Attached Garages: IAQ Implications and Solutions

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ABSTRACT

Attached garages are a staple of modern convenience. They allow access to and from the living space without exposure to the elements, and they keep vehicles and other contents warmer in cold weather than their detached counterparts. As such they are a sought after feature in both the real estate and new construction markets.

For all their conveniences, attached garages can pose a threat to a home's indoor air quality. Carbon monoxide from internal combustion engines is poisonous at moderate concentrations, and effects from chronic exposure to volatile organic compounds from chemicals such as pesticides, paints, and other frequently garaged items are likely detrimental. These contaminants and their byproducts can migrate across garage-house interfaces through bypasses in the structure, or via ductwork and HVAC equipment present in garages.

This paper presents results from an ASHRAE-sponsored project on the migration of garage contaminants into the home in five houses in central Illinois with a variety of attached garage configurations. Three of the houses had HVAC equipment present in the garage or in an adjacent connected space, and two had living space directly over the garage. Three were measured over the heating season, and two were measured over the cooling season, with one of those receiving supplemental baseline testing during the preceding heating season.

Carbon monoxide and carbon dioxide from vehicle exhaust and intentionally introduced sulfur hexafluoride tracer gas as a surrogate for general garage air were measured at approximately 12 minute intervals from two locations within the garage, and from a variety of locations within the living space and garage-adjacent attic and foundation spaces.

Over the course of each multi-week field investigation, progressive interventions were completed including implementation of temporary passive ventilation, air sealing at the house-garage interface, air sealing of ductwork in the garage (when applicable), and mechanical ventilation operating at multiple speeds and under various control strategies. The magnitude of contaminant transport, and the impacts of these interventions are analyzed and discussed.

INTRODUCTION

It is well documented in the scientific literature that harmful contaminants such as carbon monoxide and other toxic organic compounds are generated in garages (Zielinska, 2011). In the configuration where the garage is attached

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or integral to a residential building, those contaminants can migrate through the common surfaces into the living space resulting in occupant exposure. In a study of 91 homes with attached garages, and 46 without, researchers found that "benzene concentrations were four times higher in homes with attached garages than in homes without attached garages." (Schlapia, 1998)

Investigation of contaminant generation and transport in single family homes with attached garages was completed under the ASHRAE funded research project RP-1450. Five sites were selected, intentionally including multiple scenarios of HVAC equipment location and above-garage space conditions. Characteristics of included sites are described in Table 1. Concentrations of carbon monoxide (CO), carbon dioxide (CO_2), and sulfur hexafluoride (SF_6) tracer gas as a surrogate for garage air were analyzed at specific locations around the house. Various progressive interventions were completed, and the changes in house connectivity and gas transport were monitored.

METHODS

Site Selection

Single-family homes with attached garages were recruited in the central Illinois area. Volunteer homes were screened with a combination of visual inspections and/or blower door diagnostics prior to inclusion to determine if a significant portion of the house leakage was through the garage; a goal of a pre-existing minimum of 10% of total house leakage through the garage/house interface was established for inclusion.

Table 1. Site Characteristics

Characteristic	Site 1	Site 2	Site 3	Site 4	Site 5
Furnace location	Living space	Closet connected to garage	Closet connected to garage & house	Living space	Closet connected to garage
Space above garage	Attic	Attic	Living space & attic	Attic	Living space
Season tested	Spring 2014	Fall 2014	Winter 2014	Summer 2015 (plus winter baseline)	Winter 2015
Crawl access loc.	Garage	Living space	Living space	Garage	Living space
House area (sqft)	1850	1611	?	3200	2688
Year built	1979	1956	1997	?	?

IEQ Monitoring Equipment

Once a house was selected, an equipment cart (Figure 1a) was installed in the garage. Multiple sample tubes connected the cart to various locations of interest throughout the site to collect air samples and pressure readings. The cart included systems for gas sampling and analysis, tracer gas injection and distribution (Figure 1b), pressure monitoring, temperature and relative humidity monitoring, and data logging and remote communication.

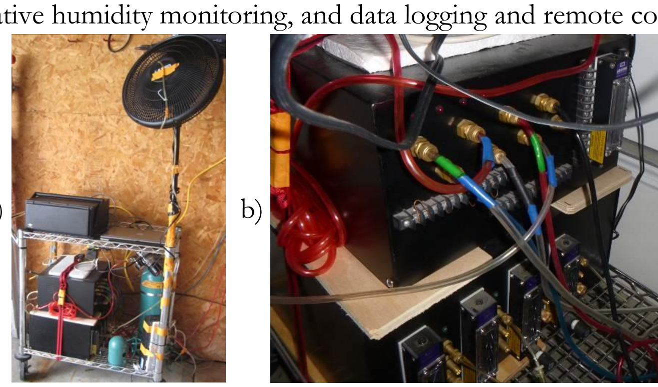

Figure 1 a) the garage equipment cart with b) a detailed view of the sample module (top) & the injection module (bottom)

The gas sampling and analysis system consisted of an automated sampling manifold and a Photoacoustic Gas Monitor (PGM). The eight-port sampling module passed gas samples to the PGM from locations throughout the site, including: a high and low point in the garage, a distant and adjacent (relative to garage) room in the living space, the crawlspace, the space above the garage (either attic, or living space), and outside (at some sites). The PGM analyzed the samples for concentrations of Sulphur Hexafluoride (SF_6), Carbon Monoxide (CO), and Carbon Dioxide (CO_2).

The tracer gas injection system consisted of a tank of 99.9% SF_6 connected to an injection module which opened a valve for a set amount of time at scheduled intervals to introduce tracer gas into the garage zone. The injections were scheduled two or four times per day at times when the garage would likely remain closed for a significant period of time (e.g. after occupants left in the morning and after they arrived home at night). The outlet from the injection module terminated at the center of a continuously operating oscillating pedestal fan which distributed the tracer gas into the garage zone, and kept the air in the zone well mixed.

An eight channel differential pressure gauge was used with logging software to record the pressure differences between various zones in the house and relative to outside. Passive loggers monitoring temperature and relative humidity were deployed in the garage, as well as the living space. The air-handler operation was monitored by a digital current switch coupled with a state sensor logger.

Interventions

At each site interventions were completed in phases. The typical simplified order of interventions was: baseline, passive ventilation, air sealing, baseline 2, duct sealing*, baseline 3*, passive ventilation 2, and mechanical ventilation (*when HVAC located in garage).

Baseline. A baseline period of nominally 1 week was conducted following equipment installation. Additional baseline periods were completed following both the air sealing and the duct sealing interventions. At site 3 an extended baseline was conducted because a significant return duct failure, which had to be resolved prior to any testing, was discovered during equipment installation. At site 4 a 25-day winter baseline was conducted in advance of the summer testing schedule to investigate seasonal differences in contaminant transport.

Passive Ventilation. Two different sizes of passive exterior ventilation were temporarily installed using a custom-built panel at each site both before and after the air/duct sealing measures.

Air & Duct Sealing. Air sealing work was completed by a local contractor, and consisted of locating and sealing bypasses on the garage/house interface with combinations of caulk, 1 and 2-part expanding polyurethane foam, weather stripping, and rigid materials. Large intentional bypasses such as crawlspace and attic hatches were repaired or replaced when necessary with commercially available products, or with custom built units (see Figure 2 for an example of a replacement crawl space access hatch). When HVAC systems were present in garages, duct sealing was completed on the exposed ductwork using mastic and foil tape. A short baseline period occurred after each air/duct sealing intervention to evaluate the improvement.

a)  b)  c) 

Figure 2 Images of the various crawlspace access hatches at site 4: a) the original hatch with one plank set aside, b) a more air-tight temporary hatch with a pass-through for sample and pressure tubing, c) the permanent hatch

Mechanical Ventilation. An apparatus (Figure 3) was designed and placed in each garage that allowed cycling between multiple fan speeds and control strategies. The apparatus includes a dial that the homeowner could toggle to switch between the fan settings at the researchers' request. This facilitated the cycling between these settings without the need to coordinate and complete a site visit. The apparatus had two fans so that it could exhaust a wide range of air flows, including a low speed of 50 cubic feet per minute (CFM) and a high speed of 290 CFM. The medium speed was 100 CFM everywhere except site 1 where the medium speed was 130 CFM. The apparatus also included controllers that operated the fan continuously, based on the CO2 levels in the garage, or based on the state of the garage door. The fan speeds and control parameters for each site are detailed in Table 2. Due to time constraints or equipment issues, not all mechanical ventilation phases were completed at each site.

At sites 1, 2, and 3 the fan state was monitored using a logging power meter. As a result of the efficient operation of the fans and the resolution of the meter, it was difficult to differentiate the on vs. off periods for the low speed settings, calling into question the functionality of the advanced control devices. At sites 4 and 5 monitoring of the fan state was completed using a logging differential pressure gauge with a tap in the fan exhaust.

Figure 3 The temporary fan apparatus installed in garages

Table 2. Interventions and Settings

Characteristic	Site 1	Site 2	Site 3	Site 4	Site 5
Major Air Sealing Efforts	Replaced plank crawl space access hatch	Sealed obsolete CAZ makeup air intake from crawl space	Rerouted CAZ makeup air from garage to attic	Replaced sagging attic stairs and plank crawl space hatch	Covered large penetrations to CAZ and open filter slots
CO2 activation (PPM)	600	600	560	560	560
CO2 deactivation (PPM)	550	550	500	500	500
Garage door delay (min)	30	N/A	30	30	30
Apparatus exhaust location	Window	Window	Roof termination	Roof termination	Wall termination

Pressure Diagnostics

At each site multiple blower door tests were completed over a range of pressures to investigate the house communication and quantify the changes made by the air sealing and duct sealing interventions.

Pressure Diagnostic Notations. Notation to differentiate between various blower door tests is borrowed from Hult et. al (2012) who identified blower door tests based on "a three-digit number, where the first digit corresponds to the house-outside interface, the second corresponds to the house-garage interface, and the third corresponds with the garage-outside interface. A 1 or 2 indicates the 1st or 2nd blower door is in this interface. Zero indicates there are large openings in this interface, such as open doors, windows or the garage door to minimize the pressure drop across this interface. 9 indicates all doors, windows and other operable vents are closed in this interface." (Hult et al. 2012). Figure 4 shows the details of the notation, and some example configurations.

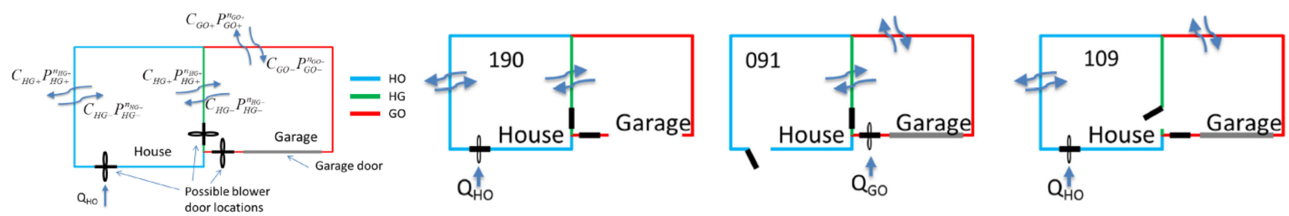

Figure 4 Example pressure diagnostic configurations (SOURCE: Hult et al. 2012)

Pressure Diagnostic Configurations. At each site the following six tests were completed at multiple pressure stations ranging from ~5 Pa to ~60 Pa:

1. Test 199 – Typical blower door configuration, fan in front door depressurizing closed house.
2. Test 109 – Fan in front door depressurizing house, door between house and garage open.
3. Test 190 – Fan in front door depressurizing closed house, door between garage and outside open.
4. Test 991 – Fan (typically not blower door fan to accommodate smaller available openings) in garage depressurizing with all doors closed
5. Test 192 – Guarded test, fans depressurizing both garage and house, with pressures equalized to negate leakage between the two spaces
6. Test 019 – Blower door in garage-house interface pressurizing garage with the house open to outside.

RESULTS

The following is a preliminary presentation of some of the research findings. Continued analysis will be completed on the collected data, and additional findings will be presented in subsequent publications.

Air Sealing Results

The leakage characteristics and air sealing results were determined using the results from the series of blower door tests and the formulas established by Hult et al. (2012), and Emmerich et al. (2003). To simplify calculations, all pressure exponents were assumed to be 0.65 in accordance with the work done by Walker et al. (2013). Table 3 summarizes the results from the pressure diagnostics. The column "nTests" refers to the total number pressure/configuration combinations used for the analysis. The columns "c…" refer to the coefficient calculated for the various interfaces. The columns "Q50…" refer to the flow in CFM through the various interfaces when the house is depressurized to 50 Pa. The column "% leakage @ HG" refers to the percentage of the house leakage that was calculated as coming through the garage-house interface. The column "Improvement" is calculated from the preceeding column, and refers to the percentage reduction of the leakage coming from the garage following an air or duct sealing intervention.

Table 3. Air Sealing Results

Site	Phase	nTests	cHO	cGO	cHG	Q50HO (CFM)	Q50GO (CFM)	Q50HG (CFM)	% leakage @ HG	Improvement
1	pre AS	32	113.59	89.73	20.69	1444	1141	263	15.4	
1	post AS	32	110.61	81.35	6.34	1406	1034	81	5.4	65%
2	pre AS	34	120.27	77.16	37.45	1529	981	476	23.7	
2	post AS	37	117.75	66.75	23.22	1497	849	295	16.5	30%
2	post DS	36	120.37	68.40	23.42	1531	870	298	16.3	-1%
3	pre AS	35	177.00	62.46	16.58	2251	794	211	8.6	
3	post AS	36	187.52	60.67	11.70	2384	771	149	5.9	31%
4	pre AS	33	178.15	121.40	11.20	2265	1544	142	5.9	
4	post AS	35	180.90	31.05	11.56	2300	395	147	6.0	-2%
5	pre AS	31	179.37	34.39	67.73	2281	437	861	27.4	
5	post AS	37	183.50	19.95	20.59	2333	254	262	10.1	63%
5	post DS	37	174.96	27.04	21.89	2225	344	278	11.1	-10%

Table 3 shows that air sealing yielded a substantial reduction in garage house connectivity at all sites except for at Site 4. At Sites 1 and 5 more than half of the leakage between the house and garage was sealed. However duct sealing made little difference in the connection between the living space and garage, as seen for sites 2 and 5.

Tracer Gas Transport Results

The tracer gas data was subset into individual decays following each garage injection. An example injection and decay is shown in Figure 5; note that after an injection, the garage high and low lines are commensurate and the non-garage zones exhibit a delayed concentration rise and subsequent decay. For each injection, metrics for the maximum concentration, the half-life, and the average over various periods (entire injection, first 2 hours of injection, and the first half life) were calculated. From those values, ratios of the value for a zone compared to the value in the garage (represented by the garage-high sample line) were calculated. Figure 6 and Table 4 show example data for the ratio of the maximum concentrations in the living zones relative to the garage zone, as an average of all uninteruped decays during a given phase. The SF_6 decay results during the non-continuous mechanical ventilation phases can be misleading, since the injection schedule and the fan operation are based on disjointed inputs. As a result, the tracer gas results during those phases are excluded from Table 4, but are included in Figure 6 for reference.

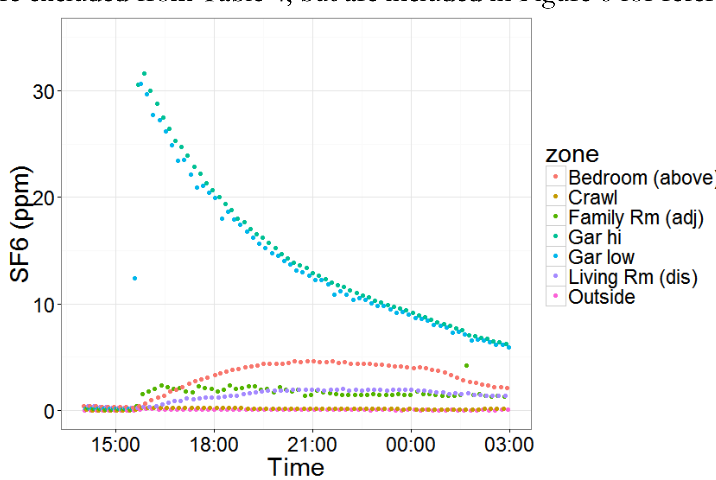

Figure 5 Example SF6 injection and decay

Notice at site 1 (Figure 6a) that the "post air sealing baseline" is significantly lower the "baseline" indicating that the air sealing was highly effective at lowering the quantity of tracer gas entering the living space. In contrast, at site 5 (Figure 6b) the "post air sealing baseline" and the "post duct sealing baseline" are only slightly lower than the original "baseline" indicating that the air sealing was only somewhat effective. Additionally, these two homes had differing impacts from the various continuous fan speeds. At site 1 all fan speeds are similarly effective at preventing tracer gas transport (ex. fan cont. high/med/low), whereas at site 5, the effectiveness of the fan is directly related to its flow (MV1, MV2, MV3).

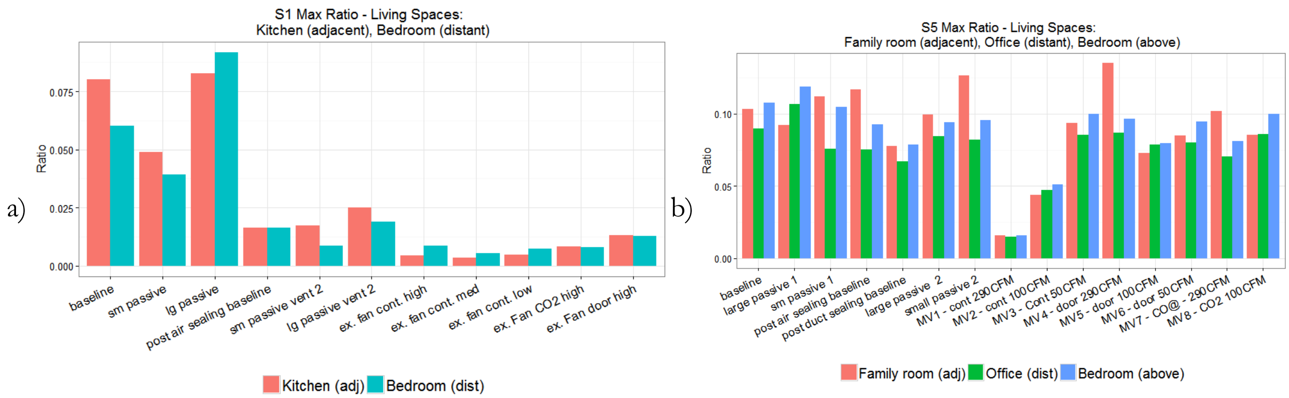

Figure 6 Living space mean maximum SF_6 ratios by phase at: a) site 1, and b) site 5

Table 4 Mean Max Ratio (Adjacent Spaces)

	Baseline	LPV1	SPV1	Post-AS	Post-DS	LPV2	SPV2	EX-C-hi	EX-C-m	EX-C-lo
S1	8.0%	8.3%	4.7%	1.6%	NA	2.3%	1.9%	0.4%	0.3%	0.5%
S2	8.8%	3.4%	7.3%	3.1%	4.5%	3.1%	2.5%	0.6%	0.4%	0.6%
S3	2.3%	2.0%	4.1%	2.6%	NA	6.7%	1.3%	2.1%	1.6%	1.5%
S4	2.1%	1.7%	0.9%	0.7%	NA	4.2%	3.4%	0.3%	1.0%	0.4%
S5	10.3%	9.2%	14.0%	11.4%	8.3%	10.0%	12.1%	0.8%	4.8%	9.4%

In Table 4 LPV1 & SPV1 refer to large & small passive ventilation respectively pre-air sealing. Post-AS refers to the post-air sealing baseline. Post-DS refers to the post-duct sealing baseline. LPV2 & SPV2 refer to large & small passive ventilation respectively pre-air/duct sealing. EX-C-hi/m/lo refers to continuous exhaust at high, medium, and low speeds respectively. Some takeaways from this data are presented in the discussion below.

DISCUSSION

Following air sealing, Sites 1, 2, and 4 had on average a 71% reduction in maximum tracer gas ratios in their adjacent zones relative to the pre-air sealing baseline. These three sites all had large bypasses between the garage and the crawlspaces that were addressed during the air sealing. This suggests that eliminating bypasses between the garage and the crawlspace should be a priority when trying to isolate the garage from the house. The use of loose wood planks as a crawl space hatch should be discouraged as they allow significant communication to the crawlspace and more effective alternatives are easily and cheaply implemented.

The passive ventilation results were inconsistent. At some sites both sizes of passive vent would result in an improvement, at some sites there was not a significant change when the passive vents were installed, and at some sites one passive vent would have a positive impact while the other would have a negative impact. This seems to indicate that the effectiveness of passive ventilation is dependent on the garage geometry and the weather conditions;

depending on if and how the wind is blowing, passive ventilation can be positive or detrimental from a garage contaminant transport perspective.

The mechanical ventilation was the most universally effective at removing the contaminants from the garage and preventing them from entering the living space. The impact of the different flow settings varied from site to site. The only site that did not experience an obvious improvement from the continuous high ventilation was site 3. This is perhaps a result of the brief testing period (that phase only lasted ~30 hours at that site) which unfortunately corresponded with a strong winter precipitation event, and wind gusts reaching 25 mph. At the other four sites, the continuous high ventilation reduced the max SF_6 ratio by an average of 71% relative to the most recent post air/duct sealing baseline.

CONCLUSION

Although much more analysis remains to be done on the data collected during this project, the preliminary findings suggest that although air sealing can reduce contaminant transport from some attached garages, it is not universally effective. The presence of ductwork in the garage appears to present a challenge that basic duct sealing techniques are unable to overcome, such that isolation strategies are insufficient in these homes to mitigate garage contaminant transport. Air sealing in homes without ducts in the garage did show more substantial reductions in transport. Mechanically ventilating garages with a sufficiently large fan was effective in all cases. The lowest flow rate was not always sufficient, whereas the highest flow rate was nearly always sufficient.

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NOMENCLATURE

CAZ = Combustion Appliance Zone, typically where the furnace and other HVAC is located

DISCLAIMER

The opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of ASHRAE.

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