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Air Leakage and Air Transfer Between Garage and Living Space

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Building Science Corporation

September 2014

Building America U.S. Department of Energy

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Air Leakage and Air Transfer Between Garage and Living Space

Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

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Prepared under Subcontract No. KNDJ-0-40337-04

September 2014

The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

ACH	Air Changes per Hour
ACH50	Air Changes per Hour at 50 Pascal Pressure Differential
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BSC	Building Science Corporation
CFM50	Cubic Feet per Minute at 50 Pascal Test Pressure Differential
DOE	U.S. Department of Energy
ELA	Effective Leakage Area
EPA	U.S. Environmental Protection Agency
IECC	International Energy Conservation Code
IRC	International Residential Code
Pa	Pascal; SI Unit of Pressure
RH	Relative Humidity
SF6	sulfur hexafluoride
wrt	With Respect To
ZPD	Zone Pressure Diagnostics

Acknowledgments

This project was supported by the U.S. Department of Energy (DOE), Office of Building Technologies, Building America Program. The author appreciates K. Hovnanian Homes – Landover Group who provided the house for testing over a 1-week period, Cheryn Metzger and Michael Gestwick of the National Renewable Energy Laboratory for technical management and field testing equipment support, Ed Hancock of Mountain Energy Partnership for field testing support, Bob Axelrad of the U.S. Environmental Protection Agency (EPA) for collaboration relative to EPA's Indoor airPLUS requirements, and Eric Martin of Florida Solar Energy Center for loaning some test equipment.

Executive Summary

This research project focused on evaluation of air transfer between the garage and living space in a single-family detached home constructed by a production homebuilder in compliance with the 2009 International Residential Code and the 2009 International Energy Conservation Code. The project gathered important information about the performance of whole-building ventilation systems and garage ventilation systems as they relate to minimizing flow of contaminated air from garage to living space. Important gaps and barriers addressed by this research were:

- Developing recommendations for effective methods for precluding the flow of contaminated air from garages to living space.
- Creating a resource for guiding home builders and retrofitters to achieve garage isolation by use of mechanical ventilation equipment.
- Providing field measurement support for revision of the EPA Indoor airPLUS program requirements, which are part of the DOE Challenge Home program.

A series of 25 multipoint fan pressurization tests and additional zone pressure diagnostic testing characterized the garage and house air leakage, the garage-to-house air leakage, and garage and house pressure relationships to each other and to outdoors using automated fan pressurization and pressure monitoring techniques.

Measured house-to-garage air leakage, using multi-point computer automation, was 89 cfm at a 50 Pa pressure differential (89 CFM50). The resulting garage-to-house effective leakage area was 12.4 in.^{2}. These values fell between the minimum and maximum values predicted by a separate computerized zone pressure diagnostic test.

With the house at –50 Pa with respect to (wrt) outdoors, and no imposed house-to-garage or garage-to-outside leakage, the garage-to-house pressure differential was –47 Pa. With 25 in^2 house-to-garage leakage imposed, the garage-to-house pressure dropped to –28 Pa, then with 100 in.^{2} garage-to-outside leakage imposed, the garage-to-house pressure raised back up to –46 Pa. This example showed that a relatively leaky house-to-garage interface can fail or pass a single garage-to-house pressure differential test criterion depending on the actual garage-to-outside leakiness.

The extensive testing to evaluate the adequacy of the draft EPA Indoor airPLUS pressure differential criterion showed that using a CFM50 differential criterion in combination with the pressure differential criterion would eliminate false positives. In the original first step of the test, while a house-to-outside CFM50 test is being conducted with all operable garage openings closed, a garage-to-house pressure measurement is taken. The garage-to-house pressure differential must be greater than 45 Pa. A new second step would require an additional measurement of house-to-outside CFM50 with the overhead garage door open, and verifying that the CFM50 with the garage door open is not more than 6% greater than the CFM50 with the garage door closed. The second step eliminates false positives that can result in the first step due to certain combinations of house-to-garage and garage-to-outside series leakage.

For this test house, the garage-to-house pressure differential was 47 Pa with the house at –50 Pa wrt outdoors and all operable garage openings closed, and the house CFM50 air leakage did not increase when tested with the overhead garage door open.

Six tracer gas tests conducted to determine the fraction of house air that came from the garage under different operating conditions yielded the following conclusions:

- The operation of different ventilation systems showed a consistent and steady difference in the fraction of house air that came from the garage. From high to low fraction, the order was: House Exhaust, Baseline, House Exhaust+Garage Exhaust, and Supply.
- The initial Baseline test showed that 1.4% ±1.4% of the air in the house came from the garage. The house pressure was about 0.5 Pa negative wrt the garage. The final Baseline test showed that 0.6% ±1.4% of the air in the house came from the garage. Averaging both Baseline tests revealed that about 1% ±1.4% of the air in the house came from the garage when no mechanical ventilation system was operating, or close to five times less than when operating 165 cfm of House Exhaust ventilation.
- The 165 cfm House Exhaust ventilation test showed that about 4.6% ±1.4% of the air in the house came from the garage. The house pressure was about 2 Pa negative wrt the garage.
- The 165 cfm House Supply ventilation test showed that the supply ventilation suppressed essentially all air transfer from the garage to the house. The house pressure maintained about 1.5 Pa positive wrt the garage.
- The 165 cfm House Exhaust plus 70 cfm Garage Exhaust test showed performance that was about the same as the initial Baseline test; however, it is possible that some tracer gas being exhausted to outdoors from the garage may have come into the house because of house depressurization due to the house exhaust ventilation. Garage Exhaust of 70 cfm was sufficient to depressurize the garage 2 Pa wrt the house and thereby preclude garage-to-house air transfer.

While the relative characteristics of this house may not represent the entire population of new construction configurations and airtightness levels (house and garage) throughout the country, the technical approach was conservative and should reasonably extend the usefulness of the results to a large spectrum of house configurations from this set of parametric tests in this one house. Based on the results of this testing, the two-step garage-to-house air leakage test protocol described above is recommended where whole-house exhaust ventilation is employed. For houses employing whole-house supply ventilation (positive pressure) or balanced ventilation (same pressure effect as the Baseline condition), adherence to the EPA Indoor airPLUS house-to-garage air sealing requirements should be sufficient to expect little to no garage-to-house air transfer.

1 Problem Statement

1.1 Introduction and Background

Indoor air contaminant control within a home begins with source control; that is, avoiding the placement of items of known high contaminant emission inside the living environment. Occupant-controlled local exhaust is used inside the home in areas where high emissions from contaminant sources cannot be avoided, such as kitchens, bathrooms (wet rooms), toilet rooms, and possibly laundry rooms. Finally, whole-building controlled mechanical ventilation is used to dilute remaining, more diffuse indoor contaminants with fresher outside air (Rudd 2011(b)).

This project focused on the source of outside air as it pertains to "ventilation" air that may come from polluted air in the garage. Garage air can enter the living space especially when the living space is at a negative pressure with respect to (wrt) the garage due to natural forces or due to use of mechanical exhaust ventilation in the living space. This project builds on previous work (Rudd and Bergey 2014; Rudd 2014a, 2014b) to further examine and evaluate the problem of unwanted air transfer from garage to living space and the effectiveness of Garage Exhaust ventilation or House Supply ventilation to provide a solution to that. The effectiveness of Garage Exhaust requirements in the U.S. Environmental Protection Agency (EPA) Indoor airPLUS Construction Specifications[1] were examined in order to consider the most effective methods of meeting the U.S. Department of Energy (DOE) Challenge Home criteria, which require meeting the EPA Indoor airPLUS criteria. This project did not address issues related to air handlers or heating, ventilation, and air conditioning system ductwork located in garages, since the EPA Indoor airPLUS requirements, and therefore the DOE Challenge Home, preclude that.

This research project supports developing the metrics for adapting existing ventilation system configurations and controls to enhance ventilation effectiveness regarding how garages relate to living spaces, while reducing capital costs and saving energy overall. The output from this work will be the input into both retrofit and new house construction best practices and can be used to update the Ventilation Measure Guideline (Rudd 2011(a) previously produced by Building Science Corporation (BSC).

1.2 Review of Prior Publications

Some studies have shown that house infiltration through attached garages can be problematic. Emmerich et al. (2003) reported that polluted garage air infiltrated into living quarters, and that being as much as 45% of total house infiltration according to Fugler et al. (2002).

Graham et al. (1999) used sulfur hexafluoride (SF6) tracer gas to test multiple Canadian houses and found that concentration peaks in the living area ranged from negligible to about 15% of the garage concentration. Similar results were found by cold starting a car engine and measuring

[1] Version 1, Revision 1 of the EPA Indoor airPLUS Construction Specifications required: "Attached garages shall be isolated from conditioned spaces as follows: Common walls and ceilings between attached garages and living spaces shall be visually inspected to ensure they are air-sealed before insulation is installed. All connecting doors between living spaces and attached garages shall include an automatic closer, and they shall be installed with gasket material or be made substantially air-tight with weather stripping. 5.6 Attached garages shall include an exhaust fan, with a minimum installed capacity of 70 cfm, rated for continuous operation, and installed to vent directly outdoors. If automatic fan controls are installed, they shall activate the fan whenever the garage is occupied and for at least 1 hour after the garage has been vacated."

carbon monoxide concentrations. Other studies found transport of carbon monoxide and other automobile engine exhaust compounds between attached garages and house living space to be common as well (Wilber and Klossner 1997; Tsai and Weisel 2000). Kaluza (1999) reported that keeping the garage at a negative pressure relative to the house prevented carbon monoxide transport into a house in Alaska. A combination of air sealing and garage exhaust was reported to be an effective strategy by Wilber and Klossner (1997). Fugler et al. (2002), Greiner and Schwab (1998), and Furtaw et al. (1993) all recommended garage exhaust to improve house and garage air quality.

1.3 Research Questions

The research presented in this report was intended to help develop a better understanding of air transfer between garages and living spaces in single-family homes. The following research questions pertain to this project relative to a home constructed by a BSC builder partner:

1. What is the measured effective leakage area (ELA) of the garage-to-house interface?
2. What is the garage-to-house pressure relationship for a range of house-to-outside pressure differentials and for a range of imposed leakage areas between: a) the garage and house, and; b) between the garage and outside? (The purpose of imposing leakage was to investigate potential improvements to the EPA Indoor airPLUS requirements.)
3. Is there a simple test criterion that could define an adequately sealed garage-to-house interface?
4. What is the fraction of house living space air that comes from the garage, and what is the house-to-garage pressure relationship, under operation of different whole-house ventilation systems, and with operation of the 70 cfm EPA Indoor airPLUS compliant Garage Exhaust?

1.4 Relevance to Building America's Goals

Overall, the goal of the DOE Building America program is to "reduce home energy use by 30%-50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes)." To this end, we conduct research to "develop market-ready energy solutions that improve efficiency of new and existing homes in each U.S. climate zone, while increasing comfort, safety, and durability."[2]

Physical isolation through good air sealing techniques is an important first step, but that may be impractical in retrofit situations and may be imperfect in new construction. The purpose of this project is to evaluate mechanical methods to preclude flow of contaminated air from garages to living space in a home where whole-building ventilation is operating. Good indoor air quality is a goal of the Building America Program and attached garage isolation from living space is an important aspect of ensuring good indoor air quality. Certain types of whole-building mechanical ventilation may contribute more than others to that goal. Situations where natural driving forces or whole-building mechanical ventilation may cause contaminated air to flow from a garage to the house should be avoided. Currently, the ENERGY STAR® Indoor airPLUS requirement of Garage Exhaust is required for compliance with the DOE Challenge Home Program. The infield performance of that requirement needs to be tested. This presents an opportunity for considering

[2] http://www1.eere.energy.gov/buildings/building_america/program_goals.html

the most effective methods of meeting the DOE Challenge Home criteria, which require meeting the EPA Indoor airPLUS criteria.

1.5 Tradeoffs and Other Benefits

Using mechanical means to control the pressure relationship between an attached garage and the living space can preclude flow of contaminated air from the garage to the house. Where whole-building mechanical exhaust ventilation is used in the living space, adding mechanical exhaust in the garage may improve indoor air quality for the occupants; however, using whole-building supply ventilation in the living space to reverse the garage-to-house pressure relationship may also solve the problem. Note that in cold climates homes with elevated wintertime indoor humidity, exterior insulated sheathing or extensive building enclosure air sealing must ensure against potential sheathing condensation when using supply (positive pressure) ventilation.

1.6 Technical Approach

The project tested a 4,252-ft^2 conditioned floor area, two-story, with full unfinished basement house in Maryland, southeast of Washington D.C. The home was constructed to comply with the 2009 International Residential Code (IRC) and the 2009 International Energy Conservation Code (IECC) by builder partner K. Hovnanian Homes. The construction specifications specifically listed: “Exterior walls and penetrations will be sealed per section 402.41 of the 2009 IECC with caulk, gaskets, weatherstripping, or an air barrier of suitable material.” The builder did not seek ENERGY STAR certification.

Figure 1. Top left: front view of the test house; top right: rear view; bottom left: front-right view; bottom-right: front left view

A suitable test home was found that had a medium to low level of garage-to-house connection. One long side of the garage and a little less than half of the short side were adjacent to the first story of the house. A second-story bathroom and a walk-in closet were adjacent to the garage attic. There was no tuck-under portion where the garage ceiling was adjacent to a conditioned space floor above. Figure 2 and Figure 3 show a plan view of this configuration for the first and second floors, respectively.

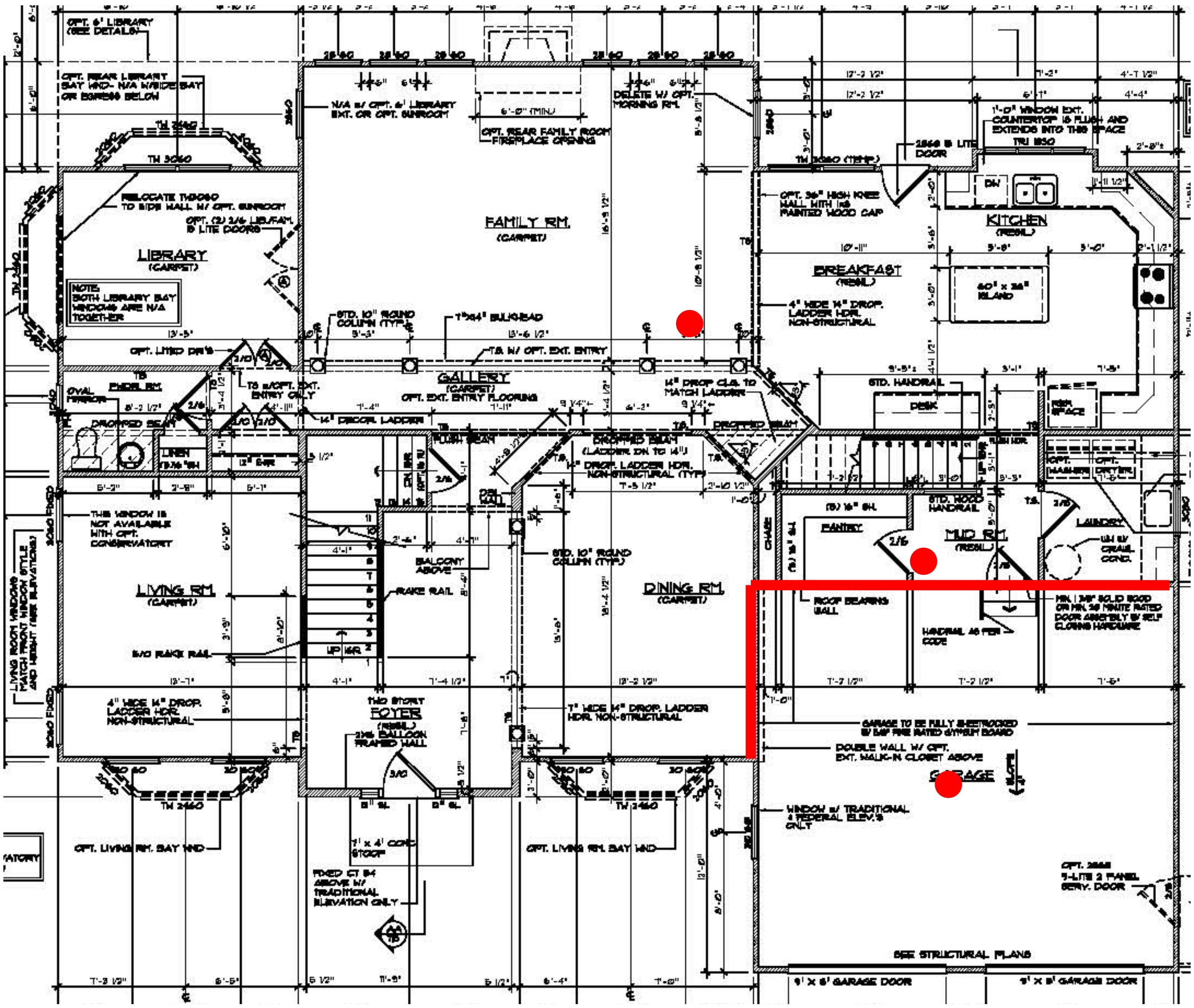


Figure 2. First-floor plan, with garage-to-house interface walls marked with thick red lines, and with red dots marking measurement station locations

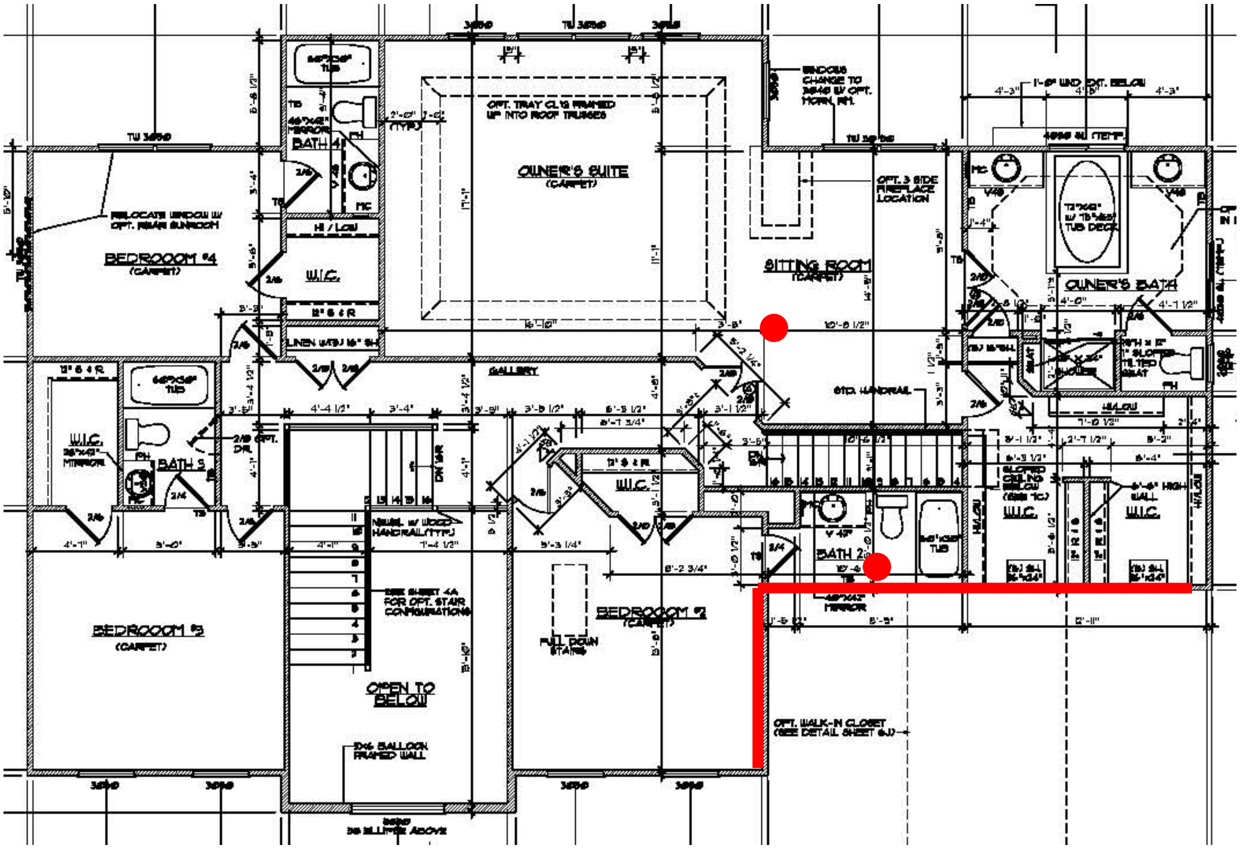


Figure 3. Second-floor plan, with garage attic-to-house interface walls marked with thick red lines, and with red dots indicating measurement station locations

The fan pressurization testing portion of this study was better served by a house with a lower level of garage-to-house connection because higher levels could be simulated by adding leakage area via measured amounts of door opening but obtaining lower levels of leakage would not be feasible. As a conservative approach, tracer gas testing results for this house, having a minimum garage-to-house surface area ratio would be expected to show a low percentage of house air coming from the garage. Smaller houses and those with a higher ratio of garage interface area to overall surface area would be expected to behave worse. Therefore, valid tracer gas test results from this house should be more valid in smaller houses or houses with a higher garage-to-house connection, making these test results appropriate to cover a large spectrum of house configurations from a single set of tests in a single house. Tracer gas testing of houses with higher levels of garage-to-house connection would be valuable and should be pursued.

Testing was designed to answer the research questions listed above (Section 1.2). The testing included measurements of:

- Building enclosure air leakage by fan pressurization
- Six channels of pressure differential monitoring, 5 s average, including:
  - House wrt outside

- Garage wrt outside
- Basement wrt outside
- First-floor garage wall cavity wrt outside
- Second-floor garage attic wall cavity wrt outside
- Garage wrt house (living space)

- Ventilation fan airflow
- Six channels of sf_6 concentration, 2 min sample interval, including:
    - Garage
    - First-floor main area
    - First-floor utility room next to garage wall
    - Second-floor main area
    - Second-floor bathroom next to garage attic wall
    - Basement
- Outdoor wind speed and wind direction
- Indoor and outdoor temperature and relative humidity (RH).

Figure 4. Location of the house-to-outdoors fan pressurization testing equipment

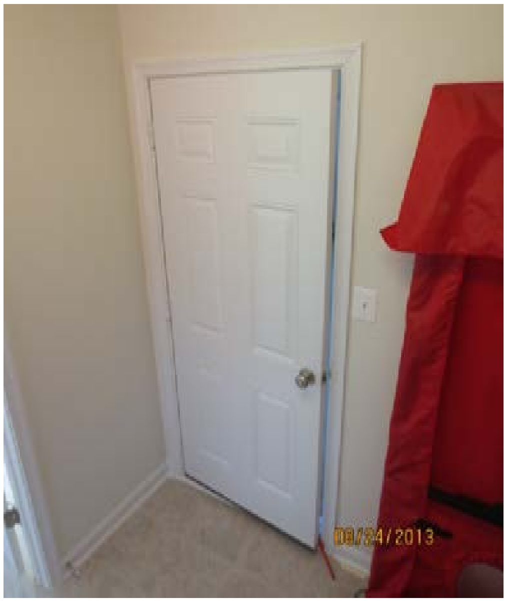


Figure 5. Location of garage-to-house fan pressurization testing equipment

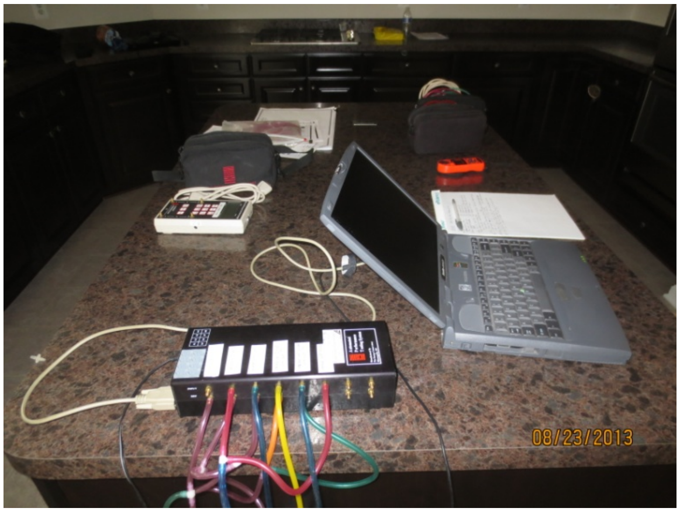


Figure 6. Six channels of pressure monitoring, using Energy Conservatory digital pressure gauge having auto ranging resolution of 0.1 Pa and accuracy of ±1% of reading or 2 times the resolution, whichever is greater

Figure 7. First-floor garage-to-house wall cavity pressure measurement location, and second-floor garage attic-to-house wall cavity pressure measurment and room air sampling location

Figure 8. Back side of house-to-garage attic wall

Figure 9. Testing equipment located in the garage: SF_6 tracer gas on a scale and mass flow controller for tracer gas injection (lower left); calibrated fan for garage exhaust (upper left); garage air concentration and temperature/RH sampling station (tripod in center); mixing fan (right); garage air pressure sampling tube (far right)

Figure 10. Six channels of tracer gas concentration monitoring, using a Bruel & Kjaer 1302 photoacoustic gas analyzer with internal temperature and water-vapor compensation, SF_6 detection limit of 5 ppb, and a repeatability specification of 1% of measured value

Figure 11. First-floor main air sampling station

A series of 25 multipoint fan pressurization tests and additional zone pressure diagnostic testing characterized the garage and house and the garage-to-house leakage areas and pressure relationships using automated fan pressurization techniques.

ELA is given in square inches at a pressure differential of 4 Pa as shown in Equation 1.

$$ELA = 0.2835 * CFM4 \qquad \text{Eq. 1}$$

where: $CFM4$ = airflow at a pressure differential of 4 Pa

Airflow calculated according to a power law curve fit of multiple test points is given in Equation 2.

$$Q = C(dP)^n \qquad \text{Eq. 2}$$

where: Q = airflow (cfm, ft^3/min)
C = constant
dP = pressure differential (Pa)
n = flow exponent

$$dP = \left(\frac{Q}{C}\right)^{\left(\frac{1}{n}\right)} \qquad \text{Eq. 3}$$

A series of six tracer gas tests were conducted to determine how air moved from the garage to the house living space under baseline conditions and operation of different whole-house ventilation systems. SF_6 was injected in the garage at a constant mass flow rate. The target SF_6 concentration in the garage was a minimum of about 5 ppm with Garage Exhaust operating. As shown in Table 1, with a Garage Exhaust flow of 70 cfm, the mass flow controller for injection of SF_6 was set to 10 SCCM (0.010 L/min). SF_6 concentration was measured in the garage and all rooms of the living space continuously throughout each test period using a Bruel & Kjaer

1302/1303 photoacoustic gas analyzer/sampler system. A Miran model 203B portable gas analyzer calibrated for SF_6 was also used periodically as a second check of SF_6 concentration. Air mixing in the garage and each living space room was accomplished using oscillating fans to ensure uniform concentration in each room. Two inline fans with flexible ductwork were used to mix/homogenize air between the first and second floors.

Table 1. SF6 Injection Rate Needed

Airflow Rate (ft^3/min)	SCCM (Standard cm^3/min) Needed To Maintain Listed ppm at Listed Airflow Rate									
	Concentration (ppm)									
	1	2	3	4	5	6	7	8	9	10
50	1.42	2.83	4.25	5.66	7.08	8.50	9.91	11.33	12.74	14.16
60	1.70	3.40	5.10	6.80	8.50	10.19	11.89	13.59	15.29	16.99
70	1.98	3.96	5.95	7.93	9.91	11.89	13.88	15.86	17.84	19.82
80	2.27	4.53	6.80	9.06	11.33	13.59	15.86	18.12	20.39	22.65
90	2.55	5.10	7.65	10.19	12.74	15.29	17.84	20.39	22.94	25.49

Data analysis included analysis of the fan pressurization testing for characterization of the building leakage area between the garage and living space, and analysis of the tracer gas testing to measure the transfer of air between the garage and living space under operation of different ventilation systems in the living space and the garage.

The fraction of living space air that came from the garage at any point in time was calculated by the ratio of SF_6 concentration in the living space to the SF_6 concentration in the garage, Equation 4. The tracer gas tests were generally run for 12 hours; however, steady state was not required for this analysis approach.

$$f_{\text{air from garage}} = \frac{c_{Living\ Space}}{c_{Garage}} \qquad \text{Eq. 4}$$

where: $c_{Living\ Space}$ = concentration in the living space (house)
c_{Garage} = concentration in the garage

The Bruel & Kjaer 1302 photoacoustic gas analyzer has internal temperature and water-vapor compensation, and has a repeatability specification of 1% of measured value. The repeatability specification, rather than an absolute accuracy specification, is the relevant specification for error analysis in this case since the Eq. 4 calculation is a dimensionless result based on the relative concentrations. For example, the error in the quotient 0.3 ppm/22 ppm is ±1.4%, resulting from the quotient propagation of error rule which sums the error of each part in quadrature $[(22*.01)/22)^2 + (0.3*.01/0.3)^2]^{0.5}$. Because the repeatability measurement error is given in percent of measured value, the Eq. 4 quotient result error will remain constant at ±1.4% for all the SF6 tracer gas tests.

2 Results

2.1 Fan Pressurization Testing

Fan pressurization testing provided a basis for determining the garage-to-house air leakage, and for evaluating the adequacy of an EPA draft Indoor airPLUS proposal. That draft proposal included a house-to-garage pressure differential criterion for determining the airtightness of the garage-to-house interface and for determining if a Garage Exhaust fan would be required or not. The draft proposal language required that the garage-to-house air barrier maintain a pressure difference of greater than 45 Pa while the home maintained a 50 Pa pressure difference wrt the outdoors. However, the testing results presented here will show that a second criterion is needed in combination with the first to eliminate false positives that would allow a not-well-sealed garage-to-house interface to pass the first criterion alone.

All fan pressurization testing was conducted with Minneapolis Blower Door equipment, including Model 3 blower door, Ductblaster B, DG-700 digital pressure gauges, Tectite automated performance testing software, an 8-channel automated performance testing pressure gauge unit operated by Teclog software for monitoring six channels of pressure differential, and Zone Pressure Diagnostics (ZPD) software.

Table 2. Listing of Pressure Differential Monitoring Channels

Channel	Description
1	House wrt outdoors
2	Garage wrt outdoors
3	Basement wrt outdoors
4	Garage-to-house wall cavity 2 (first floor) wrt outdoors
5	Garage-to-house wall cavity 1 (second floor) wrt outdoors
6	Garage wrt house

Table 3 gives a detailed description of each of the 25 fan pressurization tests conducted on the house and garage. Abbreviated forms of the Table 3 descriptions are repeated in Table 4 along with the detailed test results.

Referring to Table 3 and Table 4, one can see that Test 1 was conducted by depressurizing the house with the house closed to the garage and the garage closed to outside, while Test 2 was conducted the same except both garage doors were open during the test. The data in Table 4 show that the house air leakage at –50 Pa (CFM50) wrt outdoors did not go up when the garage doors were opened (in fact it went down slightly because of variation between tests, probably due to wind effects). This indicated that the house-to-garage air barrier in this house was substantially sealed. At 1,763 CFM50 (Test 1), and volume of 53,150 ft^3 including the basement, the house ACH50 was 1.99. Without the basement volume, the ACH50 would be 2.93. Either way, the result was well below the ENERGY STAR Version 3 requirement of ACH50 $\leq$ 5 for IECC climate zone 4. Even at the highest CFM50 measured (2,725 for Test 21), where 80 $in.^2$ of leakage area was added between the house and garage, the house ACH50 was 3.0 including the basement.

Test 3 was conducted like Test 1 except the door between the house and garage was opened. The CFM50 went up substantially in Test 3 compared to Test 1 (340 CFM50, or 19%), indicating that the house-to-garage interface was much better sealed than the garage-to-outside interface.

Table 3. Detailed Description of Each House and Garage Pressurization Test

Test #	Detailed Description
1	House depressurized, garage closed to out, house closed to garage
2	House depressurized, garage open to out via both garage doors open, house closed to garage
3	House depressurized, garage closed to out, garage open to house via door
4	House depressurized, garage closed to out, house open to garage 10 $in.^2$ via door
5	House depressurized, garage closed to out, house open to garage 15 $in.^2$ via door
6	House depressurized, garage closed to out, house open to garage 25 $in.^2$ via door
7	House depressurized, garage open 60 $in.^2$ to out via window, house open to garage 25 $in.^2$ via door
8	House depressurized, garage open 80 $in.^2$ to out via window, house open to garage 25 $in.^2$ via door
9	House depressurized, garage open 100 $in.^2$ to out via window, house open to garage 25 $in.^2$ via door
10	House depressurized, garage open 120 $in.^2$ to out via window, house open to garage 25 $in.^2$ via door
11	House depressurized, garage open to out via 1 garage door open, house open to garage 25 $in.^2$ via door
12	Garage depressurized through the house, hose open to out via many windows
13	Garage depressurized, house pressure matched to garage pressure (garage/house walls guarded)
14	House depressurized, garage closed to out, house open to garage 50 $in.^2$ via door
15	House depressurized, garage open 100 $in.^2$ to out via window, house open to garage 50 $in.^2$ via door
16	House depressurized, garage open 120 $in.^2$ to out via window, house open to garage 50 $in.^2$ via door
17	House depressurized, garage open 1020 $in.^2$ to out via window, house open to garage 50 $in.^2$ via door
18	House depressurized, garage open to out via 1 garage door open, house open to garage 50 $in.^2$ via door
19	House depressurized, garage closed to out, house open to garage 80 $in.^2$ via door
20	House depressurized, garage open 100 $in.^2$ to out via window, house open to garage 80 $in.^2$ via door
21	House depressurized, garage open 1020 $in.^2$ to out via window, house open to garage 80 $in.^2$ via door
22	Garage depressurized, garage closed to out, house closed to garage
23	Garage depressurized, garage closed to out, house open to garage 15 $in.^2$ via door
24	Garage depressurized, garage closed to out, house open to garage 40 $in.^2$ via door
25	Garage depressurized, garage closed to out, house open to garage 60 $in.^2$ via door

Table 4. Results of House and Garage Fan Pressurization Tests

Test #	Description	House Open to Garage (in.^{2})	Garage Open to Outdoors (in.^{2})	C[a]	n[b]	R^{2}[c]	ELA (in.^{2})	cfm50	cfm50 Diff	% Diff	6% Criteria	dP[d] Garage wrt House @ 50 Pa	ES IA+[e] >45 Pa Criteria
1	House depressurized	0	0	132.5	0.662	0.9993	94.0	1,763				47	Pass
2	House depressurized	0	20,352	127.4	0.670	0.9997	91.4	1,753	–10	–1%		50	Pass
3	House + garage depressurized	2,560	0	147.0	0.680	0.9998	107.0	2,103				0	
4	House depressurized	10	0	141.2	0.653	0.9992	99.0	1,820				39	Fail
5	House depressurized	15	0	144.2	0.648	0.9997	100.4	1,818				37	Fail
6	House depressurized	25	0	148.0	0.655	0.9995	104.0	1,919				28	Fail
7	House depressurized	25	60	157.8	0.660	0.9998	111.7	2,084				40	Fail
8	House depressurized	25	80	163.0	0.652	0.9997	114.1	2,085				43	Fail
9	House depressurized	25	100	158.4	0.646	0.9991	110.0	1,981				46	Pass
10	House depressurized	25	120	158.8	0.647	0.9984	110.4	1,994				47	Pass
11	House depressurized	25	10,176	162.7	0.653	0.9978	114.0	2,096	177	9%	Fail	50	Pass
12	Garage depressurized through open house	2,560	0	51.4	0.601	0.9993	33.5	539					
13	Garage depressurized, house side guarded	0	0	27.6	0.714	0.9976	21.1	450					
14	House depressurized	50	0	166.8	0.633	0.9913	113.7	1,981				15	Fail

Test #	Description	House Open to Garage (in.^{2})	Garage Open to Outdoors (in.^{2})	C[a]	n[b]	R^2[c]	ELA (in.^{2})	cfm50	cfm50 Diff	% Diff	6% Criteria	dP[d] Garage wrt House @ 50 Pa	ES IA+[e] >45 Pa Criteria
15	House depressurized	50	100	144.7	0.696	0.9963	107.7	2,204				39	Fail
16	House depressurized	50	120	200.7	0.609	0.9927	132.4	2,178				40	Fail
17	House depressurized	50	1,020	192.7	0.628	0.9960	130.5	2,250				48	Pass
18	House depressurized	50	10,176	140.8	0.706	0.9983	106.2	2,229	248	13%	Fail	49	Pass
19	House depressurized	80	0	191.3	0.594	0.9951	123.6	1,951				7	Fail
20	House depressurized	80	100	191.9	0.648	0.9922	133.6	2,418				25	Fail
21	House depressurized	80	10,176	234.7	0.627	0.9973	158.7	2,725	774	40%	Fail	47	Pass
22	Garage depressurized	0	0	31.4	0.649	0.9981	21.9	397				50	
23	Garage depressurized	15	0	51.7	0.618	0.9989	34.5	579				49	
24	Garage depressurized	40	0	73.9	0.634	0.9902	50.5	882					
25	Garage depressurized	60	0	86.8	0.633	0.9932	59.2	1,034					

[a] C = power law curve fit constant
[b] n = power law curve fit exponent
[c] R^2 = coefficient of determination, indicating how well data points fit the model (1.0 being a perfect fit)
[d] dP = pressure differential (Pa)
[e] ES IA+ = ENERGY STAR Indoor airPlus

Referring to Tests 12 and 13, this was where the air leakage through the garage-to-house interface was determined. Test 12 was conducted by depressurizing the garage through the house which was open to outdoors. Thereby, Test 12 measured the air leakage of the entire garage enclosure. Test 13 was the same except that the garage-to-house interface was guarded by depressurizing the house while the garage was depressurized such that the garage-to-house pressure was zero. Thereby, Test 13 measured only the garage-to-outside air leakage because air leakage through the garage-to-house interface was eliminated. The difference between those tests yielded the garage-to-house air leakage, which was 89 CFM50, as shown in Table 5. The resulting garage-to-house ELA was calculated to be 12.4 in^2. As shown in Table 5, these values fell between the minimum and maximum values predicted by the ZPD test performed using The Energy Conservatory ZPD software. For comparison, that test provided an alternate method of estimating airflow between the house and garage zones by adding a hole of known size between the zones and analyzing before and after pressure and airflow responses.

Table 5. Comparison of Test Results Between Guarded Blower Door Test and ZPD Test

	Guarded Test	ZPD Test	
		Minimum	Maximum
Leakage Area Garage-to-House (in.^{2})	12.4	9	18
Leakage cfm50 Garage-to House (CFM50)	89	81	156

Having established the leakage area in the garage-to-house interface, further testing was then conducted to test the adequacy of the EPA Indoor airPLUS pressure differential criterion. In Tests 4, 5, and 6, garage-to-house leakage area was increased by opening the garage-to-house door by measured amounts of 10 in.^{2}, 15 in.^{2}, and 25 in.^{2}, respectively. In each case, the measured pressure differential failed the pressure differential criterion. Then, in Tests 7 through 11, garage-to-outside leakage area was incrementally added. By Test 9, where 100 in.^{2} of garage-to-outside leakage area was added, the measured pressure differential *passed* the pressure differential criterion. In other words, without changing the garage-to-house leakage area, the failing interface could be made to pass by adding sufficient garage-to-outside leakage area. The blue highlighted cells in Table 4 help focus on this issue of passing and failing.

Note that while this parametric testing was done by making measured modifications to an existing construction, the existing construction could reasonably have been randomly constructed to result in any of the modified conditions. For example, where gas water heaters are located in garages, it would not be uncommon to see a through-wall combustion air vent in the range of 100 in.^{2}. That amount of garage-to-outside leakage area would not necessarily be adequate to cause good air quality in the garage, but it was enough to cause a not-well-sealed garage-to-wall interface to pass the pressure differential criterion.

Additional testing to confirm those same results was done via Tests 14–18, and Tests 19–21. In each case, an initially failing garage-to-house interface was made to pass by adding garage-to-outside leakage area, resulting in a false positive. This is illustrated in Figure 12, which shows the inadequacy of house-to-garage pressure differential as a single criterion for house-to-garage airtightness.

Analysis of the measured data showed that providing a CFM50 difference criterion in combination with the pressure differential criterion would eliminate the false positives. The full criteria then involved a first and second step. The first step being a garage-to-house pressure measurement taken while a house-to-outside CFM50 test was conducted with all operable garage openings closed. The second step requires an additional measurement of house-to-outside CFM50 with the overhead garage door open, and verifying that the CFM50 with the garage door open is not more than a given amount greater than the CFM50 with the garage door closed. The second step eliminates false positives that can result in the first step due to certain combinations of house-to-garage and garage-to-outside series leakage.

The repeatability of blower door tests using the Model 3 Minneapolis Blower Door with manual operation is stated to be ±3%. With computer automated operation, the repeatability is better than ±3%. So, assuming manual operation, and doubling that to move further away from the noise of measurement uncertainty, a reasonable CFM50 criterion amount could be 6%. Thus, the house CFM50 measured with the overhead garage door open could not be more than 6% greater than the CFM50 with the overhead garage door closed. The resulting rule could read as such:

> Verify that the garage-to-house air barrier can maintain a pressure difference of greater than 45 Pa while the home maintains a 50 Pa pressure difference with respect to the outdoors with all operable garage openings closed during this test AND verify that the tested house-to-outside CFM50 with the overhead garage door open does not exceed the house-to-outside CFM50 by more than 6% with the overhead garage door closed.

Figure 13 illustrates the elimination of false positives found by adding a second criterion limiting the increase in house CFM50 to 6% with the overhead garage door open compared to closed. Symbols to the left of the dashed line of the same color should pass because the change in House CFM50 was less than 6%. Symbols to the right of the dashed line of the same color should fail because the change in House CFM50 was greater than 6%.

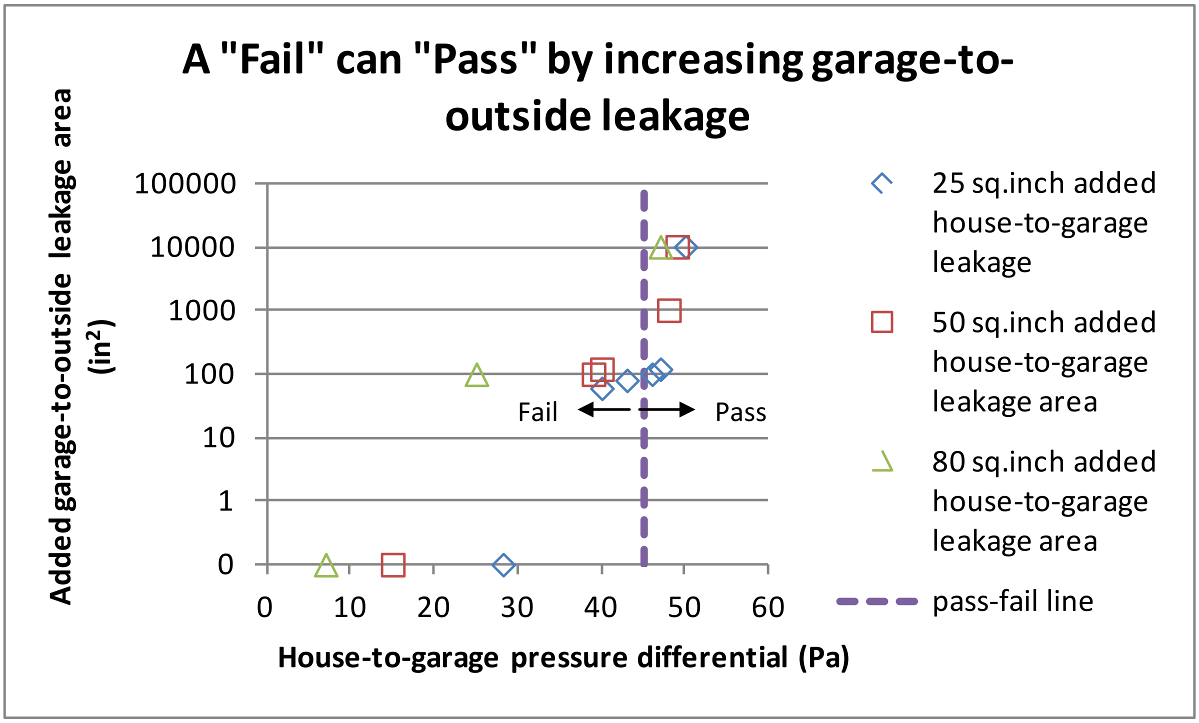


Figure 12. Test results showing inadequacy of house-to-garage pressure differential as a single criterion for house-to-garage airtightness

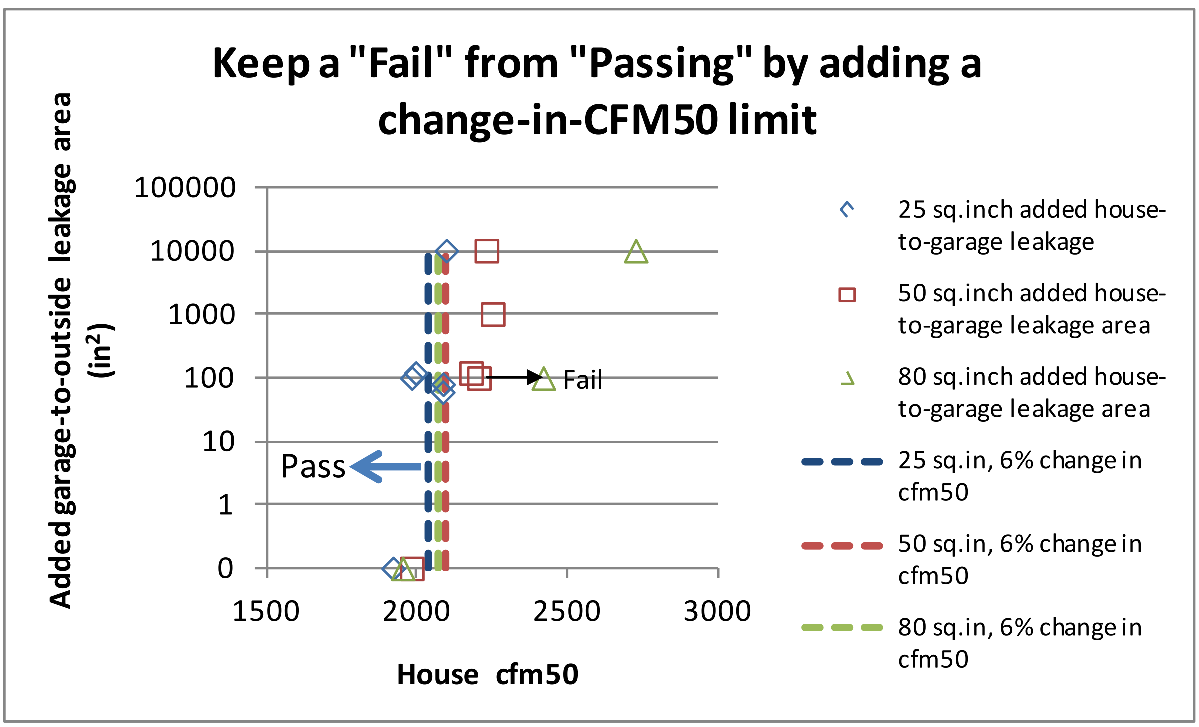


Figure 13. Elimination of false positives was found by adding a second criterion limiting the increase in house CFM50 to 6% with the overhead garage door open compared to closed

Referring to Figure 14, a plot of the added house-to-garage leakage area illustrates that the house effective leakage area was impacted by less than half the amount that was added. This is due to the series leakage resistance from the house-to-garage and the garage-to-outside.

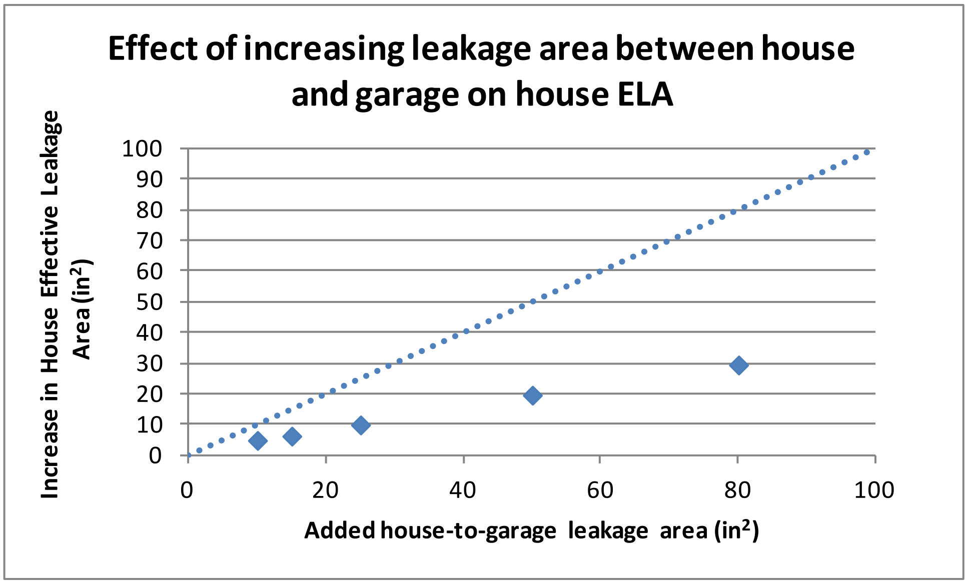


Figure 14. House leakage area increased by less than half the physical house-to-garage opening area added

2.2 Tracer Gas Testing

Tracer gas tests were conducted to determine the fraction of house air that came from the garage air, under the six following different operational conditions:

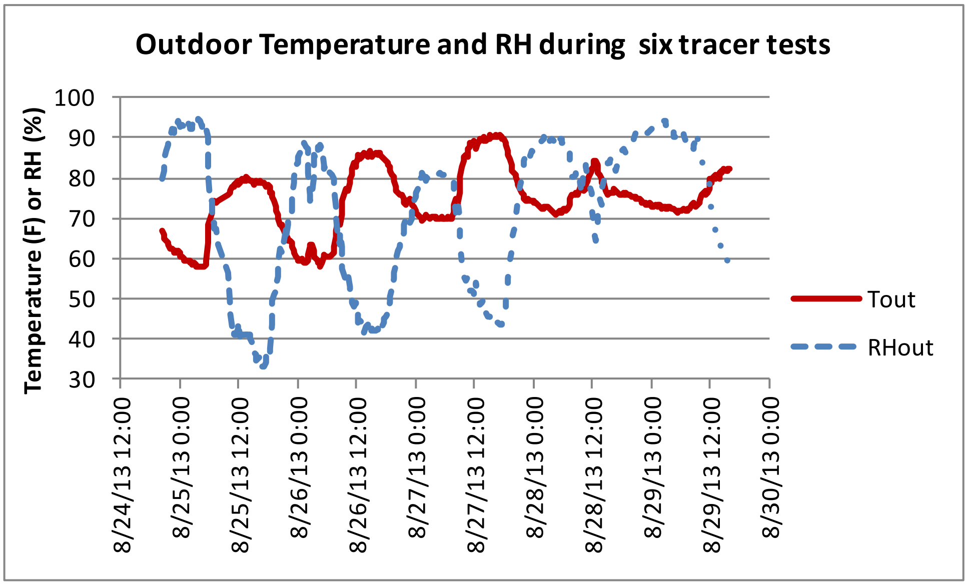
1. Initial baseline (no mechanical ventilation in the garage or house), 12-hour test
2. 165 cfm exhaust ventilation in the house to meet the ASHRAE Standard 62.2-2013 airflow rate, 24-hour test
3. 165 cfm supply ventilation in the house to meet the ASHRAE Standard 62.2-2013 airflow rate, 24-hour test
4. 165 cfm exhaust ventilation in the house and 70 cfm exhaust ventilation in the garage (EPA Indoor airPLUS Garage Exhaust airflow rate), 24-hour test
5. 330 cfm exhaust ventilation in the house which was twice the ASHRAE Standard 62.2-2013 airflow rate, 24-hour test
6. Final baseline (no mechanical ventilation in the garage or house), 8-hour test.

Figure 15 shows the outdoor weather conditions of dry bulb temperature, RH, wind speed, and wind direction during the six tracer gas testing periods. Outdoor temperature generally ranged from lows of 60°–70°F at night to highs of 80°–90°F during the day. Wind speed ranged between 0 and 6 mph. Wind direction was most prominently from the southeast.

Indoor air environmental conditions during the tracer gas testing are shown in Figure 16. The first floor dry bulb temperature was generally about 72^{o}F, with maximum variation between 70^{o}F and 75^{o}F. The second floor was warmer and varied more (between 73^{o}F and 80^{o}F) because the central system fan serving the second floor was non-functional during the tracer gas testing period. For the tracer gas measurements, the first and second floors, with no separation between them were intended to be treated as a single zone. Mixing between floors helps them behave more as a single zone. Two inline fans with ducts were used to circulate air between the first and second floor, located at both stairways. The basement dry bulb temperature was typically about 67^{o}F, with only small variation between 65^{o}F and 68^{o}F.

In the first and second floor living space, RH typically varied between 40% and 60%. The indoor dew point temperature generally varied between 50^{o}F and 58^{o}F throughout the testing, on all three levels. RH in the basement was about 70%, due to the cooler temperature (67^{o}F dry bulb and 57^{o}F dew point yields 70% RH). The spike in indoor conditions near the end of the testing occurred while the house was being flushed of SF_6 between Tests 5 and 6.

Measurement of the environmental conditions of indoor temperature and RH, and outdoor temperature, RH, wind speed and wind direction were used only in a qualitative sense, that is, no calculations quantitatively required those values. Measurement of these values is useful for helping to indicate whether conditions were dramatically different from one test to another, possibly providing background explanation for observed differences in results. Therefore, a formal measurement uncertainty error analysis with regard to the measured indoor and outdoor environmental conditions was not deemed necessary.



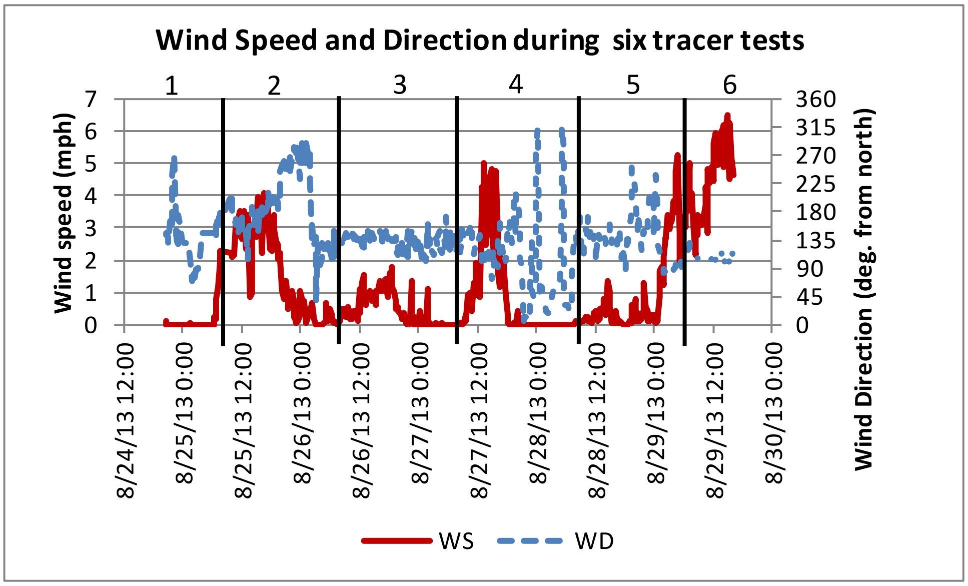


Figure 15. Weather conditions during the six tracer gas testing periods

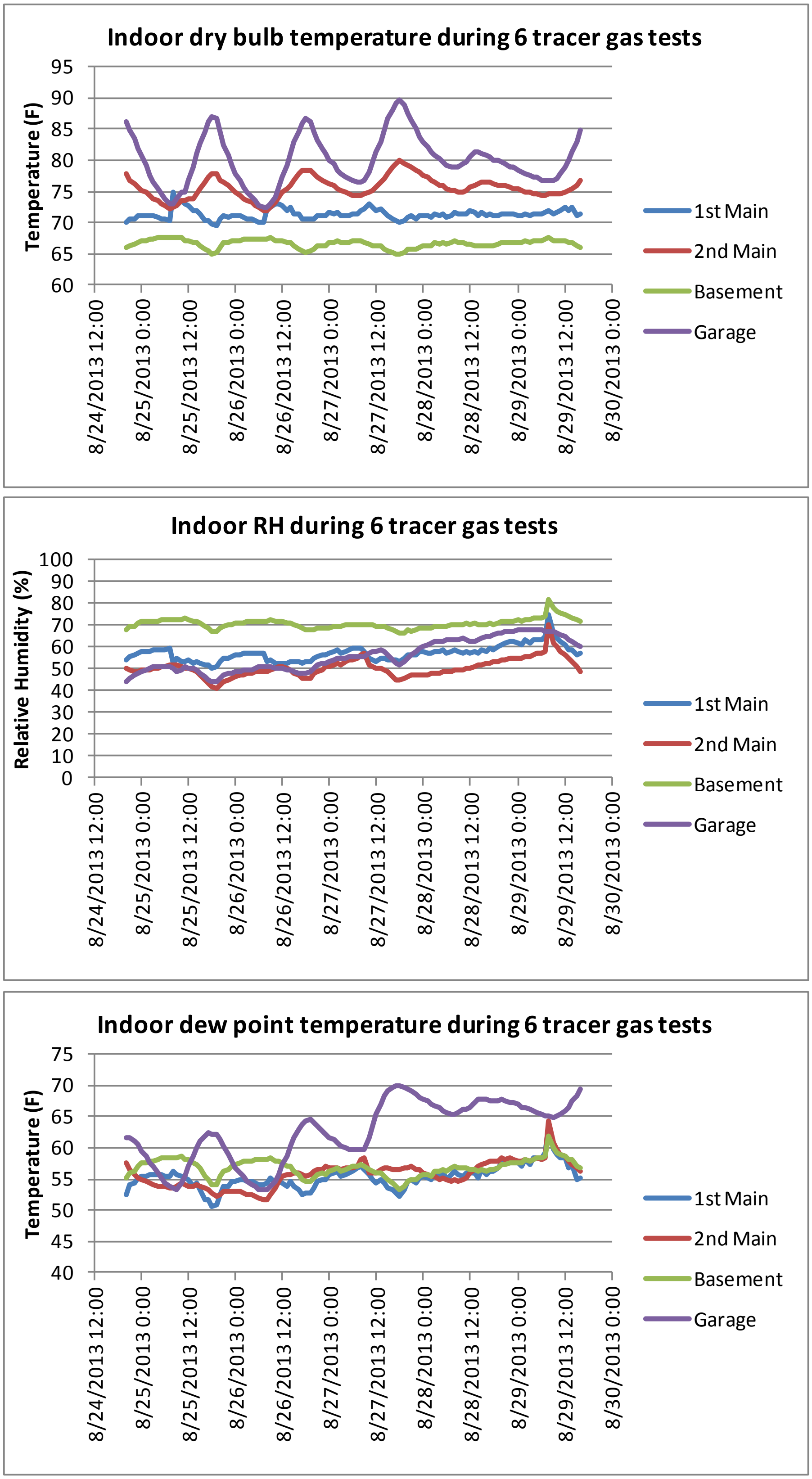


Figure 16. Indoor temperature and humidity conditions during the six tracer gas tests

2.2.1 SF_6 Test 1: Initial Baseline

Results of the first tracer gas test are shown in Figure 17. This was the initial Baseline test and there was no mechanical ventilation in the house or garage. The test started shortly after SF_6 injection (10 SCCM) began in the garage. The test ran for about 12 hours. There was essentially no wind until sunrise (Figure 15) which then started to change the previously steadily tracking pressure differentials due to stack effect alone (Figure 18). The basement pressure spikes of about 2 Pa are due to basement pressurization when the cooling system operated (more supply air than return air). The garage pressure was about 0.5 Pa positive wrt the house. By the end of the test, the garage concentration was 22 ppm and the average of the first main and main locations was 0.3 ppm. Therefore, the initial baseline test result showed that 1.4% ±1.4% of the air in the house had come from the garage (0.3/22 = 0.014, using Eq. 4).

The plots of concentration versus time do not show continuous error bars because of how that would obscure the primary time trace. Pressure differential was not used in calculations therefore pressure differential error was not calculated or plotted.

The following legend nomenclature was used for the pressure differential plots:

Hs wrt out:	House with respect to outside
Ga wrt out:	Garage with respect to outside
Bs wrt out:	Basement with respect to outside
GaW1 wrt out:	First-floor garage wall cavity (adjacent to garage) with respect to outside
GaW2 wrt out:	Second-floor garage wall cavity (adjacent to garage attic) with respect to outside
Ga wrt Hs:	Garage with respect to house

Pressure differential wrt outside was measured in the first-floor wall cavity adjacent to the garage, and in the second-floor wall cavity adjacent to the garage attic. These measurements were taken to provide indication of the relative airtightness of the outer-side air barrier compared to the inner-side air barrier. Results showed that the outer-side (garage-side wallboard) served as the primary air barrier for the first-floor wall, while the inner-side (house side wallboard) served as the primary air barrier for the second-floor wall. This is best seen in Figure 26.

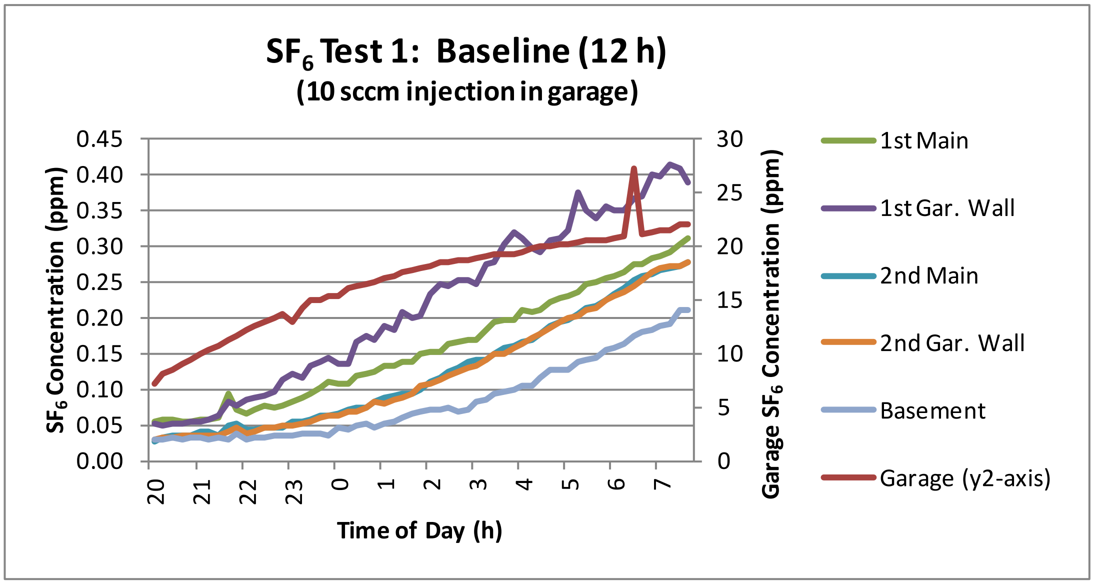


Figure 17. SF_6 test 1, initial Baseline tracer gas test showing that, by the end of the 24-hour test, about 1.4% of the air in the house came from the garage (0.3/22 = 0.014)

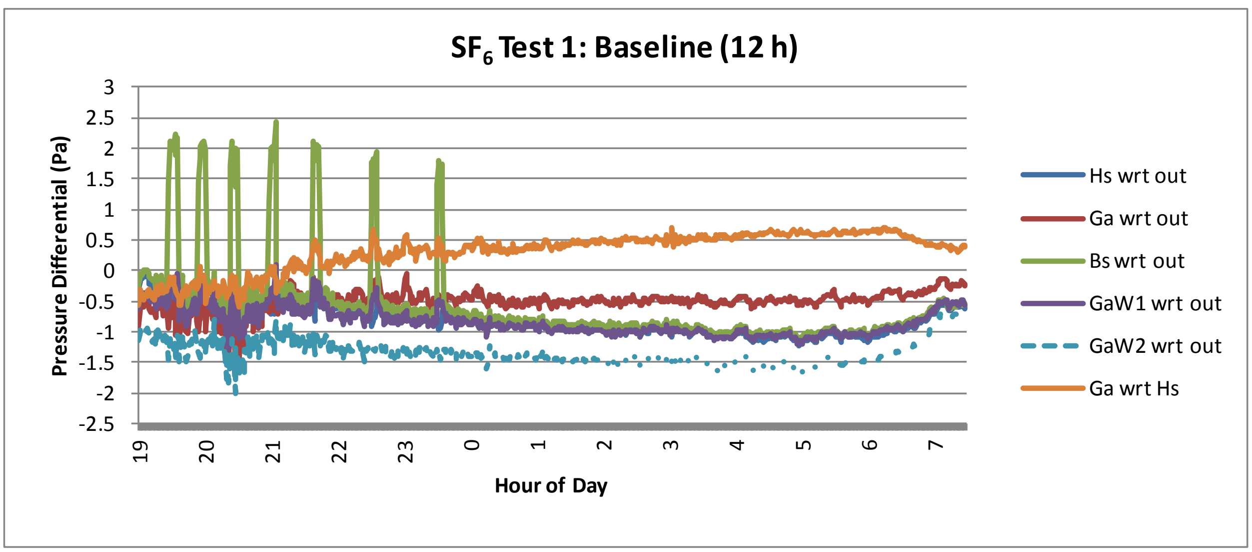


Figure 18. SF_6 Test 1, Baseline, monitored pressure differentials showing the garage pressure about 0.5 Pa positive with respect to the house

2.2.2 SF_6 Test 2: 165 cfm House Exhaust

Results of the second tracer gas test are shown in Figure 19. In this test, 165 cfm of House Exhaust was operating. No mechanical ventilation operated in the garage. The test started with the garage SF_6 concentration where it was after the end of the baseline test. SF_6 injection in the garage was continuous. The test ran for about 24 hours. Wind speed was up to 4 mph during the day and less than 1 mph at night (Figure 15). Without wind, the garage pressure tracked steadily at 2 Pa positive with respect to the house (Figure 18). By the end of the test, the results showed that 4.6% ±1.4% of the air in the house had come from the garage (0.78/17 = 0.046, using Eq. 4).

Where the garage was at a positive pressure with respect to the house, as was the case in the first Baseline test and in the two House Exhaust tests, the SF_6 concentration next to the first floor garage interface wall cavity was higher than in the house. This also confirms that garage air was moving into the house under those conditions. In contrast, the SF_6 concentration next to the second floor wall, adjacent to the vented garage attic, closely tracked the concentration in the house. This was logical since the tracer gas was vented to outside from the garage attic.

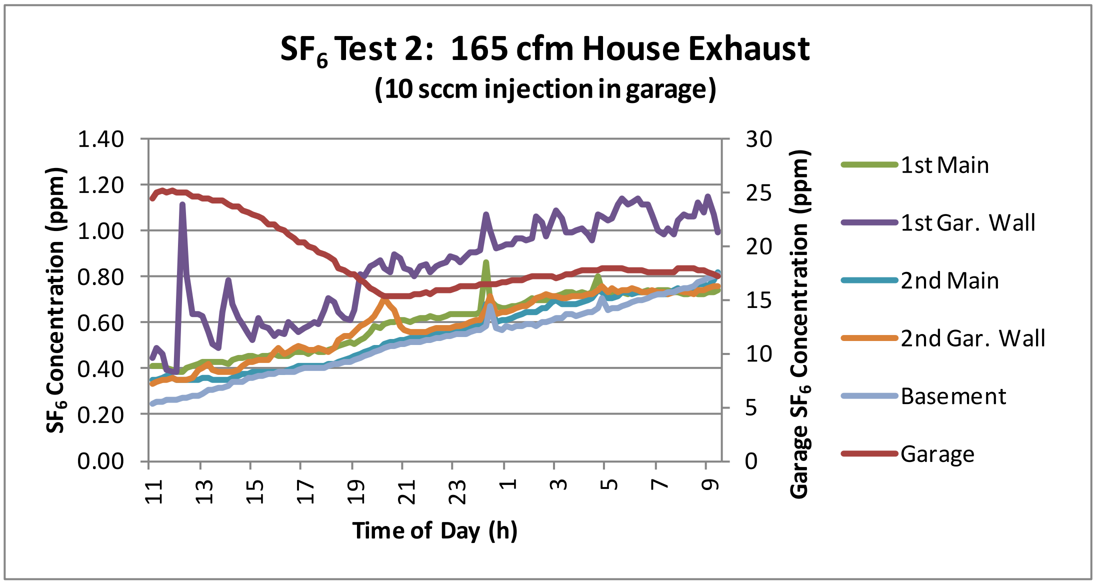


Figure 19. SF_6 test 2, 165 cfm House Exhaust ventilation tracer gas test showing that, by the end of the 24-hour test, 4.6% ±1.4% of the air in the house came from the garage (0.78/17 = 0.046)

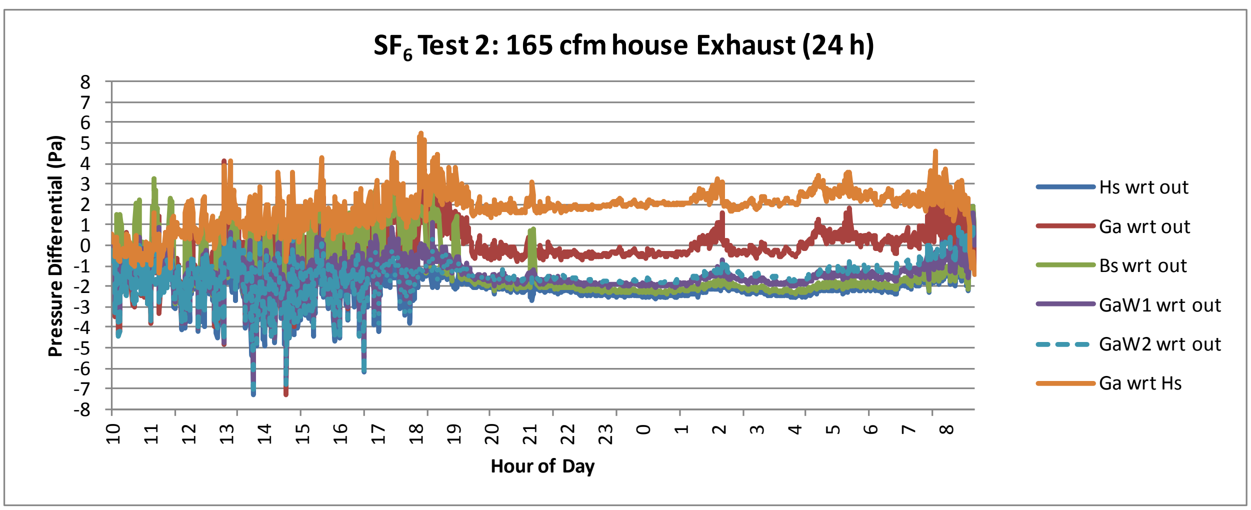


Figure 20. SF_6 test 2, 165 cfm House Exhaust, monitored pressure differentials showing the garage pressure about 2 Pa positive wrt the house

2.2.3 SF_6 Test 3: 165 cfm House Supply

SF_6 tracer gas Test 3 was with 165 cfm of House Supply ventilation operating. No mechanical ventilation operated in the garage. The test ran for about 24 hours. Wind speed was about 1 mph during the day, and near zero at night (Figure 15). Garage pressure was about 1.5 Pa negative wrt the house (Figure 18). Although Test 3 started with a significant SF_6 concentration in the house from the previous exhaust test, by the end of the supply test, the results showed that House Supply ventilation had suppressed garage-to-house air transfer such that only 0.5% ±1.4% of the air still in the house had come from the garage (0.1/20 = 0.05, using Eq. 4).

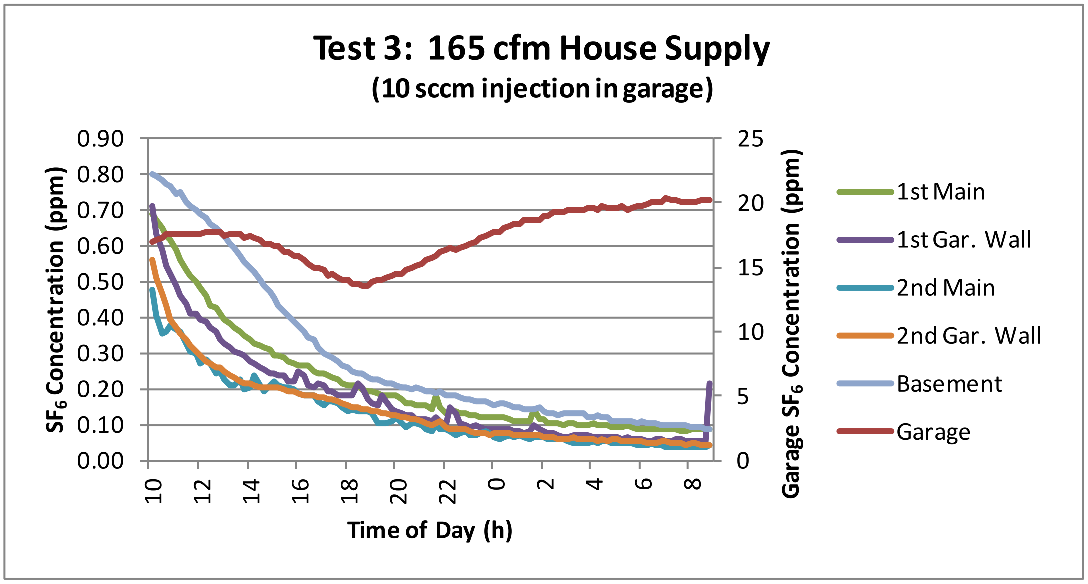


Figure 21. SF_6 Test 3, 165 cfm House Supply ventilation tracer gas test showing that, by the end of the 24-hour test, supply ventilation had suppressed essentially all air transfer from the garage to the house (0.1/20 = 0.005)

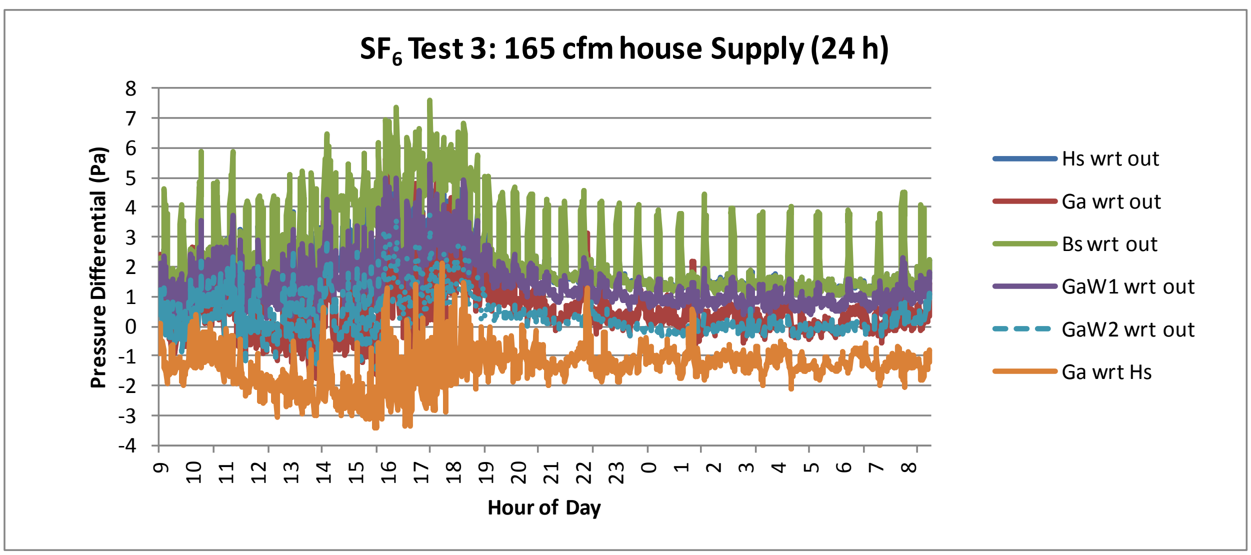


Figure 22. SF_6 test 3, 165 cfm House Supply, monitored pressure differentials showing the garage pressure about 1.5 Pa negative wrt the house

2.2.4 SF_6 Test 4: 165 cfm House Exhaust and 70 cfm Garage Exhaust

SF_6 tracer gas Test 4 was with 165 cfm of House Exhaust and 70 cfm of Garage Exhaust operating. The test ran for about 24 hours. Wind speed was up to 5 mph during the day, and near zero at night (Figure 15). Garage pressure was about 2 Pa negative wrt the house (Figure 18) and about 3.5 Pa negative wrt outdoors. The garage-to-outside pressure relationship was exactly as predicted by the garage air leakage curve for 70 cfm exhaust, as shown in Table 4, Test 22. In addition, the 5 ppm garage tracer gas concentration, with 70 cfm exhaust and 10 SCCM SF_6 injection, agreed with the calculation result shown in Table 1.

While the garage-to-house pressure relationship clearly showed that the 70 cfm Garage Exhaust had suppressed garage-to-house air transfer, by the end of this test, the results showed that about 2% ±1.4% of the air in the house had come from the garage (0.1/5.0 = 0.02). That was slightly more than for the Baseline test. A possible reason for this could have been that some SF_6 being exhausted from the garage window, parallel to the front of the house, could have been drawn into the house from outdoors by the house-to-outside negative pressure created by the House Exhaust.

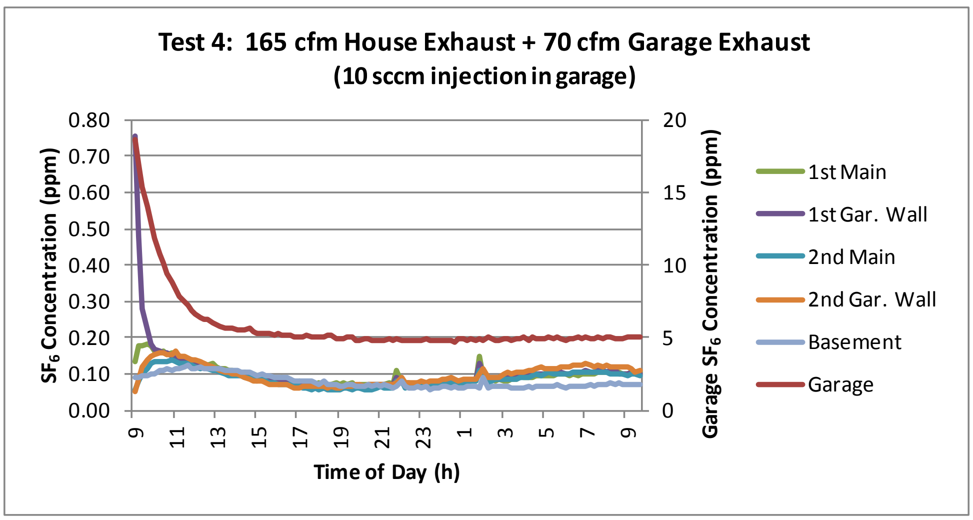


Figure 23. SF_6 test 4, 165 cfm House Exhaust and 70 cfm Garage Exhaust tracer gas test showed performance that was about the same as for the initial Baseline test (0.1/5.0 = 0.02)

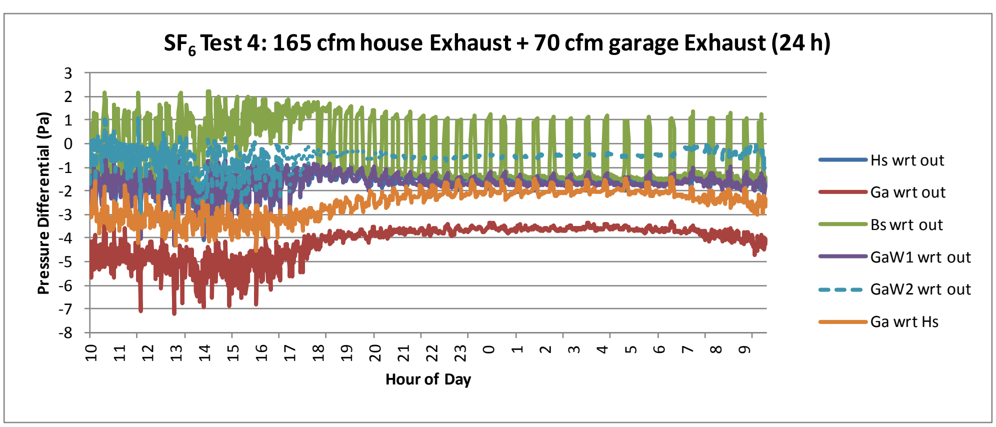


Figure 24. SF_6 test 4, 165 cfm House Exhaust and 70 cfm Garage Exhaust, monitored pressure differentials showing the garage pressure about 2 Pa negative wrt the house

2.2.5 SF_6 Test 5: 330 cfm House Exhaust

Test 5 was a second House Exhaust test to see what effect a doubling of the House Exhaust used in Test 2 would have on the amount of air in the house that came from the garage. In reality, that doubling could represent operation of a dryer or range hood, or an additional request for house ventilation. Before the test, it was postulated that the fraction of house air that came from the garage would not increase much if at all in this case because the garage-to-house interface was already known to be well sealed. That is what the test result showed. In fact, the fraction of house air that came from the garage decreased from 4.6% ±1.4% to 3.2% ±1.4% when the House Exhaust rate was doubled. It appears that the increased house-to-outside negative pressure may have had more of an impact than the increased house-to-garage pressure, due to the path of least resistance causing a greater fraction of exhaust makeup air to come from outside in the second test.

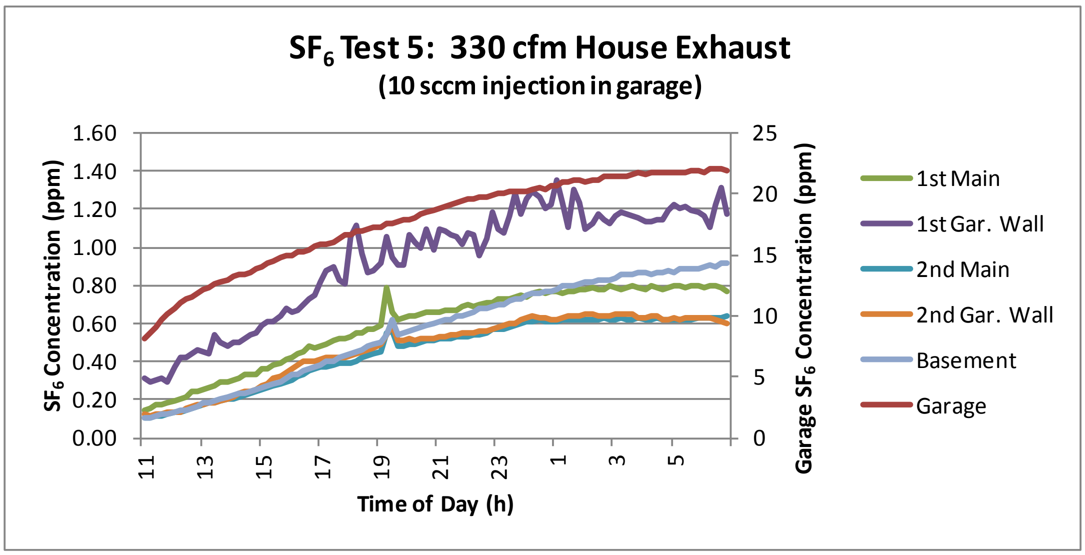


Figure 25. SF_6 test 5, 330 cfm House Exhaust tracer gas test showed that, by the end of the 24-hour test, 3.2% ±1.4% of the air in the house had come from the garage (0.7/22 = 0.032)

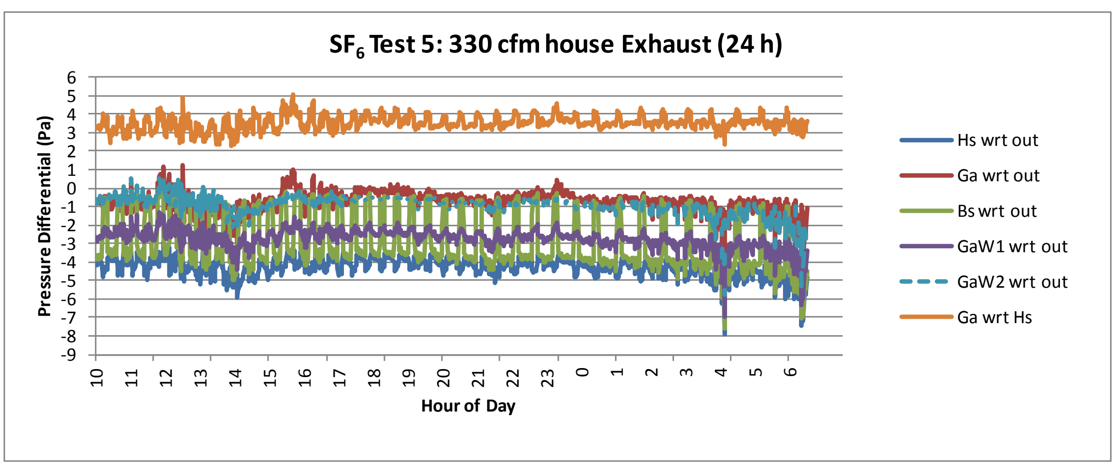


Figure 26. SF_6 test 5, 330 cfm House Exhaust, monitored pressure differentials showing the garage pressure about 3.5 Pa positive wrt the house

2.2.6 SF_6 Test 6: Final Baseline

The availability of the test house allowed for a second Baseline test (Test 6). This test was conducted for 8 hours during the daytime, while the first Baseline test (Test 1) was conducted for 12 hours overnight. In addition, Test 1 was started shortly after the SF_6 injection started, thus, there was a longer time required to ramp up the concentration than for Test 6 which was started when the SF_6 concentration in the garage was fairly steady. Between Test 5 and Test 6, the house (but not the garage) was flushed of SF_6 via open windows and doors, and a blower door fan exhausting a large quantity of air. Even with those differences between Baseline tests 1 and 6, the result was essentially the same, showing little garage-to-house air transfer due to a well-sealed garage-to-house interface. By the end of Test 6, it was shown that 0.6% ±1.4% of the air in the house had come from the garage (0.16/25 = 0.006), compared to 1.4% ±1.4% for Test 1. The average of both Baseline tests showed that about five times less air in the house came from the garage compared to Test 2 with 165 cfm exhaust operating in the house.

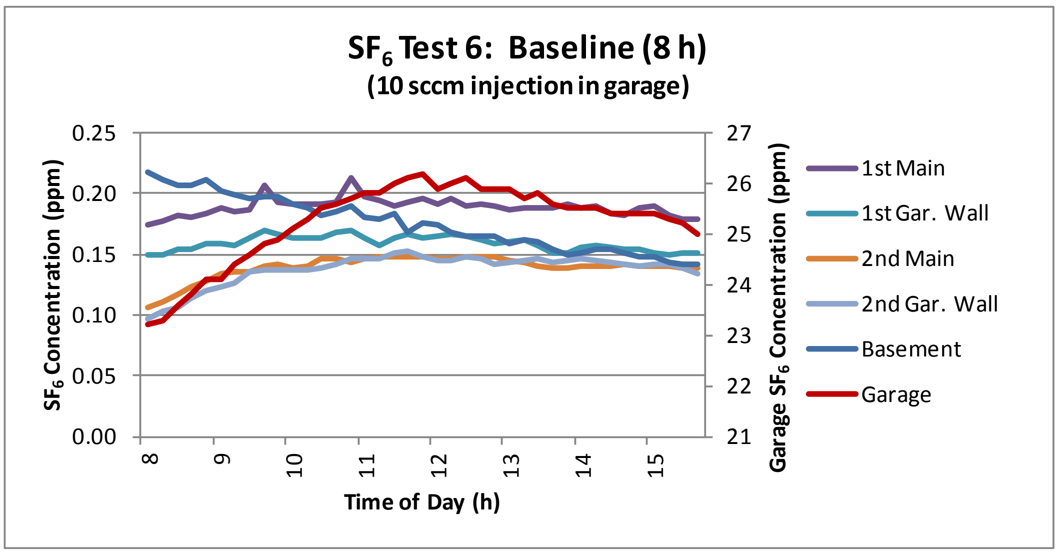


Figure 27. SF_6 Test 6, the final Baseline tracer gas test showed again that there was little garage-to-house air transfer across the well-sealed garage to house interface (0.16/25 = 0.006)

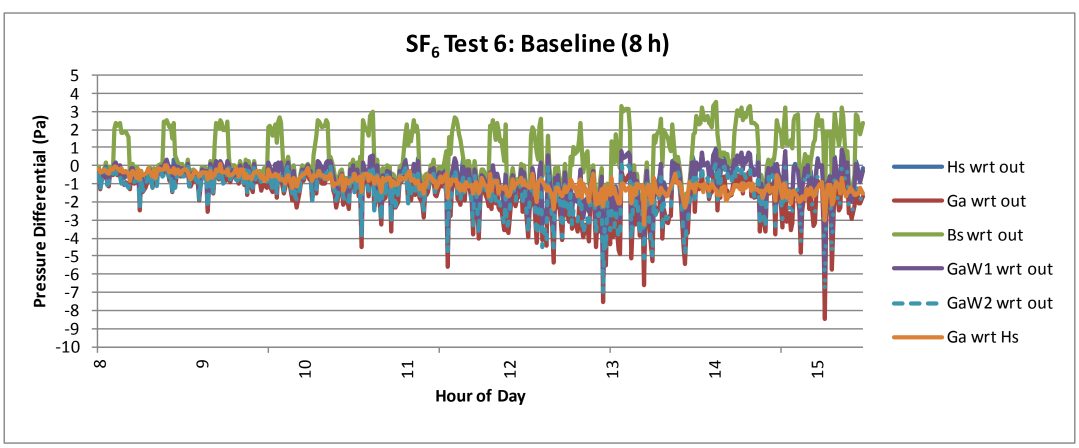


Figure 28. SF_6 Test 6, Baseline (8 h), monitored pressure differentials showing the garage pressure about 1.5 Pa negative wrt the house

Figure 29 summarizes the garage wrt house pressure differential for each tracer gas test, including the Baseline tests and each ventilation system test. As shown, Garage Exhaust and House Supply ventilation consistently kept the garage at a negative pressure wrt the house. The second Baseline test also showed this relationship, while the first Baseline test showed close to neutral pressure conditions, both of which would be indicative of balanced ventilation.

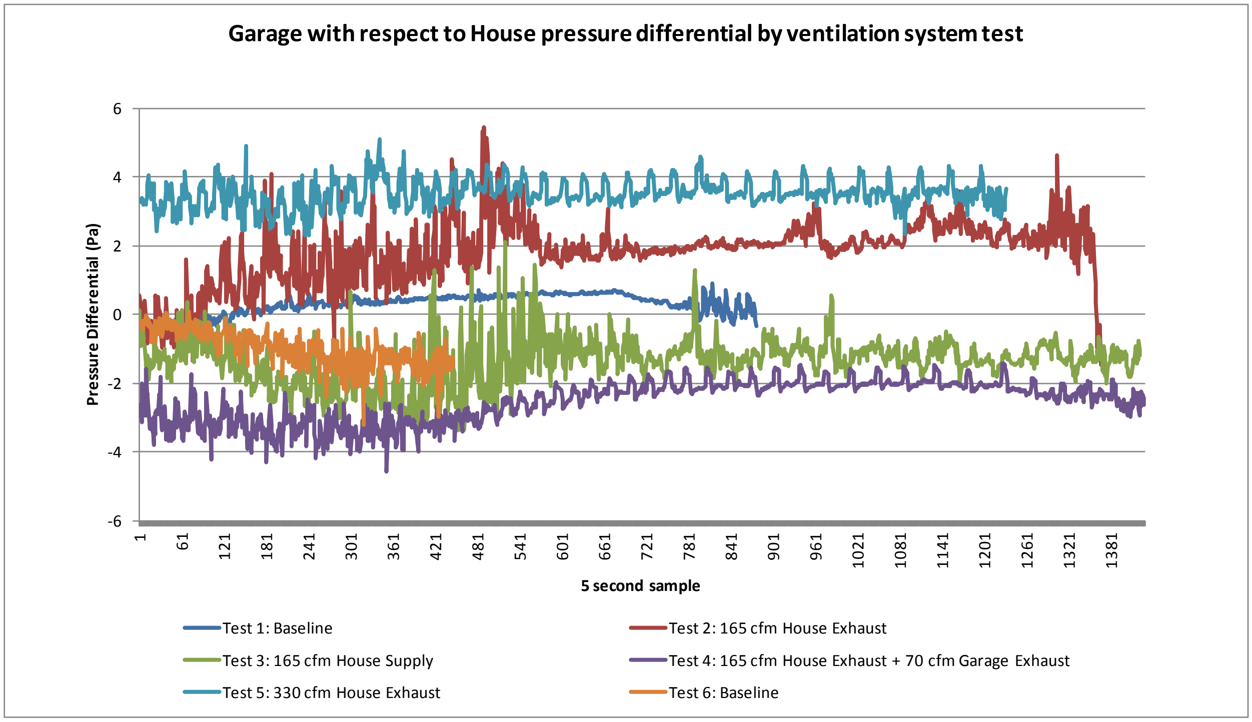


Figure 29. Pressure differential of the garage wrt house for each tracer gas test

Figure 30 is a summary graph of the average house SF_6 concentration divided by the garage SF_6 over the last 4 hours of each test. This concentration ratio shows the fraction of air in the house that came from the garage. The operation of different ventilation systems showed a consistent and steady difference in the fraction of house air that came from the garage. From high to low fraction, the order was: House Exhaust, Baseline, House Exhaust+Garage Exhaust, and Supply.

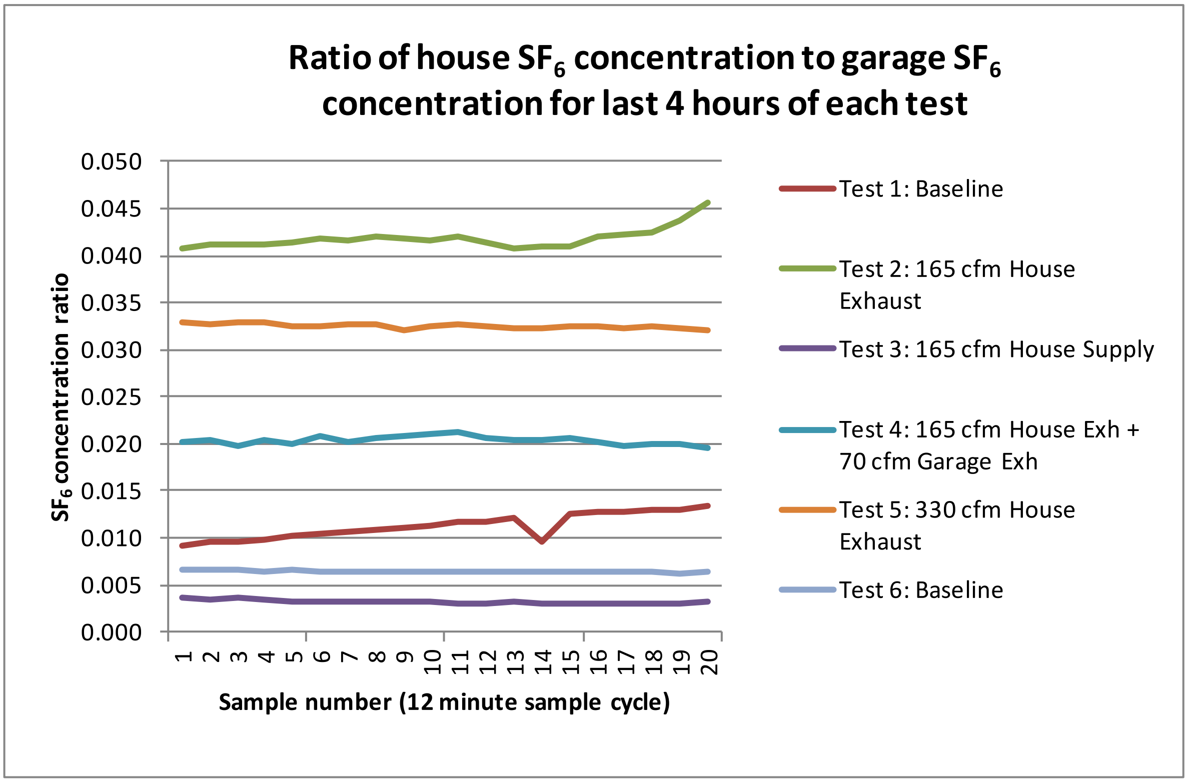


Figure 30. Ratio of average house SF_6 concentration to garage SF_6 concentration for the last 4 hours of each test, representing the fraction of house air that came from the garage

3 Conclusions

In conclusion, the project research questions were answered as follows:

1. *What is the measured ELA of the garage-to-house interface?*

   Measured house-to-garage air leakage, using multipoint computer automation, was 89 cfm at a 50 Pa pressure differential (89 CFM50). The resulting garage-to-house ELA was 12.4 in^2. These values fell between the minimum and maximum values predicted by a separate computerized zone pressure diagnostic test.

2. *What is the garage-to-house pressure relationship for a range of house-to-outside pressure differentials and for a range of imposed leakage areas between: a) the garage and house, and; b) between the garage and outside?*

   A series of 25 multi-point fan pressurization tests and additional zone pressure diagnostic testing characterized the garage and house air leakage, the garage-to-house air leakage, and garage and house pressure relationships to each other and to outdoors using automated fan pressurization and pressure monitoring techniques. The results are given in detail in Table 3 and Table 4. For example, with the house at –50 Pa wrt outdoors, and no imposed house-to-garage or garage-to-outside leakage, the garage-to-house pressure differential was –47 Pa. With 25 in.^{2} house-to-garage leakage imposed, the garage-to-house pressure dropped to –28 Pa, then with 100 in.^{2} garage-to-outside leakage imposed, the garage-to-house pressure raised back up to –46 Pa. This example showed that a relatively leaky house-to-garage interface can fail or pass a single garage-to-house pressure differential test criterion depending on the actual garage-to-outside leakiness.

3. *Is there a simple test criterion that could define an adequately sealed garage-to-house interface?*

   Testing to evaluate the adequacy of the draft EPA Indoor airPLUS pressure differential criterion showed that using a CFM50 difference criterion in combination with the planned pressure differential criterion would eliminate false positives. In a first step of the test, a garage-to-house pressure measurement is taken while a house-to-outside CFM50 test is being conducted with all operable garage openings closed. The garage-to-house pressure differential must be greater than 45 Pa. A new second step would require an additional measurement of house-to-outside CFM50 with the overhead garage door open, and verifying that the CFM50 with the garage door open is not more than 6% greater than the CFM50 with the garage door closed. The second step eliminates false positives that can result in the first step due to certain combinations of house-to-garage and garage-to-outside series leakage.

   For this test house, constructed by a production builder to comply with the 2009 IRC and IECC, the garage-to-house pressure differential was 47 Pa with the house at –50 Pa wrt outdoors and all operable garage openings closed, and the house CFM50 air leakage did not increase when tested with the overhead garage door open.

4. *What is the fraction of house living space air that comes from the garage, and what is the house-to-garage pressure relationship, under operation of different whole-house ventilation systems, and with operation of the 70 cfm EPA Indoor airPLUS compliant Garage Exhaust?*

Six tracer gas tests conducted to determine the fraction of house air that came from the garage under different operating conditions yielded the following conclusions:

- The operation of different ventilation systems showed a consistent and steady difference in the fraction of house air that came from the garage. From high to low fraction, the order was: House Exhaust, Baseline, House Exhaust+Garage Exhaust, and Supply.
- The initial Baseline test showed that 1.4% ±1.4% of the air in the house came from the garage. The house pressure was about 0.5 Pa negative wrt the garage. The final Baseline test showed that 0.6% ±1.4% of the air in the house came from the garage. Averaging both Baseline tests revealed that about 1% ±1.4% of the air in the house came from the garage when no mechanical ventilation system was operating, or close to five times less than when operating 165 cfm of House Exhaust ventilation.
- The 165 cfm House Exhaust ventilation test showed that 4.6% ±1.4% of the air in the house came from the garage. The house pressure was about 2 Pa negative wrt the garage.
- The 165 cfm House Supply ventilation test showed that the supply ventilation suppressed essentially all air transfer from the garage to the house. The house pressure maintained about 1.5 Pa positive wrt the garage.
- The 165 cfm House Exhaust plus 70 cfm Garage Exhaust test showed performance that was about the same as the initial Baseline test; however, it is possible that some tracer gas being exhausted to outdoors from the garage may have come into the house because of house depressurization due to the house exhaust ventilation. Garage Exhaust of 70 cfm was sufficient to depressurize the garage 2 Pa wrt the house and thereby preclude garage-to-house air transfer.
- The 330 cfm House Exhaust test showed that about 3.2% ±1.4% of the air in the house had come from the garage. The house pressure was about 3.5 Pa negative wrt the garage.

While the relative characteristics of this house may not represent the entire population of new construction configurations and airtightness levels (house and garage) throughout the country, the technical approach was conservative and should reasonably extend the usefulness of the results to a large spectrum of house configurations from this set of parametric tests in this one house. Based on the results of this testing, the two-step garage-to-house air leakage test protocol described above is recommended where whole-house exhaust ventilation is employed. For houses employing whole-house supply ventilation (positive pressure) or balanced ventilation (same pressure effect as the Baseline condition), adherence to the EPA Indoor airPLUS house-to-garage air sealing requirements should be sufficient to expect little to no garage-to-house air transfer.

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DOE/GO-102014-4489 ▪ September 2014