect to ducts
A = attic with respect to inside house
nvd = flow not via ducts
nva = flow not via attic
vdbnr = flow via ducts but not registers
vabnd = flow via attic but not ducts
vr = flow via registers
vd = flow via ducts
dlo = duct-leakage (to outside)

Convention: P as well as all other pressure measurements used in the derivation of *SCF* is defined to take positive values during house depressurization. However, GSCA is equally applicable to house pressurization, in which case all pressure measurements will change sign.

Innovations of GSCA

GSCA generalizes and corrects Modified Subtraction by:

- incorporating the change in attic pressure,
- assigning duct-leakage to the actual pressure-difference between the ducts and the attic,
- using an average duct-leakage instead of house-leakiness flow-exponent,
- incorporating the change of the duct-system pressure when the registers are not taped,
- allowing the calculation of duct-leakage at house depressurizations other than 50 Pa,
- calculating duct-leakage when the pressure-difference between the attic and ducts is 25 Pa,
- testing and confirming its own applicability, and

- allowing for a posteriori reviews of the calculated and observed parameters that help confirm the accuracy of data collection and check the reliability of both house-leakiness tests.

Data Collection Procedure

1. Perform a depressurization test with a blower-door to depressurize the house to P.

   A. Record the flow as Q for untaped.
   B. Record the pressure in the duct system with respect to the attic, P_D.
   C. Record the pressure in the attic with respect to inside, P_A.

2. Remove the HVAC filters and tape all the registers. Perform a second depressurization test with a blower door to depressurize the house to P.

   A. Record the flow as Q' for taped.
   B. Record the pressure in the duct system with respect to the attic, P'_D.
   C. Record the pressure in the attic with respect to inside, P'_A.

Under these conditions, duct-leakage at 25 Pa (also called CFM25) is defined as the flow from the ducts to the attic when the pressure-difference between the ducts and the attic is 25 Pa. (1.00 CFM = 4.72 x 10^{-4} m^3/s.) This value of duct-leakage cannot be measured directly by the procedure just described since the measurement apparatus is set to the house depressurization with respect to the outside, P, and not the duct-system's depressurization with respect to the attic, P_D. This procedure calculates duct-leakage but the pressure between the ducts and the attic, P_D, at which the measurement is performed, cannot be known at the time the house depressurization pressure, P, is chosen. We first show that, although we cannot expect to directly obtain the duct-leakage at 25 Pa or at 50 Pa by a single application of this procedure at one pressure, P, it is possible to extract these values through a coordinated set of two or more runs of this same experiment, i.e., each set at a specific value of P for two or more different values of P.

When the home is depressurized twice (once before, and once after the duct-registers are taped), the difference in the flow through the blower door is taken to be, as a first approximation, the duct-leakage (to outside the conditioned space) at some specific pressure. However, for the same pressure regime P, the pressure-difference between the ducts and attic differs in the taped and untaped cases; i.e., P_D does not equal P'_D. To correct for this experimental situation, a Subtraction Correction Factor (*SCF*) is introduced in which the two flows, Q and Q', are taken at different pressures, P_D and P'_D:

$$\text{Duct-Leakage (to Outside)} = (Q - Q') \bullet SCF$$

Derivation of the Generalized *SCF*

We start by deriving the formula for the *SCF*. Several limiting conditions on this derivation will be addressed in the comments that follow the description of GSCA.

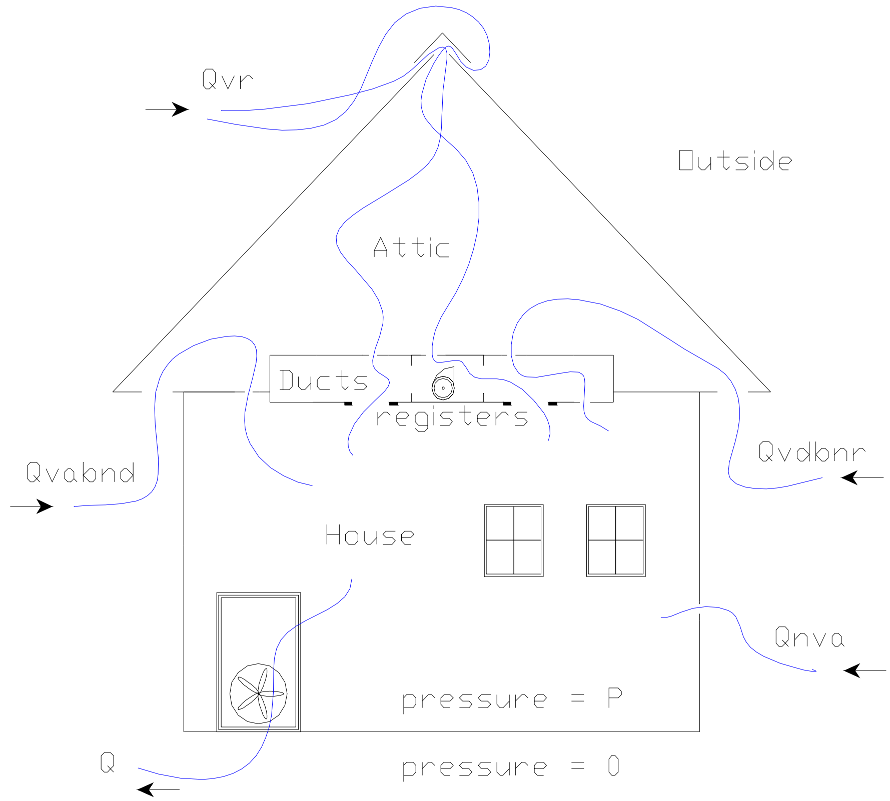

FIG. 1—*Airflows Generated by Using a Blower Door to Depressurize a Home*

Holes between the ducts and the attic provide the area where duct-leakage must occur.

Q	=	flow from house to outside = flow through blower-door		
	=	flow not via ducts	+	flow via ducts
Q	=	Q_{nvd}	+	Q_{vd}

Notice that both of these flows are divided into two flows as described in the diagram.

Q_{vd}	=	flow via ducts		
	=	flow via registers	+	flow via ducts but not registers
	=	Q_{vr}	+	Q_{vdbnr}
Q_{nvd}	=	flow not via ducts		
	=	flow not via attic	+	flow via attic but not ducts
	=	Q_{nva}	+	Q_{vabnd}

However, for the remainder of the derivation of *SCF*, the distinction between these last two flows, Q_{nva} and Q_{vabnd}, will not be needed; therefore, only Q_{nvd} will be utilized. Thus

$$Q = Q_{nvd} + Q_{vd}$$

$$= Q_{nvd} + Q_{vr} + Q_{vdbnr}$$

Q_{dlo} = duct-leakage (to outside)

= flow into the ducts from the attic

= flow out of the ducts to the house

$$Q_{dlo} = Q_{vr} + Q_{vdbnr}$$

Thus:

$$Q = Q_{nvd} + Q_{dlo} \qquad (1)$$

The analysis in E 799 assumes that airflow for house-leakiness, as a function of the pressure-difference between the home and outside, typically follows a power-law over the range of pressures utilized in these measurements

$$Q = \kappa P^{n} \qquad (2)$$

Experience from alternative testing methods [5,6] has confirmed that the same power-law relationship applies to duct-leakage, namely

$$Q_{dlo} = \kappa_D P_D{}^{m}$$

where κ_D is the coefficient for the flow-equation for duct-leakage as a function of the pressure-difference between the attic and the ducts. Note that the exponent for duct-leakage, *m*, may be different from *n*, the exponent for house-leakiness. Also note that P_D is the pressure-difference between the ducts and the attic with the registers untaped. In each case, the exponents, *n* and *m* apparently depend on all of the conditions of the test, and κ; κ_D, *n* and *m* are constants for any particular home. For each home, the empirically obtained values of *n* and *m* have been found to vary within the range of 0.5 to 0.8, while their average values over a large number of homes were reported to be close to 0.65 for *n* and 0.60 for *m* [5,6].

We define

Q' = the flow with the registers taped.

$$Q' = Q'_{nvd} + Q'_{vr} + Q'_{vdbnr}$$

Since the registers are taped, $Q'_{vr} = 0$ and

$$Q' = Q'_{nvd} + Q'_{vdbnr} \qquad (3)$$

During the taped case, the flow into the ducts must equal the flow out of the ducts. Thus:

$$Q'_{dlo} = Q'_{vdbnr} = \kappa'_D P'_D{}^{m'} \qquad (4)$$

$$Q' = Q'_{nvd} + Q'_{dlo} \qquad (5)$$

As defined in Step 2 of the data-collection procedure, P'_D is the pressure-difference between the ducts and the attic with registers taped. The m' in Eq. (4) is primed because it refers to the taped case and, from our measurements, depends on all the parameters of the test. Similarly, κ'_D is the (constant) coefficient for the flow-equation restricted to flow through the attic to the ducts. From Eq. (1) and Eq. (5) we obtain

$$Q - Q' = (Q_{nvd} + Q_{dlo}) - (Q'_{nvd} + Q'_{dlo}) \tag{6}$$

Assuming house-leakiness to be independent of the change in the flow through the ducts, $Q_{nvd} = Q'_{nvd}$ (this relationship can be relied upon when empirical observation confirms that P_A is essentially the same as P'_A; see the *Untaped and Taped Attic Pressures* comment), we obtain

$$Q - Q' = Q_{dlo} - Q'_{dlo}$$

Substituting Eq. (4) into this equation, we obtain

$$Q - Q' = \kappa_D P_D^{\,m} - \kappa'_D P'^{\,m'}_D \tag{7}$$

By definition

$$SCF = \text{duct-leakage} \;/\; [\, Q - Q' \,] \tag{8}$$

Thus

$$SCF = \kappa_D P_D^{\,m} \;/\; [\, \kappa_D P_D^{\,m} - \kappa'_D P'^{\,m'}_D \,] \tag{9}$$

We now assume that $\kappa_D = \kappa'_D$. This is a reasonable assumption since the flow coefficient for the flow across the boundary between the duct system and the attic, at various pressure-differences between the ducts and attic, is clearly independent of whether the registers are taped or not; similarly, $m = m'$. Thus

$$SCF = P_D^{\,m} \;/\; [\, P_D^{\,m} - P'^{\,m}_D \,] \tag{10}$$

We believe that the best assumption for the value of m is to use a value obtained by averaging a large set of duct-leakage results, $m = 0.60$ [5,6] (as opposed to that obtained by averaging over a large set of house-leakiness results, namely $n = 0.65$; see the *Choice of Flow Exponent* comment). Therefore

$$SCF = P_D^{\,0.6} \;/\; [\, P_D^{\,0.6} - P'^{\,0.6}_D \,] \tag{11}$$

This completes the derivation of SCF for any depressurization pressure, P; but it should be stressed again that, the calculated SCF should be assigned to the value of P_D, not the value of P. However, although it seems that the value of SCF depends upon P or P_D, as we shall see below, in most cases SCF does not depend upon the choice of either P or P_D used for the test.

Theorem: If the values of P_D and P'_D are directly proportional to P, then the value of SCF does not depend upon P.

Proof: The values of P_D and P'_D are directly proportional to P. That is, for any given house

$$P_D = K * P \tag{12}$$

$$P'_{\mathrm{D}} \quad = \quad K' * P \tag{13}$$

for some constants K and K'.

Then, substituting Eqs. (11) and (12) into Eq. (9)

$$\begin{aligned} SCF &= (K * P)^{0.6} \;/\; [\,(K * P)^{0.6} - (K' * P)^{0.6}] \\ &= K^{0.6} \;/\; [\,K^{0.6} - K'^{0.6}\,] \end{aligned} \tag{14}$$

GSCA has proven to provide a significant benefit over Modified Subtraction for homes that have all of their duct-systems limited to conditioned space and a single attic, and when the attic's pressure changes by more than 2 Pa when the home is depressurized to 50 Pa. In the experience of the authors in almost one hundred homes within Louisiana, each with a single HVAC system, almost invariably P_{D} and P'_{D} appeared to be directly proportional to P and GSCA was applicable. The following result characterizes the situation where we should expect this very common linearity and gives insight into the physical situation in a home when this condition is not met.

Theorem: When duct-leakage (to the attic) is very small with respect to house leakage to the attic, P_D is proportional to P.

Proof: As defined in the nomenclature section, singly-subscripted pressures are referenced to outside, Q_{ad} = flow from attic to ducts and Q_{dh} = flow from ducts to house. Therefore

$$Q_{\mathrm{dh}} = Q_{\mathrm{ad}}$$

From Eq. (4), assuming the same exponent, m, for all duct-leakage flows

$$\kappa_{\mathrm{dh}}\,(P_{\mathrm{d}} - P_{\mathrm{h}})^m = \kappa_{\mathrm{ad}}\,(P_{\mathrm{a}} - P_{\mathrm{d}})^m \tag{15}$$

Therefore, solving for P_{h}

$$P_{\mathrm{h}} = \{[1 + (\kappa_{\mathrm{ad}}/\kappa_{\mathrm{ah}})]^{1/m}\}P_{\mathrm{d}} - (\kappa_{\mathrm{ad}}/\kappa_{\mathrm{ah}})^{1/m}P_{\mathrm{a}} \tag{16}$$

We shall now show that P_{d} and P_{a} are proportional to P_{h}.

Consider the flows into and out of the attic:

Q_{oa} = flow from outside to attic

Q_{vabnd} = flow (from attic to house) via attic but not ducts

Q_{vd} = flow (from attic to house) via ducts

By conservation of mass out of and into the attic, respectively

$$Q_{\mathrm{oa}} = Q_{\mathrm{vabnd}} + Q_{\mathrm{vd}}$$

Utilizing Eq. (2) and assuming all the exponents are the same (to within a reasonable approximation; see the *Choice of Flow Exponent* comment)

$$\kappa_{\mathrm{oa}}\,(P_{\mathrm{a}})^m = \kappa_{\mathrm{vabnd}}\,(P_{\mathrm{h}} - P_{\mathrm{a}})^m + \kappa_{\mathrm{vd}}\,(P_{\mathrm{d}} - P_{\mathrm{a}})^m \tag{17}$$

Since, for the vast majority but not necessarily all homes, the leakage from the house to the attic is much greater than the leakage from the ducts to the attic, i.e.

$$\kappa_{\mathrm{vabnd}}\,(P_{\mathrm{h}} - P_{\mathrm{a}})^m >> \kappa_{\mathrm{vd}}\,(P_{\mathrm{d}} - P_{\mathrm{a}})^m \tag{18}$$

Eq. (17) becomes

$$\kappa_{oa}P_a{}^{m} \simeq \kappa_{vabnd}\,(P_h - P_a)^m \tag{19}$$

Thus, for homes satisfying the approximation of Eq. (18), the pressure in the attic, P_a, is essentially proportional to P_h, the house pressure. Since P_a is proportional to P_h, then from Eq (16), P_d is also proportional to P_h.

Corollary: When duct-leakage (to the attic) is very small compared to house leakage to the attic, the attic-to-home pressure-coupling ratio, P_A/P, is constant.

Calculation of Duct-Leakage at 25 Pa

As mentioned above, when the data is appropriate, GSCA takes the next step – the calculation of duct-leakage when the pressure-difference between the ducts and attic is 25 Pa. With data collection at two or more values of P, the value of *SCF* can be calculated for each P to see if *SCF* is constant. (As explained by the previous two theorems, for nearly all homes, the calculation of the generalized *SCF* is applicable and the value of *SCF* for a home is independent of P.) Since in both the untaped and taped cases house-leakiness has been measured at two (or more) pressures, one can calculate two flow exponents and coefficients for house-leakiness and use these flow-equations to express the difference between untaped and taped house-leakiness flows as a function of P.

$$Q \quad - \quad Q' \quad = \quad \kappa P^n \quad - \quad \kappa' P^{n'} \tag{20}$$

From Eq. (8), duct-leakage at 25 Pa equals *SCF* times this difference when P is chosen so that $P_D = 25$. Since P_D is proportional to P, the required choice of P is $25*(25/P_{D25})$ where P_{D25} is the pressure-difference between the ducts and attic when the house is depressurized to 25 Pa.

$$\text{Duct-leakage at 25 Pa} = SCF\,\{\kappa[25\,(25/P_{D25})\,]^n - \kappa'\,[25\,(25/P_{D25})\,]^{n'}\} \tag{21}$$

GSCA Generalizes Modified Subtraction

When tests are performed at P = 50 Pa, P_A = 50 Pa, and the untaped duct-system has the same pressure as the house, the *SCF* just derived reduces to the one provided by Modified Subtraction, except the exponent of *SCF* for GSCA is taken to be 0.60.

Comments

Accuracy of House-Leakiness Data—When Q and Q' (the flow of the home when it is depressurized to a pressure P, taped and untaped, respectively) have measurement errors similar in size to the difference between their values, it is hard to put any confidence in the accuracy of that difference. Since the most common application of Modified Subtraction derives from manually collected data, it is very important to minimize the size of the error of these measurements. A common method employed to ameliorate these errors is to repeat the collection of the value of Q and Q' three or more times. We believe that an automatic data-collection procedure, wherein a very large number of data are collected at each of a series of pressures, provides much greater accuracy. The system we employed comprised Automated Performance Testing (APT™) equipment with four manometers connected to a laptop computer running Tectite™ software; in default mode, Tectite™ controls the blower-door fan while collecting 1000 data-sets and outputs the required flow-equation parameters via a regression analysis performed to model the house-leakiness flow-equation, Eq. (2) [7,8]. Experience indicates that when the resulting correlation coefficient is less than 99%, such data is of dubious value for ascertaining duct-leakage. However, when this level of accuracy is not obtained, the requested data collection can be easily modified, extended and/or errors in test procedures repaired, thereby obtaining acceptable data in almost all homes and weather conditions.

Untaped and Taped Attic Pressures—The derivation of the generalized *SCF* assumes that the airflow Q_{vabnd}, via the attic but not the ducts, is essentially independent of whether or not the ducts are taped. The essential equality of P_{A} and P'_{A} is the primary check to confirm this condition. Clearly the greater the duct-leakage, the greater will be the potential change in attic pressure. Moreover, empirical evidence gives good insight: we have found that in over fifty homes [6], when calculated duct-leakage was less than 200 CFM 25, the change in attic pressure did not exceed 1 Pa. Since the greatest accuracy is desired only when duct-leakage is smaller than 200 CFM 25, the derivation of GSCA can be considered to be essentially complete since the only dubious assertion in the derivation can be empirically quantified when needed.

Data from more than fifty homes in the greater New Orleans area indicate that the magnitude of P_{A} is rarely greater than 48 Pa when the house is kept at negative 50 Pa with respect to outside and less than 40 Pa for one third of the same sample. As stated earlier, this observation is quite different from the assumption of Modified Subtraction that P_{A} will always be negligibly different from P (= 50 Pa).

P_{A} and P'_{A} can be used to help predict the numerical accuracy of the *SCF*: as the magnitudes of P_{A} and P'_{A} decrease, the magnitudes of P_{D} and P'_{D} must decrease, thus any error in the denominator will be grossly exaggerated in *SCF*.

This paper reintroduces [4] the need for collecting P_{A} in order to calculate P_A / P, and calls this quantity the attic-to-home pressure-coupling ratio. This parameter is important for interpreting house-leakiness since it gives an indication of the airflow between the house and the attic at various pressures. As the corollary to the second theorem indicates, it is normally independent of the pressure P used to observe it and takes a constant value. However, when P_A / P is variable, GSCA may not be applicable.

Pressure in the Ducts with respect to the Home during the Untaped Test—Unlike the implicit assumption of Modified Subtraction, the pressure in the ducts with respect to the home during the untaped test is not assumed to be zero by GSCA. Modera was also concerned about this [9]. Using a pressure pan [10], the authors have found pressure-differences as high as 15 Pa.

Although this datum can be collected at any register by sealing that register alone and piercing that seal with a pressure-probing tube, one cannot expect every register to be equally representative. In fact, by sampling all of the untaped duct registers, it is not unusual to find a 5 to 10 Pa difference between the highest and lowest values. Thus the question arises as to where to place the probe for untaped and taped data. We recommend the following procedure: The energy rater should precede the data collection for *SCF* with a duct-testing regime consisting of a complete set of pressure-pan tests. These tests will demonstrate the range of pressures for that particular duct-system. Once the tester has found the range, the tester should pick a register that exhibits a value closest to the average value. This procedure does not add additional time to the house measurement process since pressure-pan tests are normally performed for other diagnostic purposes. This procedure is also applicable to choosing the best place to probe the supply registers when setting up duct-leakage testing with a Duct Blaster™ [11].

Linear Dependency of P_D upon P—The proof of the linear dependency of P_D upon P assumed that 1) the exponents of all the leakages are the same (a passable assumption in relation to the accuracy of the testing procedure), 2) the pressure of the ducts are uniform throughout the ducts (an assumption not satisfied in most houses, and in some houses to a rather significant extent), and 3) the attic pressure in the taped and untaped cases are approximately the same (a reasonable assumption in most houses since attic pressure is determined much more by leaks from the house than from the ducts).

Checking the Applicability of GSCA—Both the *SCF* and the attic-to-home pressure-coupling ratio are practically constant with respect to the house pressure if the leaks from the house to the attic are much greater than the leaks from the ducts to the attic. In such a case, P_A would be negligibly different from P'_A, and the GSCA is applicable. Thus, a non-constant value of *SCF* or a variable attic-to-home pressure-coupling ratio raises doubts about the applicability of GSCA.

Even when the *SCF* is not constant with respect to pressure in a specific home, it is still possible for P_A to be negligibly different from P'_A (for each pressure P), because the variability in *SCF* may be associated with a variable attic-to-home pressure-coupling ratio. Although this situation does not invalidate the calculation of the generalized *SCF* for such homes at a given pressure, it does compromise the a posteriori determination of duct-leakage at 25 Pa, the second step in GSCA, since that requires using two or more values of P. Although there is sufficient data to determine the house-leakiness flow exponents and coefficients associated under these variable conditions – enabling one to calculate the value of a pure subtraction at any value of P – the value of *SCF* for each value of P is unknown. Thus, the second step of GSCA may not be applicable.

Choice of Flow Exponent—In the original derivation of the *SCF* in Modified Subtraction, the value of m was set at 0.65; namely, the mean value of the exponent, n, of the flow-equation for house-leakiness obtained phenomenologically from data taken from thousands of tested homes [1]. Our testing of 55 homes in Ruston, Louisiana found a similar value of 0.64 [6]. Alternatively, m can be taken to be the average of two values of n, obtained for the flow-equation for house-leakiness for the specific home being tested from the two sets of data collected, namely the untaped and taped cases. Although there are plausible arguments for each of the above choices, we believe the best recommendation is to use a value of m derived from the data obtained by averaging a sample of a large set of duct-leakage (as opposed to house-leakiness) results, m = 0.60 [5,6]. Although 0.60 seems to be a better choice, we have found that the resulting calculated duct-leakage to be only slightly affected by the choice of exponent.

Conclusions

Since GSCA is applicable to arbitrary values of *P*, various a posteriori considerations and improvements are realized. If manual collections are the best practical choice, we recommend that GSCA be performed at three or more different depressurization pressures. Since standard testing for house-leakiness [3] with automated testing equipment [8] performs tests at more than three pressures, all of the following benefits follow.

Calculation of the Coefficient and Exponent of the House-Leakiness Flow-Equation—When two or more depressurization pressures are used in a house-leakiness test, the coefficient and exponent of the flow-equation can be calculated. In the homes that cannot be depressurized to 50 Pa but, nevertheless, allow the flow-exponent to be calculated to sufficient accuracy, the use of the "Can't-Reach-Fifty-Factor" becomes superfluous [1].

Calculation of Effective Leakage Area—Infiltration is commonly estimated via the Lawrence Berkeley Laboratory model [7] that uses house-leakiness expressed as Effective Leakage Area (ELA) as an input; the same model calculates ELA by multiplying CFM4 by a constant. (1.00 CFM = 4.72 x 10^{-4} m^3/s. CFM50 is the flow through a blower-door when the home is depressurized to 50 Pa). According to ASTM E779, CFM4 is determined by a power-law fit to flows measured at two or more pressures. When house-leakiness is input as CFM50, energy-rating software commonly assumes a flow-exponent of 0.65 to estimate CFM4; this assumption can cause a significant error since, in practice, a calculated flow-exponent can be as low as 0.50 or as high as 0.80. *Confirmation that SCF is Constant*—When two or more depressurization pressures are used in the pair of house-leakiness tests, the value of the *SCF* can be calculated for each pressure to determine if it is constant. For nearly all homes where the calculation of the generalized *SCF* is applicable, the value of *SCF* for a home is independent of the pressure, *P*, used in the depressurization of the house. Thus, energy-auditing software has a tool to test the accuracy of the input data, correct for slightly inaccurate data collection, and determine if the *SCF* should be calculated at all for this home.

Confirmation that the Attic-to-Home Pressure-Coupling Ratio is Constant—When two or more depressurization pressures are used in a house-leakiness test, the value of the attic-to-home pressure-coupling ratio can be observed for each pressure to see if it is constant. For nearly all homes where the GSCA is applicable, the value of the attic-to-home pressure-coupling ratio is independent of the pressure, *P*, used in the depressurization of the house. Thus energy auditing software has another tool to test the accuracy of the input data, correct for slightly inaccurate data collection, and determine if GSCA should be used.

Calculation of Duct-Leakage at 25 Pa—When two or more depressurization pressures are used in the pair of house-leakiness tests, the energy rater has the ability to calculate duct-leakage at 25 Pa. This calculation can be performed since in both the untaped and taped cases house-leakiness has been measured at two (or more) pressures. One can then calculate two sets of flow exponents and coefficients for house-leakiness and use these flow-equation parameters to express the flow-difference between untaped and taped house-leakiness as a function of the untaped pressure-difference between the ducts and attic. Since the *SCF* of GSCA is constant, duct-leakage at 25 Pa can be directly calculated.

Modeling Duct-Leakage with a Flow-Equation—However, the calculation of an exponent and coefficient for the flow-equation of duct-leakage (to outside) from these data is dubious since the difference between two exponential functions is not an exponential function of the type we normally use to describe the flow-equation. This is a modeling error of the kind discussed by Sherman and Palmiter [12]. That is, although phenomenologically collected data conform to the standard house-leakiness flow-equation model, we know that once we conform and interpret the home's flow data to that model we have forced subsequent calculations to depend upon the strict mathematical restrictions just described. These restrictions make the calculation of the key parameters of the flow-equation for duct-leakage inaccessible if the home's data have already been placed in software utilizing the house-leakiness flow-equation model. If the data are collected manually, as we would expect to be the case for most energy auditors with a limited equipment budget, it may be possible to circumvent this mathematical dilemma, but we are then confronted by the more significant problem that the error in the data collection of a home's leakiness flow may be comparable to the difference between two such measurements. (This is further discussed in the *Accuracy of House-Leakiness Data* comment, above.)

Checking Reliability and Confidence in House-Leakiness Data—With three or more depressurization readings for each untaped and taped case, it is possible to calculate a correlation coefficient for each regression analysis that is used to best-fit the data and calculate house-leakiness flow exponents and coefficients [3,8]. These correlation coefficients provide reliability indicators for each house-leakiness test, thereby providing a measure of the confidence in that data.

When a house-leakiness test is performed as part of data collection for GSCA, at least two additional data, P_D and P_A, are collected for each P, the depressurization pressure of the home. Since a standard house-leakiness test includes tests at a series of pressures, these data effectively arrive as a series of triplets. Since a GSCA measurement requires two house-leakiness tests, two sets of series of triplets are available for a posteriori review – one for a registers untaped test and one for a registers taped test. If:

- P_A and P'_A differ by more than 2 Pa when estimated duct-leakage is less than 200 CFM25,
- P_D is negative when P and P_A are positive, or
- P_A/P is not constant even though P_A and P'_A differ by less than 1 Pa,

then the energy rater should suspect that something is probably wrong with the data collection. In such a case, the setup should be rechecked and one or both of the house-leakiness tests should be repeated.

Enhancing the Characterization of House-Leakiness—Both the magnitude and variability of the attic-to-home pressure-coupling ratio, P_A/P, give insights into the leakiness of the pressure-boundary between the home and attic.

Example Calculations

Duct-leakage calculations on data collected from three greater New Orleans homes provide example calculations that compare Modified Subtraction to GSCA. Using an APT™ setup to simultaneously measure P_A and P_D, three pairs of multi-pressure, house-leakiness tests were conducted during 2001 through 2003. These tests were chosen because:

1. They exhibit typical attic pressures for this geographic region.
2. House-leakiness tests indicate high correlation coefficients and low CFM @ 50 Pa errors.

3. The attic-to-home pressure-coupling ratios were constant.
4. Duct-leakage CFM @ 25 Pa was in the diagnostically significant 90 to 275 range.

The first table shows Tectite™ house-leakiness and zone-pressure data [8]; the second table displays duct-leakage calculation results.

TABLE 1–*Untaped and Taped House-Leakiness and Zone Data for Three Homes*

	House Leakiness									**Zone Data Pressure**	
	Regression Results on Multiple Pressure Tests						**Descriptors**				
	CFM @ 50 Pa	Error		**Flow Equation**		**Correlation**	**@ 4 Pa**			**@ 50 Pa**	
		%	**Max**	**Coefficient**	**Exponent**	**Coefficient**	**NACH**	**ELA** (sq in)		**Attic** (Pa)	**Duct** (Pa)
Untaped											
G B	5824	0.4	23	476.8	0.640	0.99946	0.68	328.1		37.08	1.90
P A	3360	1.4	47	199.9	0.721	0.99457	0.33	154.0		44.89	1.00
T H	1830	0.2	4	149.1	0.641	0.99990	0.49	102.8		48.11	1.27
Taped											
G B	5672	0.1	6	467.9	0.638	0.99995	0.66	321.1		38.86	26.21
P A	3139	1.4	44	203.3	0.700	0.99379	0.33	152.0		46.66	39.59
T H	1748	0.5	9	141.7	0.642	0.99898	0.47	97.9		48.02	37.22
	% Error of CFM@50 is a prescribed output of the CSGB Standard 149.10-M86										

TABLE 2—*Calculated Duct-Leakage: Modified Subtraction Compared to GSCA*

	@ 50 Pa			Duct-Leakage							
				Modified Subtraction				GSCA			
	Attic Pressure – Duct Pressure		Attic Pressure	SCF	CFM 50	CFM @ 25 Pa		SCF	P_{D25}	CFM @ 25 Pa	
	Untaped (Pa)	Taped (Pa)	Change (Pa)	*	*	**	† Error Estimate		‡ (Pa)		† Error Estimate
G B	35.18	12.65	1.78	2.611	397	253	39	2.180	17.59	262	51
P A	43.89	7.07	1.77	1.564	346	220	47	1.502	21.95	175	71
T H	46.84	10.80	-0.09	1.701	139	89	9	1.708	23.42	97	15

* Duct-leakage is assigned to 50 Pa even though Modified Subtraction does not use or require the measurement of the actual pressure-difference between the ducts and the attic.

** Since Modified Subtraction is not designed to estimate duct-leakage at any pressure besides 50 Pa, the number in this column is the CFM @ 50 Pa flow multiplied by $(25/50)^{0.65}$. It is displayed for comparison with the GSCA results.

† The error estimates listed in this table are not provided by either duct-testing theory. They are given here for comparison purposes only and merely "predict" an over-estimate of the size of the error propagated from the house-leakiness data into the duct-leakage results, assuming that each of the theories has no other source of error.

‡ *SCF* is calculated at P = 25 Pa. GSCA then adjusts P to $25*(25/P_{D25})$ to calculate the duct-leakage @ 25 Pa displayed in the next column.

This comparison reveals that:

1. GSCA usually calculates a lower *SCF* than Modified Subtraction.
2. GSCA's calculation of duct-leakage at 25 Pa is raised because P_{D25} is less than 25 Pa.
3. Modified Subtraction and GSCA tend to give similar results because both effects above tend to compensate for each other.
4. Modified Subtraction "predicts" lower errors than GSCA.

The accuracy of both methods depends upon very accurate house-leakiness data.

Acknowledgements

This work was funded by the Louisiana Department of Natural Resources Interagency Agreement No. PVE29-01-12 and the U.S. Department of Energy.

We also wish to acknowledge Gary Nelson of the Energy Conservatory for his helpful comments and extensive insights on the research and procedures presented in this paper.

References

[1] *Minneapolis Blower Door Operation Manual*, The Energy Conservatory, Minneapolis, MN, www.EnergyConservatory.com, December 1993.

[2] ANSI/ASHRAE Standard 136-1993 (RA 2001), *A Method of Determining Air Change Rates in Detached Dwellings,* American Society of Heating, Refrigeration and Air Conditioning Engineers.

[3] CSGB Standard 149.10-M86 (1986), *Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method*, Canadian General Standards Board, Ottawa.

[4] Fitzgerald, J., Nevitt, R., and Blasnik, M., 1994. User-Friendly Pressure Diagnostics, September/October 1994. *Home Energy Magazine*, Berkeley, California.

[5] Nelson, G., Principal and President of The Energy Conservatory, Minneapolis, MN, 612-827-1117, www.EnergyConservatory.com, private communication, 2001.

[6] Witriol, N., Erinjeri, J., Katz, M., McKim, R. and Nassar, R., (August 2003), *Testing HVAC Duct Leakage in Existing Residential Buildings in North Louisiana*, Trenchless Technology Center, Louisiana Tech University.

[7] Sherman, M. H.; and Grimsrud, D. T., "Infiltration-Pressurization Correlation: Simplified Physical Modeling," *ASHRAE Transactions*, Vol. 86, No. 2, 1980, pp. 778-807; Lawerence Berkeley Laboratory Report LBL-10163.

[8] *Automated Performance Testing Manual*, The Energy Conservatory, Minneapolis, MN, www.EnergyConservatory.com, 2000.

[9] Modera, M. P., "Field Comparison of Alternative Techniques for Measuring Air Distribution System Leakage," *Airflow Performance of Building Envelopes, Components, and Systems*, *ASTM STP 1255*, M. P. Modera and A.K. Persily, Eds., ASTM, Philadelphia, 1995, pp. 284-298.

[10] *Using a Pressure Pan to Diagnose Duct Leakage*, The Energy Conservatory, Minneapolis, MN, www.EnergyConservatory.com, 2000.

[11] *Minneapolis Duct Blaster (Series B) Operation Manual*, The Energy Conservatory, Minneapolis, MN, www.EnergyConservatory.com, 12th Ed. September 2000.

[12] Sherman, M. and Palmiter, L., "Uncertainties in Fan Pressurization Measurements", *Airflow Performance of Building Envelopes, Components, and Systems*, *ASTM STP 1255*, M. P. Modera and A.K. Persily, Eds., ASTM, Philadelphia, 1995, pp. 266-283.