NISTIR 7072

Air and Pollutant Transport from Attached Garages to Residential Living Spaces

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ABSTRACT

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 equipment-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 summarizes 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 a sample of U.S. homes.

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 more questions than 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.

In order to address one gap in understanding these issues, the airtightness of garages and HG interfaces was measured in five residences using fan pressurization. While the small sample of houses limits generalization 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 changes per hour at 50 Pa. The leakiness of the garage envelope, based on surface area normalized 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 leakier than 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 leakier than 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 leakier than the 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 associated IAQ problems.

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

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Background

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 influencing this transport include temperature differences, wind, the placement of the air handler or ducts in the garage, duct leakage, and equipment operation, such as exhaust fans and vented combustion appliances. Although this issue has long been identified in residential indoor air quality (IAQ) studies (Wallace 1987, Traynor and Nitschke 1984, Hawthorne et al. 1986, Lindstrom et al. 1995, Colome et al. 1994, Levsen et al. 1999, Lebowitz et al. 1999 and Brown 2002), 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 summarizes 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.

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 modeling efforts. The body of published literature on this topic is small and only reports that treated the topic in detail were reviewed. Note that there has also been 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 commercial building 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 characterize 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 h for each test procedure. Additionally, sulfur 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 h, while the average CO concentration in the houses ranged from 0.5 mg/m^3 to 38 mg/m^3 (note: 1.0 mg/m^3 = 0.86 ppm(v)). The average CO concentrations in both garages and houses was 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, heating and cooling 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) used 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) summarizes the research described above and also briefly describes measurements of air leakage from attached garages in 25 houses (a mix of ages, sizes, number of stories, and configuration of shared house-garage (HG) interface) and a related modeling effort. Researchers tested the airtightness of the HG interface during summer and winter seasons using depressurization techniques. They found that, normalized 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 summer and winter conditions. The pressure difference averaged 1.6 Pa during the winter and 0.5 Pa during the winter (both with a higher pressure in the garage than the house). Little detail is provided on a modeling 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, behavioral, 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 min for a period of 90 min. 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 enters 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 concludes 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 on a study on the potential transport of methanol, benzene, and toluene into a residence from a methanol-fueled vehicle parked in an attached garage. The garage was attached at the first floor to a two-story 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-fueled 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 h and were done 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 h tests. Concentrations in the living room were about one-third the adjacent room concentrations on average. The authors cited sink effects as a potential reason for differences between concentration ratios for the three pollutants. 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 the garage door opening. In an earlier pilot study, Weisel and Lawryk (1993) also measured transport of methanol and benzene from a garage to an adjacent room, but little detail was provided.

Marr et al. (1998) and Nazaroff et al. (1996) both reported a modeling 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-hemoglobin (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 (i.e., a garage located both below and adjacent to living space), furnaces and ductwork in garages, airtightness of walls between houses and garages, and house depressurization 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 h 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 of unspecified capacity to maintain a very slight negative pressure in the garage relative to the house (1 Pa) prevented CO from entering the house.

Furtaw et al. (1993) reported a measurement and modeling study of the potential exposure in residences to evaporative emissions of benzene from gasoline-fueled vehicles parked in attached garages. Measurements of benzene concentrations and air change rates based on tracer gas tests were made in several homes although very little detail was reported on the houses, garages, internal conditions and ambient conditions during the tests. They reported garage air change rates ranging from 0.3 h^{-1} to 1.5 h^{-1} with closed garage doors, garage air change rates ranging from 17 h^{-1} to 103 h^{-1} with open garage doors, and house air change rates ranging from 0.5 h^{-1} to 0.8 h^{-1}. They also found that about 1 % of the air entering the house came from the garage during warm weather compared to 8 % to 9 % during cool weather. A simple two-zone (i.e., the living space and the garage) mass balance model was also developed with an evaporative benzene source dependent on the ambient temperature. Two cases were modeled – a winter case with house and garage air change rates constant at 0.5 h and 10 % of the house air entering from the garage and a summer case also with garage and house air change rates of 0.5 h but with only 1 % of the house air entering from the garage. In this example case, calculated average benzene concentrations were much higher in the garage during the summer (240 $\mu g/m^3$ in summer vs. 70 $\mu g/m^3$ in winter) but were higher in the house during the winter (6 $\mu g/m^3$ in winter vs. 2 $\mu g/m^3$ in summer). Based on the study, the authors recommend ventilating the garage to the ambient by some means although specific amounts of ventilation are not recommended. One alternative suggested is for occupants to leave the garage door open after parking a vehicle.

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 characterize 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) at the tailpipe. The CO was pushed into the living space due to the high pressure of the garage relative to the house. This study also found that a garage exhaust fan with a 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. Since operation of the garage exhaust fan also caused depressurization of the house and raised concerns about water heater vent backdrafting, a 150 mm combustion air/make-up air opening was added to the house and a powered induced-draft fan blower, with safety shut-off, was added to the water heater.

A study by Wilber and Klossner (1997) for 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 was a potential CO source in 74 % of the study homes based on an evaluation of the houses and CO events including consideration of homeowner interviews, the timing of the events, depressurization tests, CO production from appliances, and measurements of pressures between the house and garage. However, 30 % of the homes were found to have multiple potential CO sources. 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.

Thomas et al. (1993) conducted indoor, personal, and outdoor monitoring of benzene exposure at eleven homes in New Jersey over multiple 12 h 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 suggest that under some conditions, an attached garage can introduce as much or more benzene into a home's living areas as the other indoor sources, including tobacco smoke. However, since only a few homes could be monitored extensively, the authors cautioned that the results here couldn't 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.

Summary

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 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 simulation 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, potential contaminant sources in the garage, and 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 characterizing garage airtightness and the house-garage interface. Another conclusion is that the simulation effort should be focused on the airflow modeling of the house and garage rather than the contaminant sources. The literature reveals that the potential source types and strengths in garages vary too widely to adequately study them in detail. Also, one can assume that any significant airflow into the living space from an attached garage is undesirable, and therefore, that airflow is more important than any particular source or source strength. However, contaminant modeling will be included to illustrate the potential impact of the airflows on contaminant concentrations.

Field Study

This section describes a small field study of 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.

Houses

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.

Building A is a split-level single family home with the attached garage adjacent to one wall of the living space. This building was constructed in 1964, and has the heating and air-conditioning (HAC) equipment and ductwork located in the basement and crawlspace respectively. The garage has three openings (two doors and a window) to the outside, in addition to the garage door, and is a converted carport.

Building B is a middle unit, three-level townhouse built in 1988. This building has a finished tuck-under garage that takes up part of the lowest level, and shares three surfaces with the living space. Due to the tuck-under design, the garage has only one side exposed to the outdoors. One of the sidewalls is shared with the unit next door while the remaining two sidewalls are shared with the living space. The garage ceiling is also shared with the living space of the level above. The lowest level is thermally conditioned living space. Both the HAC equipment and the ductwork are located in the living space.

Building C is a single-family home built in 1908 that has a basement and an attic in addition to two main levels. The HAC equipment is located in the basement while the ductwork is located in the living space and the attic. The garage is unfinished and is adjacent to the living space, sharing one surface with the living space.

Building D is a single-family home with a tuck-under garage built in 1995. This building consists of two floors and a basement, which is mostly below grade. The HAC equipment is located in the basement and the ductwork is in the living space. The garage shares three surfaces with the living space. The garage is finished and was previously used by the builder as an office.

Lastly, building E is a single level single-family home built in 1968. The garage is adjacent to the living space, sharing two surfaces with the living space and one surface with a laundry/furnace room that extends out from the living space. The garage was formerly used as a living space.

Table 1. Building Description Summary

Building	A	B	C	D	E
Year Built	1964	1988	1908	1995	1968
Type	Single-Fam. split level	Townhouse-middle unit	Single-Family	Single-Family	Single-Family
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

Method

Pressurization 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 pressurization 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 two different 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 airflow from the 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 each test configuration are designated as ΔP_H, while ΔP_G designates the pressure differences across the garage exterior envelope.

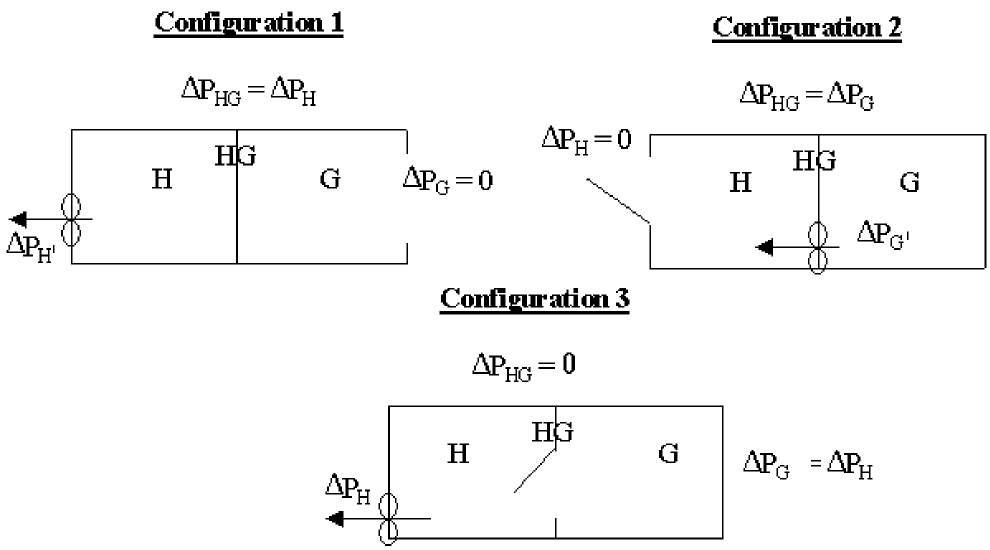

Figure 1 Test Configurations for Buildings B, C, D, and E

<u>Symbol Legend for Figures and Equations</u>

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

$\mathbf{Q}_{\#\ \mathbf{or}\ \mathbf{L}}$ – Airflow rate from blower door in configuration # or for surface designation (L)

$\mathbf{\Delta P}_{\#\ \mathbf{or}\ \mathbf{L}}$ – Pressure difference across a surface

$\mathbf{C}_{\#\ \mathbf{or}\ \mathbf{L}}$ – flow coefficient for $Q_{\#\ or\ L}$

$\mathbf{n}_{\#\ \mathbf{or}\ \mathbf{L}}$ – flow exponent for $Q_{\#\ or\ L}$

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 .

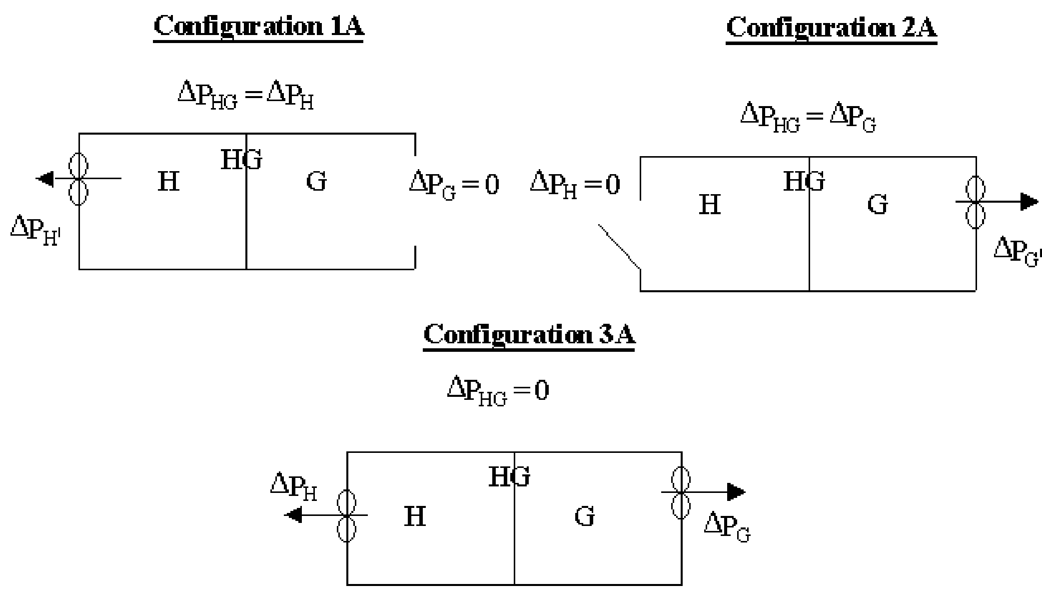

Figure 2 Blower Door Configurations for Building A

Analysis

For each blower door test, measured airflows were recorded at four to seven pressures ranging from 10 Pa to 70 Pa (not all spaces could be pressurized to 70 Pa). The airflows and pressures are then fit to a power law equation: $Q = C (\Delta P)^n$. The airflow and pressure data from each blower door test are logarithmically transformed and fitted with a linear regression, yielding the flow coefficients, C, and flow exponents, n, for each configuration. A sample plot of typical data is illustrated in Figure 3 for configurations 1 and 3 in Building E. Configuration 1 includes flow through the house exterior envelope and HG interface combined (called H') and configuration 3 includes flow through the combination of the house exterior envelope, H, and the garage exterior envelope, G.

The flow 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 (ELAs) 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 E779-99 (ASTM 1999).

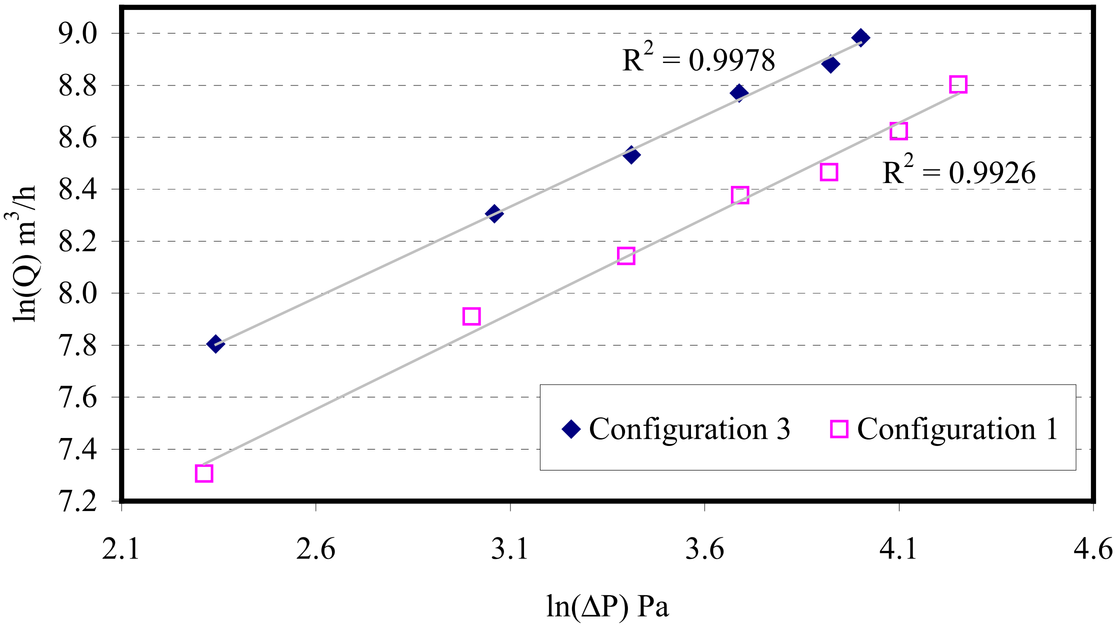

Figure 3. Sample plot of blower door test of Building E for two test configurations.

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, depressurizing 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, H, 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 envelope surfaces of the garage, G, 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 airflow 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 ELAs 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 determined 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 determined 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 uncertainties 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 from equation (1):

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

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 airflow 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. Uncertainties in the ELA values, at 95 % confidence level, 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 airflow 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 airflow 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:

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

Again, uncertainties in the ELA values, at 95 % confidence level 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.

Results

All flow coefficients and flow exponents used in the calculations for each building are shown in Table 2.

Table 2. Building Orifice Parameters

(Units for flow coefficients, C, and flow coefficients uncertainty, ΔC, are $m^3/h \cdot Pa^n$)

Building A	$C_{H'}$	535	$\pm\Delta C_{H'}$	45	$n_{H'}$	0.67	$\pm\Delta n_{H'}$	0.016
	C_H	300	$\pm\Delta C_H$	32	n_H	0.75	$\pm\Delta n_H$	0.027
	$C_{G'}$	1330	$\pm\Delta C_{G'}$	72	$n_{G'}$	0.59	$\pm\Delta n_{G'}$	0.011
	C_G	1670	$\pm\Delta C_G$	220	n_G	0.46	$\pm\Delta n_G$	0.020
	$(C_{HG})_{H'-H}$	160	$(\pm\Delta C_{HG})_{H'-H}$	67	$(n_{HG})_{H'-H}$	0.65[1]	----	----
	$(C_{HG})_{G'-G}$	176	$(\pm\Delta C_{HG})_{G'-G}$	136	$(n_{HG})_{G'-G}$	0.65[1]	----	----
Building B	C_1	194	$\pm\Delta C_1$	12	n_1	0.77	$\pm\Delta n_1$	0.014
	C_2	58	$\pm\Delta C_2$	1	n_2	0.76	$\pm\Delta n_2$	0.005
	C_3	168	$\pm\Delta C_3$	8	n_3	0.81	$\pm\Delta n_3$	0.011
Building C	C_1	299	$\pm\Delta C_1$	34	n_1	0.80	$\pm\Delta n_1$	0.026
	C_2	750	$\pm\Delta C_2$	68	n_2	0.65	$\pm\Delta n_2$	0.018
	C_3	1010	$\pm\Delta C_3$	180	n_3	0.67	$\pm\Delta n_3$	0.043
Building D	C_1	291	$\pm\Delta C_1$	28	n_1	0.73	$\pm\Delta n_1$	0.020
	C_2	104	$\pm\Delta C_2$	4	n_2	0.63	$\pm\Delta n_2$	0.007
	C_3	309	$\pm\Delta C_3$	21	n_3	0.74	$\pm\Delta n_3$	0.014
Building E	C_1	283	$\pm\Delta C_1$	29	n_1	0.73	$\pm\Delta n_1$	0.021
	C_2	221	$\pm\Delta C_2$	14	n_2	0.63	$\pm\Delta n_2$	0.012
	C_3	474	$\pm\Delta C_3$	27	n_3	0.70	$\pm\Delta n_3$	0.011

[1]Assumed value (see Analysis section).

Table 3 summarizes the house-garage interface leakage, 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 garages, 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 and 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.

Table 3. 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

Leakage values of different buildings can be compared by normalizing 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 2.5 cm^2/m^2 and 0.57 cm^2/m^2 respectively. The average ELA_4/SA for the garage exterior envelope is 14 cm^2/m^2 with a standard deviation of 15 cm^2/m^2. The average and standard deviation of the ELA_4/SA for the HG interface is 5.9 cm^2/m^2 and 8.1 cm^2/m^2 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 normalized by the garage envelope surface area divided by the living space ELA_4 normalized by the house envelope surface area. The NLA_{HG-H} ratio is the HG interface ELA_4 normalized by the surface area divided by the living space ELA_4 normalized 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.

Discussion

Broad conclusions cannot be drawn from this study due to its small sample size; but this study does provide useful data related to the transport of air and pollutants from attached garages. Despite the small sample size, the broad range of building ages and designs and airtightness values serve to establish a range of conditions useful to the simulation effort.

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 ELAs from 4 cm^2 to 400 cm^2 with an average of 140 cm^2. This study shows a range of HG interface ELAs from 33 cm^2 to 450 cm^2 with an average of 160 cm^2. This study indicates the leakages of the house-garage interface and of the house exterior envelope, when normalized by surface area, are similar for 4 of the 5 houses. Fugler also found house-garage interface leakage to be similar to house exterior envelope leakage, which serves to confirm the reasonableness of this study's results. A difference between this study and that by Fugler 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 are 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. In fact, 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 normalized ELAs 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 residential building airtightness.

The five houses tested range in garage type, size, and use. This large variation carries through to the airtightness results. 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 normalized 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 are needed.

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