Air and Pollutant Transport from Attached Garages to Residential Living Spaces – Literature Review and Field Tests

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Abstract

The National Institute of Standards and Technology (NIST) is conducting a study on the indoor air quality (IAQ) impacts and engineering solutions related to the transport of pollutants from attached garages to residential living spaces. Natural or fan-induced pressure differences across air leakage paths in house-garage (HG) interfaces can result in the transport of the contaminants generated in garages into adjacent living spaces. This paper summarises a literature review on the transport of pollutants from garages to residential living spaces and describes a field study to estimate the range of airtightness of attached garages and of HG interfaces in the United States.

Although the body of literature on pollutant transport from attached garages to residential buildings is limited, the studies reviewed provide substantial evidence that transport of contaminants from garages has the potential to negatively impact residential IAQ in either an acute (e.g., carbon monoxide from automobiles) or chronic manner (e.g., storage of chemical products). However, the literature contains few answers on issues such as the airtightness and geometry of the HG interface, the impact of heating and cooling equipment in the garage, and the effectiveness of potential engineering solutions.

To address one gap in understanding these issues, the airtightness of garages and HG interfaces was measured in five residences using fan pressurisation. While the small sample of houses limits generalisation of the results, a range of house ages, styles, and sizes was included. For all homes tested, the garage was found to be at least twice as leaky as the house, based on air change per hour at 50 Pa. The leakiness of the garage envelope, based on surface area normalised effective leakage area at 4 Pa (ELA_4/SA), ranges from a high of nearly eleven times to a low of two and a half times that of the house exterior envelope leakage. On average, the HG interface was almost two and a half times as leaky as the rest of the house envelope, when based on ELA_4/SA. However, this average is somewhat skewed due to one HG interface measured in this study that is almost eleven times as leaky as the rest of the house envelope. Conversely, a larger Canadian study found HG interfaces to be comparable to house envelopes but found the average garage to be about ten times as leaky as houses – possibly because Canadian houses are consistently tighter than U.S. houses (Fugler et al. 2002).

The knowledge gained from this review and the field study will be used in a simulation study of the potential occupant exposure to pollutants from attached garages and to explore potential engineering solutions to this IAQ problem.

Key words: house-garage interface, attached garage, blower door, indoor air quality, living space, pollutant transport, airtightness.

1. Introduction

Many pollutant sources are commonly stored or used in residential attached garages such as gasoline-fired engines (automobiles, lawnmowers, etc.), paints, and solvents. Pressure differences across air leakage paths between the garage and adjoining living space can result in the transport of these contaminants to the living space. Factors impacting this transport include temperature differences, wind, the placement of the air handler or ducts in the garage, duct leakage, and exhaust fan operation. Although this issue has long been identified in residential indoor air quality (IAQ) studies (Wallace 1987, Traynor and Nitschke 1984, Hawthorne et al. 1986, and Colome et al. 1994), there has not been extensive study to identify key parameters impacting occupant exposure to emissions from sources in attached garages or methods to reduce this exposure.

The objective of this project is to use a multizone model to study the potential for occupant exposure to contaminants transported from residential attached garages. Multizone model simulations will identify important parameters affecting the concentrations in the home and potential methods to reduce occupant exposure.

This report summarises a review of the published literature on the transport of pollutants from garages to residential living spaces and presents the results of a small field study of garage airtightness. These tasks were performed in support of the planned simulation effort.

2. Literature Review

A literature search was conducted on the impact of attached garages on residential IAQ with the objectives of providing a sound base for this research effort and identifying potential case study buildings upon which to base the modelling efforts. The body of published literature on this topic is small. There has been significantly more work published on large, commercial garages including a recent review (Limb 1994). Although there are some issues in common between residential and commercial garages, there are many differences such that this work is not directly relevant to the current effort and thus is not reviewed here.

One of the most significant studies of the transport of contaminants from attached garages to houses was conducted in Canada (Graham 1999, Graham et al. 1999, Noseworthy and Graham 1999). Graham (1999) described measurements performed to characterise the tailpipe emissions of a single car, which was used in later experiments. Graham et al. (1999) reported on the transport of vehicle emissions from attached garages in 16 Canadian houses over two winter seasons. Pollutants measured included carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs) and carbonyl compounds. Two test procedures were followed including a hot soak test (the warmed-up vehicle was parked in the garage in the afternoon) and a cold start test (the vehicle was started in the garage in the morning then backed out of the garage and the garage door was closed). Contaminant monitoring continued for 4 hours for each test procedure. Additionally, sulphur hexafluoride (SF_6) was used as a tracer gas during some tests to estimate garage air change rates. They found strong evidence that IAQ in the homes was influenced by the vehicle emissions with the largest influence observed during morning cold start of vehicles. During cold start tests, the average CO concentration in the garages ranged from 16 mg/m^3 to 298 mg/m^3 over 4 hours, while the average CO concentration in the houses ranged from 0.5 mg/m^3 to 38 mg/m^3. The average CO concentrations in both garages and houses were 2.2 mg/m^3 or less during all hot soak tests. The ratio of house SF_6 concentration to garage SF_6 concentration during both types of test ranged from about 0.2 % to a high of 16 %. However, questions were raised about the accuracy of some SF_6 measurements in the garage, due to potentially incomplete mixing. Significant amounts of VOCs entered the house from the garage, with the increases varying widely depending on the compound, house, and test condition. It was difficult to detect a contribution of the vehicle to carbonyl compounds, due to already significant levels in the houses. Two sets of tests were performed at one house that showed qualitatively greater transport from the garage to the house during colder weather due to a larger stack effect. Although one house consistently showed greater transport of contaminants from the garage to the house, no explanation was offered. Almost no details of the houses (floorplans, construction, HVAC system, etc.) were reported. Estimates of garage air change rates from SF_6 measurements for 4 of the garages ranged from 1.8 h^{-1} to 2.7 h^{-1}. Neither ambient conditions nor garage temperatures were reported for these estimates. Noseworthy and Graham (1999) reported use of a chemical mass balance model to apportion measured VOC concentrations in the houses to their sources (i.e., outdoor air, garage air, and pre-test air). They found that from 10 % to 75 % of the house concentrations were attributable to the garage air depending on the house and test type.

Fugler et al. (2002) summarised the research described above and also briefly described measurements of air leakage from attached garages in 25 houses (a mix of ages, sizes, number of storeys, and configuration of shared house-garage (HG) interface) and a related modelling effort. Researchers tested the airtightness of the HG interface during summer and winter seasons using depressurisation techniques. They found that, normalised by wall surface area, the garages were about 10 times leakier than the houses on average and the HG interface was about equal in leakiness to the rest of the house envelope. However, the ratio of air leakage through the HG interface to the total air leakage into the house had a wide range with a low near zero and a high near 45 %. The pressure difference across the HG interface was also measured during winter and summer conditions. The pressure difference averaged 1.6 Pa during the winter and 0.5 Pa during the summer (both with a higher pressure in the garage than the house). Little detail is provided on a modelling effort that was intended to extend the range of exposure scenarios considered beyond the limited cases that were tested. After a model calibration exercise, the model was used to examine the potential effectiveness of operating a 100 l/s exhaust fan in the garage during the first half hour of an automobile cold start test. The model showed that the exhaust fan was not useful for the typically leaky garages but could limit transport of CO into the house from the tightest garage.

Moore and Kaluza (2002) monitored carbon monoxide, among other parameters, inside 65 homes in four Alaskan cities that were built since the adoption of the Alaska Building Energy Efficiency Standard in 1992 (AHFC 1992). This study observed that, for the majority of homes for which they had data, the house CO reading followed the same temporal pattern as the garage CO. Since the house CO levels tracked garage CO levels, they assumed that most of the CO found in the living space could be attributed to CO produced by cars in the garage migrating into the living space. No other architectural, behavioural, or environmental factor was as strongly associated with elevated CO as garage concentrations. This study also suggests installing a garage mounted exhaust fan as a potential solution to this problem.

Lansari et al. (1996) describes a study predicting pollution concentrations in a residence with an attached garage using an early version of NIST's CONTAM IAQ model. Experiments were also performed in a test house to validate the model. The experiments involved evaporating 5 ml of methanol over a 13-min period in the two-car garage. The garage was located in the back of the house with storage areas in the back of the garage. The attached garage is adjacent to the kitchen and dining room. The floor plan consists of a single level with one bedroom, one bathroom, a living room, family room, and dining room. There was no mention of any HAC equipment or ductwork in the garage. The garage concentrations of methanol were measured every 5 minutes for a period of 90 minutes. One limitation of the study was the lack of measurements of methanol in the remainder of the house. Dispersion of methanol throughout the house was then simulated. Air leakage and ventilation flows in the model were not based on test house measurements. Instead of additional methanol measurements, SF_6 was used to test the model's performance by measuring the percentage of contaminant that infiltrates the house from the garage, determining how rapidly the concentration in the garage drops after the door is opened, and testing the assumption that the garage contaminants were well mixed. The kitchen area adjacent to the garage was predicted to have the highest methanol concentration in the house. The study concluded that the model over-predicted garage methanol concentration during the release period and under-predicted methanol concentrations by about 15 % after evaporation was complete.

Tsai and Weisel (2000) reported a study on the potential transport of methanol, benzene, and toluene into a residence from a methanol-fuelled vehicle parked in an attached garage. The garage was attached at the first floor to a two-storey house. Although the HAC system did not include intentional connections in the garage, it was not reported whether any ductwork was located in the garage. Two ventilation conditions were studied, HAC fan on and off. Other conditions considered included the integrity of the evaporative emissions control, the ambient air temperature, and the fuel tank temperature. Experiments were performed by driving the methanol-fuelled vehicle until warm, then parking it in the garage and shutting both the garage door and the door to the residence. Pollutant concentrations were measured at three sample locations: in the garage, the room adjacent to the garage, and the living room on the other side of the house. The experiments each lasted 3 hours and were performed over 16 sampling days during the summer in New Jersey with each condition pair (ventilation on or off and canister connections on or off) conducted four times. The canister connection was altered to simulate a poorly maintained or spent emission control device. On average, pollutant concentrations in the room adjacent to the garage ranged from one-tenth to one-fifth of the garage concentrations over the 3-hour tests. Concentrations in the living room were about one-third the adjacent room concentrations on average. Differences between concentration ratios for the three pollutants were potentially attributed to sink effects. Due to increased mixing, pollutant concentrations in the adjacent room were lower when the HAC fan was on than when it was off, while the average concentrations in the living room were higher. The ambient air temperature had no effect on concentrations, but only varied over a limited range from 24 °C to 32 °C during the tests. An interesting observation was a sharp rise in the adjacent room concentrations near the end of the test coinciding with a sharp drop in garage concentrations due to garage door opening.

Marr et al. (1998) and Nazaroff et al. (1996) reported a modelling study of the risk of accidental death due to CO poisoning from automobiles in residential garages. The study employed a Monte Carlo simulation technique and looked at 1 h and 3 h scenarios of CO emissions in either a 90 m^3 (two-car garage) or a 400 m^3 (single-family house with garage) well-mixed enclosure. CO emission rates were based on a distribution using measured California data, and whole house air change rates were based on a distribution from a study of U.S. housing. Due to the lack of reported garage air change rates, the garage air change rate distribution was assumed to range from the same as the house air change rate distribution up to 3 times the house air change rate distribution. A model for blood carboxyl-haemoglobin (COHB) was used to determine the risk of fatality from the predicted CO concentration data. The authors found no risk of death from the 1 h exposure in the house scenario but a risk ranging from 3.5 % to 21 % for the other scenarios. A CO emission rate of 1 g/min was reported to be an approximate threshold for causing accidental deaths from CO poisoning.

Kaluza (1999) provides an overview of the issues involved in the transport of pollutants from attached garages. Issues discussed include contaminant sources in garages, stack effect, “tuck-under” garages, furnaces and ductwork in garages, airtightness of walls between houses and garages, and house depressurisation due to exhaust fans. Kaluza tested one residence in Alaska using CO generated by a car in the garage. The garage was a tuck-under design with no heating appliance located in it. A CO peak about one-tenth of the peak in the garage was measured in the house and occurred about 5 hours after the garage peak. Operation of a whole-house ventilation system caused a 50 % reduction in the peak CO level in the home. Operation of a garage exhaust fan to maintain a slight negative pressure in the garage relative to the house prevented CO from entering the house.

Greiner and Schwab (1998) describe the investigation of CO contamination of a home from a source in the garage (combustion engine vehicle startup). They measured various home appliances, heating equipment, and a fireplace for CO emission to determine the source(s) of the elevated CO concentrations found in the house, none of which were found to be the sources. Blower door and other tests were used to characterise the house, the garage, and the house-garage interface. Blower door tests revealed a large proportion (over 40 %) of the air entering the house came from the garage. From pressure measurements, smoke tests, and a tracer gas test, startup of the homeowner’s car was found to be the only source of CO. When first started, the vehicle produced high concentrations of CO (102,000 mg/m^3). The CO was pulled into the living space due to the high pressure of the garage relative to the house. This study also found that a variable speed garage exhaust fan with measured flow of 131 l/s maintained a negative pressure of 4.0 Pa in the garage relative to the house and was effective at preventing CO transport from the garage into the house.

A study by Minnegasco (1997), a natural gas utility, consisted of monitoring houses in the greater Minneapolis area where two or more carbon monoxide complaints had been investigated by technicians who were unable to identify the CO source. This study found CO transport from attached garages accounted for 74 % of the potential CO sources in study homes, based on an evaluation of the houses and CO events including consideration of the timing of the events, depressurisation tests, CO production from appliances, and measurements of pressures between the house and garage. It was found that the average air leakage from the garage to the homes was over 25 % of the total house leakage. Along with the stack effect, this leakage played a key role in CO migration into the houses. Extensive data logging of some of the homes showed complex interactions between pressure boundaries, vent connectors, and the main vent, thus making further testing necessary.

Thomas et al. (1993) conducted indoor, personal, and outdoor monitoring of benzene exposure at eleven homes in New Jersey over multiple 12-hr periods. A major finding of this study is that the concentrations of a majority of the VOCs found in indoor air exceeds those measured in outdoor air. This study also found mean benzene concentrations in the garages two to fifteen times higher than outdoor air levels and two to three times higher than main living area concentrations in three of the four homes having attached garages. Indoor benzene levels at homes that did not have attached garages were not elevated far above outdoor levels during most monitoring periods. Data from this study suggests that, under some conditions, an attached garage can introduce as much or more benzene into a home's living areas as other indoor sources, such as tobacco smoke. However, since only a few homes could be monitored extensively, the authors cautioned that the results here could not be used to make inferences to the general population.

Mann et al. (2001) recently reported a study on the transport of benzene from automobiles in attached garages in five homes in the United Kingdom. Concentration measurements were made in the house (living room, main bedroom, and room above the garage), in the garage, in the car, and outdoors. In the four homes that had cars parked at least some of the time in the attached garage, garage concentrations of benzene averaged at least 25 times the outdoor level. Concentrations in the houses were much lower than in the garages but still averaged at least several times the outdoor concentration.

2.1 Summary of Literature Review

The primary goal of the literature review was to support a planned simulation study on the transport of pollutants from attached garages to the living spaces of homes. Although the body of literature on the pollutant transport from attached garages to residential buildings is small, the studies reviewed provide a good overview of the issues on which to base the NIST research effort. There is substantial evidence that transport of contaminants from garages has the potential to negatively impact residential IAQ in either an acute (e.g. CO from cold starting a vehicle) or chronic manner (e.g. VOCs from storage of household chemical products). Many questions are raised including the leakage of the HG interface, presence of heating and cooling equipment and ductwork in the garage, significance of the potential contaminant sources in the garage, and the role of potential IAQ control options.

One conclusion drawn from this literature review is that additional measurements in houses with attached garages are needed prior to undertaking the simulation effort. These measurements will supplement the data characterising garage airtightness and the house-garage interface. Another conclusion is that the simulation effort should be focused on the air flow modelling of the house rather than the contaminant sources. The literature reveals that the potential source types and strengths in garages vary widely and the resources are not available to adequately study them in detail. However, contaminant modelling will be included to illustrate the potential impact of the air flows on contaminant concentrations.

Table 1. Building description summary.

Building	A	B	C	D	E
Year Built	1964	1988	1908	1995	1968
Type	Single-Fam.	Townhouse-middle unit	Single-Fam.	Single-Fam.	Single-Fam.
Garage Type	Adjacent	Tuck-under	Adjacent	Tuck-under	Adjacent
House-Garage Shared Surfaces, #	1	3	1	3	2
House Floor Area, m^2	150	140	420	190	160
Garage Floor Area, m^2	49	17	54	20	21
House Envelope Surface Area, m^2	280	140	370	340	330
Garage Envelope Surface Area, m^2	98	7.4	120	29	83
HG Interface Surface Area, m^2	22	38	22	45	27

3. Field Study

This section describes a small field study conducted on five homes located in the Washington D.C. metropolitan area. The purpose of this study is to supplement the data in the literature on the airtightness of garages and house-garage interfaces. The data will serve to establish a range of conditions for a planned simulation study.

In this study, four single-family homes; buildings A, C, D, and E, and one townhouse; building B, were tested. Buildings B and D have tuck-under garages (i.e. adjacent and under living spaces), while the remaining buildings have garages adjacent to the living spaces. A summary of the building descriptions for the five buildings including floor areas and envelope surface areas can be found in Table 1.

3.1 Method

Pressurisation tests were conducted on the houses to measure the leakage of the house, garage, and the HG interface using various configurations to target specific zones and boundaries. The pressurisation tests were generally conducted according to ASTM Standard E 779-99 (ASTM 1999) using blower doors. Three configurations were used with buildings B, C, D, and E while five configurations were used with building A. The three configurations used on each of the three houses and one townhouse, shown in Figure 1, are as follows:

1. Blower door in the living space with the garage door open;
2. Blower door at the house-garage interface with the living space doors open;
3. Blower door in the living space with the HG interface door open.

In the figure and the analysis, each building is represented as two zones; a house zone and a garage zone separated by the house-garage interface. Arrows indicate the location of the blower door for each test and the direction of the air flow from the

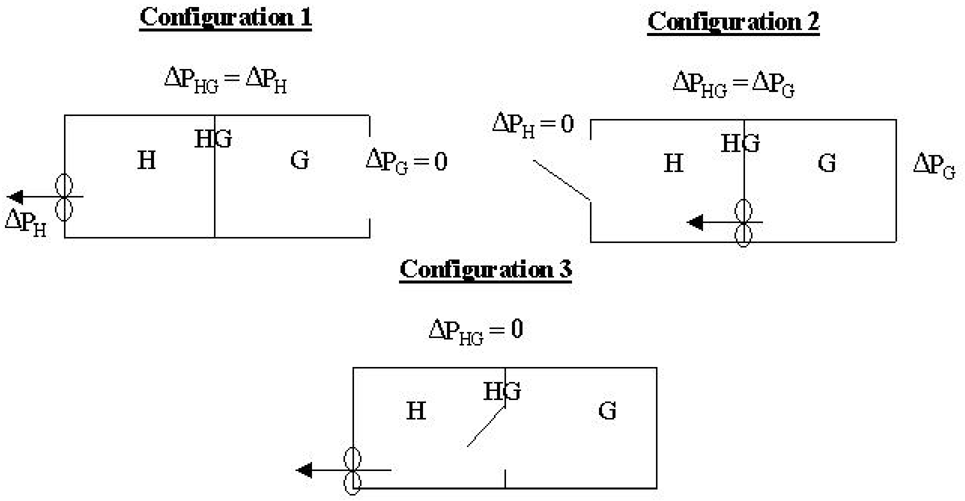

Figure 1. Blower door configurations for buildings B, C, D, and E.

Symbol Legend for Figures and Equations

H – exterior envelope of house (living space)
H' – house exterior envelope and HG interface combined (H+HG)
G – exterior envelope of garage
G' – garage exterior envelope and HG interface combined (G+HG)
HG – HG interface
$\mathbf{Q}_{\# \text{ or } L}$ – Airflow rate from blower door in configuration # or for surface designation (L)
$\mathbf{\Delta P}_{\# \text{ or } L}$ – Pressure difference across a surface
$\mathbf{C}_{\# \text{ or } L}$ – flow coefficient for $Q_{\# \text{ or } L}$
$\mathbf{n}_{\# \text{ or } L}$ – flow exponent for $Q_{\# \text{ or } L}$

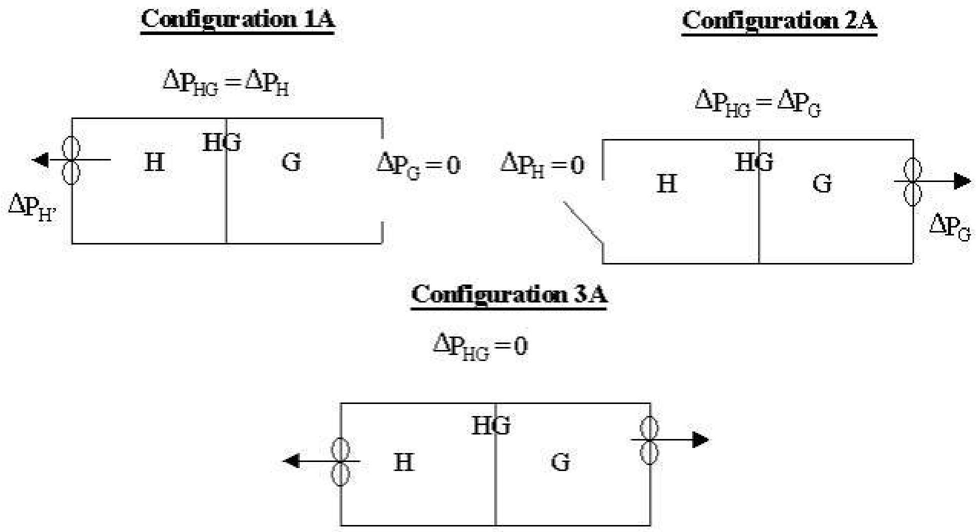

Figure 2. Blower door configurations for building A.

blower. The pressure difference, ΔP_{HG}, is the pressure difference across the house-garage interface. The pressure differences across the living space exterior envelope for the respective test configurations are designated as ΔP_H, while ΔP_G designates the pressure differences across the garage exterior envelope at the respective test configurations.

For building A, the blower door configurations are different because of an exterior door located in the garage. This extra door allows for the use of a blower door in the garage in addition to the blower door located in the house. The three configurations used on building A, shown in Figure 2, are as follows:

1A Blower door in the living space with the garage door open (same as configuration 1 in Figure 1);

2A Blower door in the garage with the living space doors open;

3A One blower door in the living space and a second blower door in the garage.

3.2 Analysis

For each blower door test, measured air flows were recorded at four to seven pressures ranging from 10 Pa to 70 Pa (not all spaces could be pressurised to 70 Pa). The air flows and pressures are related via a power law equation: $Q = C\,(\Delta P)^n$. The air flow and pressure data from each blower door test is logarithmically transformed and fitted with a linear regression, yielding the flow coefficients and flow exponents for each scenario. A sample plot of typical data is illustrated in Figure 3 for configurations 1 and 3 in Building E. These coefficients and exponents are then used to calculate various leakage parameters for each of the buildings. Also, from the blower door data and conservation of mass equations, effective leakage areas (ELA's) are calculated for all of the distinct interfaces (house and garage envelopes and the house-garage interface) for each of the houses. Error analysis and confidence intervals are also calculated for all the parameters and the blower door data, as prescribed in the ASTM standard 799-99 (ASTM 1999).

Calculations for the envelope and house-garage interface parameters for building A are different than those for buildings B, C, D, and E due to the different blower door test configurations performed on building A (see Figure 2). The calculations for building A are described first.

For test 1A, depressurising the living space (H), while the garage door is open, effectively changes the garage space to an ambient zone. The house zone is bounded by the exterior envelope surfaces of the living space and the HG interface surface. The reverse is performed for the garage in test 2A, in which the garage zone is bounded by the exterior

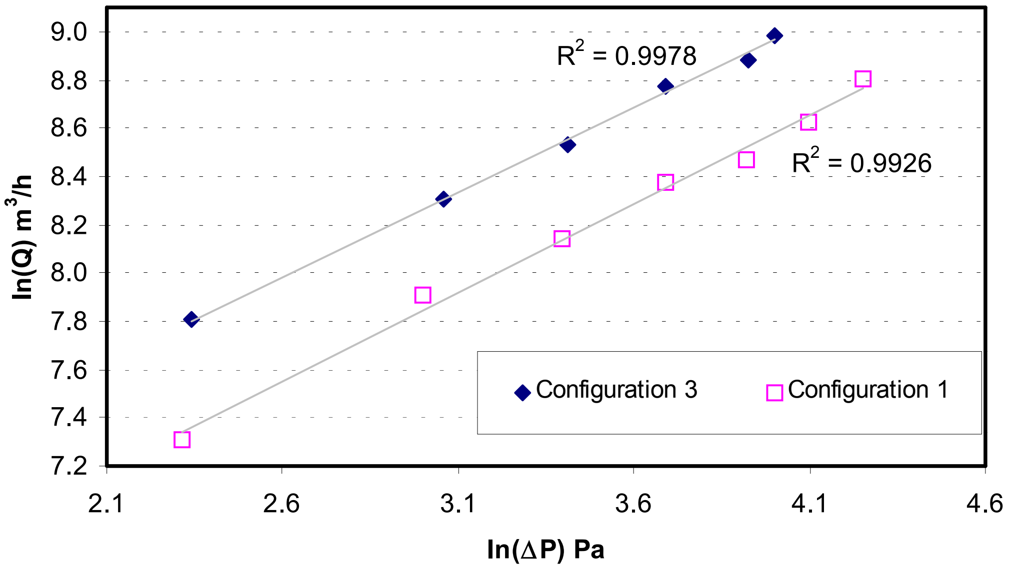

Figure 3. Sample plot of blower door test of building E for two test configurations.

envelope surfaces of the garage and the HG interface surface. Test 3A consists of two blower doors simultaneously operating, one in the living space and another in the garage. The pressure difference across the house-garage interface is monitored with both fans operating. The pressures in both zones relative to the ambient are raised at multiple points while the monitored pressure difference across the HG interface is held at approximately zero as measured by a digital micro-manometer. This effectively eliminates air flow through the HG while the two blower doors separately yield the flows and pressures for H' and G'.

Using continuity equations, the power law orifice equation, and Bernoulli's equation, the ELA's for the exterior envelopes of the living space and the garage, as well as the ELA for the HG interface is calculated. The flow coefficient and flow exponent, C_H and n_H are produced from the linear regression to the data from the blower door positioned in the living space during the simultaneous blower test (test 3A). The coefficient and exponent, C_G and n_G, are produced from the linear regression to the data from the blower door positioned in the garage during the simultaneous blower test (test 3A) also. The flow coefficients and exponents, $C_{G'}$, $n_{G'}$, $C_{H'}$, and $n_{H'}$, are obtained from the linear regressions to the data from tests 2A and 1A respectively. Corresponding errors at 95% confidence are also obtained from the regressions as described in ASTM Standard 779-99. The effective leakage areas for the exterior envelopes of the living space and the garage, subscripted H and G respectively, are calculated per equation (1):

$$ELA = \frac{C \cdot \Delta P^{n}}{\sqrt{\left(2 \cdot \Delta P / \rho\right)}} \qquad (1)$$

where C = the flow coefficient for surface H or G, n = the flow exponent for surface H or G, ΔP = the reference pressure difference, and ρ = the density of air at standard conditions.

To solve for the ELA of the HG interface, continuity equations at a reference pressure of 25 Pa combined with the orifice equation are solved for both the house zone and the garage zone. The reference pressure of 25 Pa is chosen as opposed to 4 Pa, which is often used in ELA calculation, with the intent to eliminate errors associated with extrapolating values from outside the range of the experimental data. The pressure of 25 Pa is approximately midrange of the blower door data for this building, thus it is used as the reference pressure for this part of the calculation. The equation can be written as two different yet equal expressions:

$$Q_{HG,25} = Q_{G',25} - Q_{G,25} = C_{G'} \cdot (25)^{n_{G'}} - C_G \cdot (25)^{n_G} \tag{2}$$

$$Q_{HG,25} = Q_{H',25} - Q_{H,25} = C_{H'} \cdot (25)^{n_{H'}} - C_H \cdot (25)^{n_H} \tag{3}$$

where $Q_{HG,\,25}$ = the air flow rate of the HG interface at 25 Pa.

Assuming a flow exponent of 0.65 for the HG interface, the flow coefficient at this interface is found from:

$$C_{HG} = \frac{Q_{HG,25}}{(25)^{0.65}} \tag{4}$$

This coefficient is solved two ways, one using the G' – G equation and one using the H' – H equation. Analytically, the two values for the coefficient should be identical. From the calculated value of C_{HG}, the ELA of the HG interface at any reference pressure, ELA_{HG}, can be calculated from Equation 1.

This ELA value is also calculated two ways, one using C_{HG} derived from equation (2) and one from equation (3). The reported ELA_{HG} is the average of the two values. Errors in the ELA values, at 95 % confidence intervals, are also propagated through these calculations from the errors in the flow coefficients and exponents obtained from the linear regressions.

Calculations for the remaining buildings, B, C, D, and E, are also based on continuity, ELA, and power law orifice equations. The exterior envelope surfaces of the living space and the garage are again designated H and G respectively, and the house-garage interface is again designated HG. Applying the law of conservation of mass and the power law orifice equation, yields a three by three matrix of air flow rates:

$$Q_1 = C_1 \cdot \Delta P^{n_1} = Q_H + Q_{HG} \tag{5}$$

$$Q_2 = C_2 \cdot \Delta P^{n_2} = Q_G + Q_{HG} \tag{6}$$

$$Q_3 = C_3 \cdot \Delta P^{n_3} = Q_G + Q_H \tag{7}$$

Here, C_1 and n_1 are the flow parameters obtained from the data for blower door test 1, C_2 and n_2 are obtained from the data for test 2, and C_3 and n_3 are obtained from the data for test 3. With three equations and three unknowns, this matrix can be solved for Q_H, Q_G, and Q_{HG}, all at a specific reference pressure across surfaces H, G, and HG. Using these three air flow rates, the zone envelope and HG interface ELA's are calculated at the same reference pressure using the same ELA equation used with building A:

$$ELA_H = \frac{Q_H}{\sqrt{\left(2 \cdot \Delta P \big/ \rho\right)}} \tag{8}$$

Again, errors in the ELA values, at 95 % confidence intervals are also propagated through these calculations from the errors in the flow coefficients and exponents obtained from the linear regressions that were applied to the blower door data.

3.3 Results

Table 2 summarises the leakage of the house-garage interface, and its relative magnitude to the house and garage envelope leakages and other results. The average air change rate at 50 Pa (ACH_{50}) for the living space of the five homes in this study is 9.6 h^{-1}, with a range from 5.6 h^{-1} to 12.5 h^{-1}. For the garage, the average ACH_{50} is 48.4 h^{-1} with a range from 20.8 h^{-1} to 106 h^{-1}. The average effective leakage area at a reference pressure of 4 Pa (ELA_4) for the house exterior envelope is 736 cm^2 with a standard deviation of 169 cm^2, with a range from 491 cm^2 to 917 cm^2.

For the garage exterior envelope, the average ELA_4 and standard deviation are 1220 cm^2 and 1440 cm^2. The corresponding range of ELA_4 is from 64 cm^2 to 3430 cm^2. For the HG interface, the average and range of ELA_4 is 157 cm^2 and from 33 cm^2 to 446 cm^2 respectively.

A method for comparing leakages of different buildings is to normalise the ELA_4 by the surface area associated with the leakage, designated as ELA_4/SA. For the house exterior envelope, the average and standard deviation for the ELA_4/SA is 2.54 cm^2/m^2 and 0.57 cm^2/m^2 respectively. Average ELA_4/SA for the garage exterior envelope is 13.8 cm^2/m^2 with a standard deviation of 15.1 cm^2/m^2. The average and standard deviation of the ELA_4/SA for the HG interface is 5.91 cm^2/m^2 and 8.10 cm^2/m^2

Table 2. House and Garage Envelope Leakage Summary

Building	A	B	C	D	E	Average	σ
$ACH_{50,H}$ (h^{-1})	11.6	11.1	7.6	5.6	12.5	9.6	2.9
±Δ (h^{-1})	-----	1.0	1.2	0.8	1.8		
$ACH_{50,G}$ (h^{-1})	106	26.8	36.7	20.8	51.5	48.4	38
±Δ (h^{-1})	-----	0.9	5.2	1.1	4.6		
$ELA_{4,H}$ (cm^2)	917	491	885	756	811	736	169
±Δ (cm^2)	100	9	98	19	22		
$ELA_{4,G}$ (cm^2)	3430	64	1893	166	540	1220	1440
±Δ (cm^2)	454	9	98	19	22		
$ELA_{4,HG}$ (cm^2)	446	114	90	103	33	157	165
±Δ (cm^2)	154	9	98	19	22		
$(ELA_4/SA)_H$ (cm^2/m^2)	3.00	1.71	3.09	2.64	2.24	2.54	0.57
±Δ (cm^2/m^2)	0.44	0.17	0.46	0.27	0.23		
$(ELA_4/SA)_G$ (cm^2/m^2)	28.6	1.08	31.79	2.79	4.81	13.8	15.1
±Δ (cm^2/m^2)	4.75	0.18	3.58	0.42	0.52		
$(ELA_4/SA)_{HG}$ (cm^2/m^2)	20.4	2.97	2.35	2.67	1.20	5.91	8.10
±Δ (cm^2/m^2)	7.32	0.37	2.56	0.56	0.81		
NLA_{G-H}	9.5	0.63	10.3	1.1	2.2	4.7	3.8
NLA_{HG-H}	6.8	1.7	0.76	1.0	0.5	2.6	0.8

respectively. The relatively large standard deviations of the ELA_4 and ELA_4/SA for the three surfaces can be attributed to building A, which when compared to the rest of the homes, appears to be very leaky in all respects.

To quantify the amount of leakage of the garage envelope relative to the living space envelope and the HG interface relative to the living space envelope, two parameters are used: NLA_{G-H} ratio and NLA_{HG-H} ratio. The NLA_{G-H} ratio is the garage ELA_4 normalised by the garage envelope surface area divided by the living space ELA_4 normalised by the house envelope surface area. The NLA_{HG-H} ratio is the HG interface ELA_4 normalised by the surface area divided by the living space ELA_4 normalised by the house envelope surface area. The average and standard deviation of the NLA_{G-H} is 4.7 and 3.8 respectively. For NLA_{HG-H}, the average and standard deviation is 2.6 and 0.8 respectively.

4. Conclusions

As a reference point, these results are compared to a similar set of data from 25 homes in Canada (Fugler et al. 2002). Garage airtightness for the Canadian homes average about 47 h^{-1} at 50 Pa with a range from 11 h^{-1} to 97 h^{-1}, while the five homes studied here average 48 h^{-1} with a range from 20 h^{-1} to 100 h^{-1}. These reported values for both studies are consistent. Fugler also reported a range of house-garage interface ELA's from 4 cm^2 to 400 cm^2 with an average of 140 cm^2. This study shows a range of HG interface ELA's from 33 cm^2 to 450 cm^2 with an average of 160 cm^2. This study indicates the house-garage interface and the rest of the house envelope, when normalised by surface area, are similar for 4 of the 5 houses. Fugler also found this observation, which serves to confirm the reasonableness of this study's results. A difference between this study and that by Fugler et al. is that homes in Canada are typically tighter than homes in the U.S.

Sherman and Dickerhoff (1998) found for 12,902 homes throughout the U.S., the average ACH_{50} is 29.7 h^{-1} with a range from 0.47 h^{-1} to 83.6 h^{-1}. While the average (9.6 h^{-1}) ACH_{50} for the five houses in this study is significantly lower than that reported by Sherman and Dickerhoff, the values measured in this study are well within their range.

However, a few conclusions may be drawn for the buildings in this study. Of the five buildings examined here, the garages are never as tight as the living space. Here, the garages were all at least twice as leaky as the living spaces, as indicated by the measured ACH_{50}. This is also the case when looking at the surface area normalised ELA's of the house and garage exterior envelopes. If the very leaky building A is ignored, the older houses generally tend to be leakier than newer homes, possibly indicating age as a factor in residential building airtightness.

The five houses tested vary in garage type, size, and use. This large variation carries through with the results, demonstrating that garages are used for many different purposes; they can be nearly anything. One of the garages (that of building E) was previously a living space, while another garage (that of building D) was originally used as an office by the builder. The garage envelopes in these buildings may be purposefully tighter than is generally the case as they have lower ELAs as normalised by surface area (ELA/SA). On the other hand, one garage (that of building A) is a converted carport, which could explain why it is extremely leaky. Some garages examined in this study are finished and have weather stripping while others have exposed studs with visible leaks. This wide variation in garage construction and use, considered along with the variation in leakage parameter values, suggests more extensive field measurements and simulation are needed.

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