

REPORT ON SOUTH CENTRAL VENTILATION STUDY

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EXECUTIVE SUMMARY

Alaska Housing Finance Corporation (AHFC) and Cold Climate Housing Research Center (CCHRC) commissioned this study of ventilation in new construction housing in the Anchorage area. This project studied a commonly used furnace-fan supply-ventilation system during the winter and spring months of 2004. Results from data logging and testing of various ventilation parameters provide information on ventilation rates in new homes.

This study monitored nine Anchorage area houses in a new subdivision for four months to assess the effectiveness of their “Skuttle” ventilation system and their compliance with the Alaska Building Energy Efficiency Standard (BEES) ventilation requirements. To evaluate the Skuttle system, this study estimated the mechanical and natural air leakage flows, their contribution to the total effective ventilation rate¹, and how that rate compared to the BEES requirement. Each house in the study has a furnace-fan-integrated supply duct and bathroom exhaust fans. The Skuttle system consists of a six-inch duct bringing outside air into the return side of the furnace plenum, thus pulling fresh air into the house when the furnace fan comes on. Either two or three bathroom fans exhaust stale air. Each bathroom exhaust fan has one of three different controls: a manual switch, a dehumidistat, or a timer. The control for each bathroom fan operates independently and none of the controls interconnects with the furnace fan supply. Thus, the Skuttle system operates primarily as a “supply only” ventilation system when the furnace fan is on. During the study, motor runtime loggers monitored the furnace fan supply and the bathroom fan exhaust. Fan runtime and airflow measurements provided estimates of the mechanical ventilation rate in each house. Blower door tests of the houses estimated the natural air leakage contribution. Results were used to calculate the daily averages of the total effective ventilation rate provided by the Skuttle ventilation system and natural air leakage. All of the houses were occupied, and data was recorded for the occupants’ normal living patterns.

The BEES allows for a combination of mechanical ventilation and natural air leakage to provide the required ventilation flow rates. The study used American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) air leakage models² to calculate natural air leakage and mechanical ventilation flow rates. AHFC ventilation testing policy excludes air coming in through the crawl space and garage in calculating ventilation flow rates for compliance with BEES. This exclusion applied to the ASHRAE calculation results. In this study, it left an average of 38% of natural air leakage usable for ventilation.

The daily average mechanical ventilation airflow provided by the Skuttle ventilation system, as operated by participants in this study, ranged from 6.4 to 40.8 cubic feet per minute (CFM). The runtime for the furnace fan supply was more significant to the amount of mechanical ventilation than the type of bathroom fan control. The total mechanical ventilation flows alone did not provide the 90 to 140 CFM ventilation rates required by the Alaska BEES for these houses.

¹ Total Effective Ventilation is described in appendix A.

² ASHRAE119-1988 Air Leakage for Detached Single-Family Residential Buildings and ASHRAE136-1993 A Method of Determining Air Change Rates in Detached Dwellings.

Homeowners may turn off noisy fans, thereby reducing the contribution of bathroom fans to mechanical ventilation.

Estimates of the natural air leakage contribution to ventilation varied widely. Several participants left crawl space vents open for the study period, while vents were closed in other houses. The air leakage model assumes leakage is evenly distributed throughout the house envelope. If actual leakage is largely in the crawl space, and the upper house is relatively tight, then airflow through the leaks will be reduced, and will be overestimated by the model. Calculations of the daily average total effective ventilation were likely over-estimated for the houses in this study that had crawl space openings. Calculations range from 73 CFM to an unlikely high of 657 CFM. Other methods corroborated the lower estimates.

To better assess ventilation effectiveness, numerous other indoor air quality (IAQ) parameters were monitored for the four-month study period. Measurements of carbon monoxide and benzene levels showed a pattern of garage-to-house pollutant transfer, carbon dioxide (CO₂) accumulated in bedrooms at night, and decayed slowly. These results support the estimates of relatively low total effective ventilation. They also reinforce the probability that the higher estimates of natural infiltration misrepresent the actual contribution of infiltration to the total ventilation. The pollutant transfer pattern and the CO₂ buildup also indicate that mechanical ventilation is more important than natural infiltration in distributing ventilation air effectively.

In one house, when the furnace fan supply ran continuously for five weeks, the effective mechanical ventilation rate rose from an average of 15.3 CFM to 67.6 CFM. If the system design had provided balanced flow by linking the bathroom exhaust fans and the furnace supply, the total effective ventilation rate would have met the 110 CFM BEES requirement for this house. Balanced flow is possible with an interlocking control that operates the furnace supply and bathroom exhaust at the same time.

Exhaust-only ventilation pulls air from polluted crawl space and garage zones and likely increases ventilation needs. Balanced flow gives better source control for clean supply ventilation air. It also avoids the potential for a supply-only ventilation system to drive moisture into walls and ceiling assemblies. The recommended improvements for the Skuttle system in this study are to provide interlocked control on the furnace supply and bathroom exhaust fans and to switch to low-noise bathroom exhaust fans. This would increase the effective ventilation flow rates with better distribution to bedrooms and give balanced ventilation with cleaner source air.

INTRODUCTION

The Alaska Building Energy Efficiency Standard (BEES) requires that new construction meet minimum ventilation standards. The ventilation standard provides two options for meeting required ventilation airflow in cubic feet per minute (CFM) based on a house volume or a room count calculation. The houses in this study did not meet requirements for BEES Ventilation Option I- ASHRAE 62 that requires garage ventilation; therefore, this study used BEES Ventilation Option II as the basis for comparing calculated ventilation flow rates to the required ventilation flow rates.³ Typically, the builder certifies that the house meets the ventilation standard.

Recent studies raised concerns about indoor air quality in Alaska homes, and little data is available on the effectiveness of current ventilation systems. CCHRC contracted with Sunrise Energy Works to assess actual ventilation rates in new homes built with common construction techniques. In particular, this study examined the performance of the Skuttle ventilation system with respect to the new-construction BEES ventilation requirements. Builders commonly install the Skuttle system in the Anchorage area as a BEES ventilation compliance system.

For the nine houses in this study, the BEES ventilation requirement ranged from 90 to 140 CFM. Houses can meet this ventilation flow requirement through a combination of mechanical and natural air leakage flows. To evaluate the Skuttle system, this study estimated the mechanical and natural air leakage flows, their contribution to the total effective ventilation rate⁴, and how that rate compared to the BEES requirement.

The study strategy was to collect as much data as possible from January to May 2004. Generous access provided by the homeowner volunteers made for a unique data collection opportunity. Two-minute sampling periods for more than 150 sensors over four months generated massive and complex data sets. This report is the initial effort to mine this data and address the primary question of effective ventilation in these houses.

Alaska Housing Finance Corporation provided grant funds through the Cold Climate Housing Research Center. Spinell Homes assisted in soliciting participant households. Phil Kaluza of Arctic Energy Systems and Alan Mitchell of Analysis North provided exceptional support for equipment, methodology, data analysis, and report development.

³ Alaska Building Energy Efficiency Standard, Alaska Housing Finance Corporation, 2002.

⁴ Total Effective Ventilation is described in appendix A.

OBJECTIVES

The primary study objective was to determine if a Skuttle ventilation system provides adequate ventilation to meet the BEES requirements for ventilation airflow⁵. This includes evaluation of different types of bath fan controls for their contribution to the Skuttle system ventilation rate.

Further objectives were:

- To evaluate the effectiveness of the Skuttle system for delivery and distribution of ventilation air by monitoring CO₂ levels in the bedrooms and living area.
- To evaluate the suitability of ventilation air by monitoring benzene and carbon monoxide.
- To evaluate the connection of garage and crawl space zones to the house.
- To suggest possible solutions to any shortcomings identified in the course of the project.

METHODOLOGY

Testing Period. Houses were tested between January 6 and May 14, 2004.

House Selection and Characteristics. Nine houses were selected to represent current typical Anchorage building practices. All nine were equipped with a Skuttle furnace-integrated supply duct. Three different bathroom exhaust fan controls were tested: a manual switch, a dehumidistat, and a timer. Three of each control type was distributed among the nine houses. The control for each bath fan operated independently and none of the controls were interconnected with the furnace fan supply. The homes were one or two stories with two-car or three-car attached garages. House size ranged from 1,544 to 2,152 square feet of living area and from 13,290 cubic feet to 21,185 cubic feet in volume. Subject houses all had a furnace in the garage and two or three bath fans in the house. All houses were tested “as-is”; the configuration used by the current occupants was not changed except for the following:

- Three of the houses did not initially have the Skuttle furnace supply duct installed. These were installed during the first three weeks of the study and only the period with the Skuttle furnace supply is included here.
- Two of the bath fan controls were changed from dehumidistats to timers. This was done to distribute three of each control type among the nine houses.
- Timer-controlled bath fans were set to run the fans for 20 minutes every two hours.
- Dehumidistat-controlled bath fans were set to run the fans above 35% relative humidity (RH).
- Manual-switch controlled bath fans were operated by occupants as needed for ventilation.

Skuttle System: The Skuttle system makes up the mechanical ventilation system and consists of a six-inch duct bringing outside supply air into the return side of the furnace plenum, thus pulling fresh air into the house when the furnace fan is on (**Figure 1**).

⁵ Alaska Building Energy Efficiency Standard, Chapter 2.5 Ventilation Requirements Alaska Housing Finance Corporation, 2002.



Figure 1: Outside air duct brings fresh air into the furnace return through a Skuttle damper.

There are also bathroom exhaust fans as part of the Skuttle mechanical ventilation system. These had three different independent bath fan controls (**Figure 2**): Timer, dehumidistat, and, manual switch.

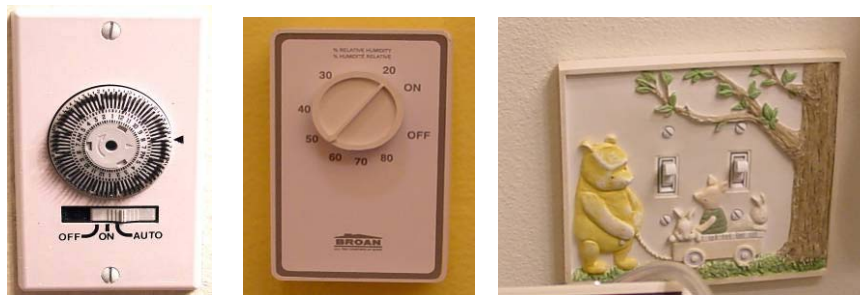


Figure 2: Bathroom fan controls: Timer, Dehumidistat, and Manual switch.

Measurements

House characteristics: Each house was measured to determine the

- house floor area and volume,
- garage volume, and
- crawl space volume.

Airflow: Each house was measured to determine the

- furnace fan Skuttle supply,
- bathroom fan exhaust,
- natural air leakage, and
- where house conditions permitted, zonal leakage from crawl space and garage.

Mechanical airflow:

Mechanical airflow from the Skuttle intake hood for the furnace supply, and each of the bathroom fan exhausts, was measured in CFM with The Energy Conservatory's Exhaust Fan Flow Meter with DG700 Pressure & Flow Gauge.



Figure 3: The Energy Conservatory's Exhaust Fan Flow Meter with DG-700 Pressure & Flow Gauge.

Fan motor runtime: Fan motor runtime was logged using the Runtime Data Watcher from Analysis North, which logged the hourly runtime of the furnace fan and each of the bathroom fans over the four-month study period.

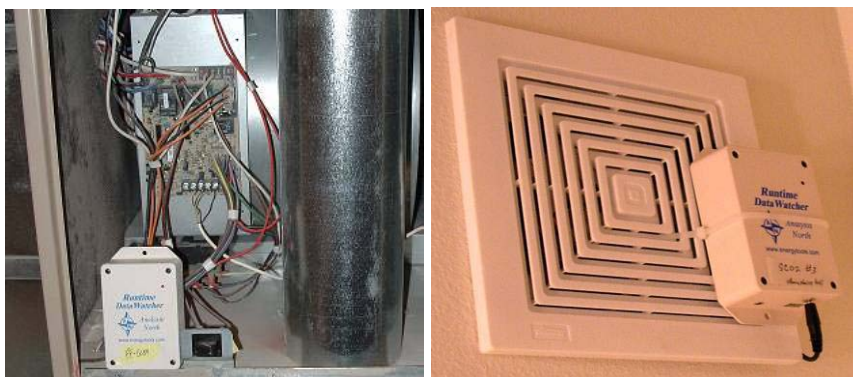


Figure 4: Runtime Data Watcher on furnace fan and bath fan.

Blower door tests: Blower door tests of the house “as lived in” during the study period were done to estimate (1) the house natural air leakage, and (2) the zonal air leakage coming into the house through the garage and the crawl space. Natural air leakage was calculated from blower door depressurization tests using the AHFC blower door test standard⁶ and The Energy Conservatory's Tectite 3.0 software. All exterior doors and windows were closed; all interior doors were open except the house-to-garage door and the house-to-crawl space hatch. All mechanical systems were off, however, the flue and combustion air in the garage for the furnace, water heater, and unit heater were unsealed. Fireplaces, where present, were direct vent type and

⁶ AHFC Blower Door Test Standard BD1.97

untreated. The crawl space vents were left as found in order to evaluate the houses as operated by the homeowners during the study period. All pressure measurements were taken with The Energy Conservatory's automated pressure testing system and Tectite software. This system uses computer-controlled measurements and verifies the reliability and repeatability of the data collected.

The Energy Conservatory's zonal pressure diagnostics utility (ZPDU) was used to calculate the leakage between the house and connected zones: the garage and the crawl space. The ZPDU calculations are in cubic feet per minute at 50 Pascals (CFM50) and given as a minimum to maximum range. The average of the leakage through the zones was taken from this range in the ZPDU calculation. The blower door tests were first taken with the zones closed, as noted above, then re-tested with the zone to house doors open. Six of the nine houses had complete zonal blower door test data. The houses are of similar design by the same builder in the same subdivision and of similar age. To give a consistent and equal zonal exclusion, the average zonal leakage from the six houses was applied to all nine. This averaged percent of leakage through the zones was subtracted from each house total to estimate the portion of ventilation air into the house that was **not** coming through these zones. This procedure generates an estimate of the usable natural air leakage contribution to house ventilation. This exclusion reflects the concern that pollutants in the garage and the crawl space air make it unsuitable for ventilation. Moreover, AHFC policy requires the exclusion of air coming through the crawl space and garage in calculating airflow rates for compliance with the BEES ventilation standard.

These blower door test results, with the exclusion of crawl space and garage air, provided the inputs for ASHRAE 119 calculations, which estimate the effective ventilation from natural air leakage. They were also used with the ASHRAE 136 calculations that estimate the effective ventilation rates for mechanical airflow⁷.

Data Loggers Descriptions

To monitor indoor air quality parameters, data logging stations were assembled and installed in the master bedroom, a second bedroom, the living area, and the garage of each of the nine homes (**Figure 5**).

The following parameters were monitored:

1. Carbon monoxide (CO) – a harmful product of incomplete combustion of fuel typically found in car exhaust and gas cooking ranges, measured in parts per million (ppm).
2. Benzene – a carcinogenic compound release from gasoline, measured in parts per billion (ppb).
3. Carbon dioxide (CO₂) – a byproduct of exhalation, cooking, measured in parts per million (ppm).
4. Temperature – measured in degrees Fahrenheit.
5. Relative humidity (RH) – measured as a percent of moisture in the air relative to the saturation point at that temperature.

⁷ Total Effective Ventilation is described in appendix A.

6. Pressure – pressure difference between the inside and outside of the house, measured in Pascals (Pa).

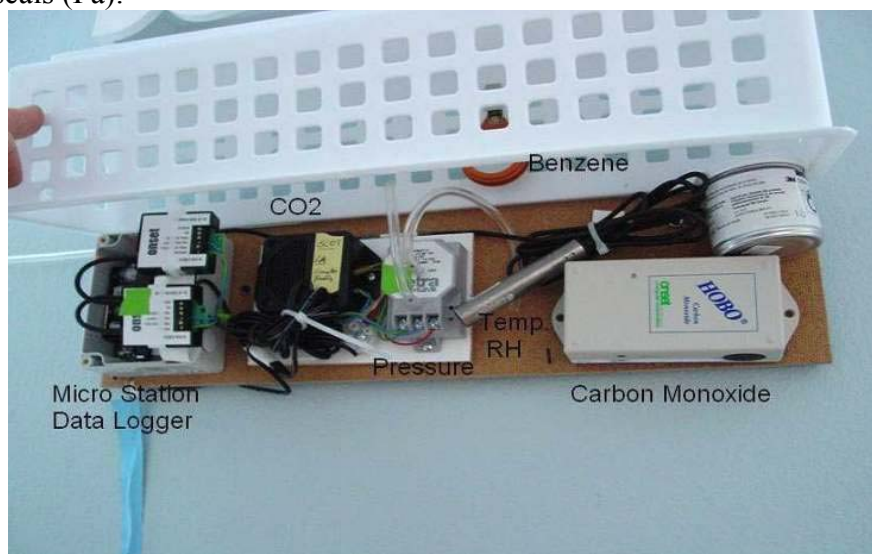


Figure 5: Data logger station.

CO data collection: Carbon monoxide samples were collected in all four sampling locations with Hobo carbon monoxide (Model H11-001) data loggers: the garage, the master bedroom, a second bedroom, and the main living area of each house. The data loggers measured and recorded CO levels at two-minute intervals throughout the four-month study period.

Benzene data collection: Benzene samples were taken with a passive air-monitoring badge made by 3M (Model 3M-3500) located in three sampling locations: the garage, the master bedroom, and the main living area of each house. To compare levels in the garage with those in the living area, all three badges in each house were exposed for the same periods (ranging from 10 to 33 days).

The following four indoor air quality parameters were logged with sensor outputs recorded by Onset's Hobo Micro Station (Model H21-002).

Temperature data collection: Temperature was recorded in all four sampling locations: the garage, the master bedroom, a second bedroom, and the main living area of each house. An Onset "smart" sensor (Model S-THA-M002) recorded directly to the Micro Station. Temperature was recorded in two-minute intervals for the four months using output in degrees Fahrenheit. Onset's Hobo temperature, RH logger (Model H08-007-02) was used in the second bedroom location instead of the Onset "smart" sensor.

Relative humidity data collection: Relative humidity was also recorded in all four sampling locations: the garage, the master bedroom, a second bedroom, and the main living area of each house. An Onset "smart" sensor (Model S-THA-M002) recorded relative humidity in two-minute intervals for the four months. Onset's Hobo temperature, RH logger (Model H08-007-02) was used in the second bedroom location instead of the Onset "smart" sensor.

CO₂ data collection: CO₂ samples were collected in three sampling locations with a Telaire Carbon dioxide (CO₂) sensor (Model 6004): the garage, the master bedroom, and the main living area of each house. CO₂ was recorded as a voltage output from the sensors through a 0-5 volt input adapter (Model S-VIA-CM14). These voltage outputs can be converted to parts per million (ppm). The sensor output of 5 volts was logged by the Hobo Micro Station (Model H21-002) through the Hobo volt input adapter (S-VIA-CM14). Micro Station data was recorded at two-minute intervals for the entire four-month study period.

Pressure data collection: The pressure differential was recorded in three sampling locations: the garage, the master bedroom, and the main living area of each house. Pressure was recorded as a voltage output from the sensor through a 0-5 Volt Input Adapter (Model S-VIA-CM14). This voltage output was then converted to Pascals. Setra's (Model 2651R25WB45T1C) pressure sensor with a 5-volt output recorded to the Micro Station through the Hobo volt input adapter (S-VIA-CM14). An outside reference hose ran from the sensor to outside through 1/4-inch flexible tubing. Several methods were used to penetrate the exterior wall. Typically, a 3/32-inch brass tube was passed through a gap in the window weather-stripping and terminated with an aquarium air bubble diffuser for a wind damper (**Figure 6**).



Figure 6: Outside reference pressure hose was terminated with an aquarium air bubble diffuser as a wind damper.

Outside temperature and wind speed data collection: Hourly average outside temperature and wind speed data from Anchorage International Airport weather station was used for the ASHRAE 119 and 136 natural air leakage calculations.

Logger Station Location

The location of the data logger station was a compromise between the need for proximity to an outlet for power, a window for outside pressure reference, and to the breathing zone of the sampling area. Also important was a simple, low-impact installation that could be completed quickly and be accessible for performance checks and downloading data. Finally, the logger station could not be objectionable to volunteers and should minimize damage to new homes. A wall mounting, at approximately head height to minimize child tampering, was typical for the living and bedroom locations. Garage installations were similar, with the outside reference hose going through the combustion air opening.



Figure 7: Logger location in living area.

Data Collection

Volunteer occupants were asked to continue with their normal lifestyles and the houses were studied as-is with the following exceptions:

- Four of the houses were not initially equipped with the outside air supply duct to the furnace return. These houses eventually had this part of the Skuttle system installed. Only the period **with** the full Skuttle system is included here. This accounts for some of the variation in the start time of the data collection among the houses.
- Two volunteers with dehumidistat controls were asked to convert to timer controls on their bathroom exhaust fans to provide equal distribution of each of the three bath fan controls among the nine houses.
- Volunteers were asked to operate their bathroom exhaust fan controls as follows:
 - Manual switches: continue “normal” use as needed for ventilation.
 - Dehumidistat controls: these were initially set at 35% RH. Some homeowners later changed the settings.
 - Timer controls: these were initially set to run 20 minutes per 2 hours. Some homeowners later changed the settings.

RESULTS

The data analysis focused on generating an effective ventilation calculation from a combination of usable natural air leakage and the Skuttle ventilation system. This generated a total effective ventilation flow for each house that was then compared to the BEES requirement. To start the process of calculating the effective ventilation flow, the blower door test estimates of natural air leakage were converted into hourly average flow rates. The furnace supply flow and the bathroom exhaust flow, along with the runtime data, were combined for estimates of the hourly average mechanical flow. The natural air leakage flow rates were combined with outside hourly weather data to calculate the effective ventilation using an ASHRAE 119 calculation. The mechanical flow was calculated using ASHRAE 136. These results were reduced to flows considered usable for ventilation in compliance with BEES requirements. (See *Appendix A* for detailed description of these calculations.)

One of the difficulties in calculating the effective ventilation contribution of the fans is that the flows will change depending on which fans are on at the same time. Due to the complexity of this calculation, it was assumed that each fan was contributing its flow separately. A probability analysis on the fans running together, and the difference in that flow, showed a difference of 2.4%. Given the limited operation of the bath fans, this is thought to be a small error in the airflow calculations and therefore the effective mechanical ventilation reported here is based on each fan running separately.

To progress towards a summary of total effective ventilation, the mechanical and natural air leakage results were averaged from hourly into daily averages. These daily averages have been plotted on the total effective ventilation graphs for each house on pages 18 to 20. The process to calculate the total effective ventilation flow rates involved numerous steps that are described in the headings below:

- Blower door tests
- Natural air leakage flow rate calculations
- Usable natural air leakage amount
- Mechanical system contribution (Usable amount also applies to the mechanical bath exhaust portion - see *Appendix E*)
 - Furnace fan supply
 - Bath fan exhaust
 - Runtime results
- Total effective ventilation

The results in these headings progress towards the summary table and the graphs of the daily total effective ventilation flow rates for each house. These flow rates are then compared to the BEES requirement.

Blower Door Tests

Total EqLA -- total equivalent leakage area at 10 Pascals is an estimate of the cumulative hole size of all air leaks in the house exterior. The EqLA ranged from 164.8 sq. inches to 465.5 sq. inches.

CFM50 -- cubic feet of air per minute at 50 Pascals. For a given house size, an increase in CFM50 indicates increasing air leakage in the house exterior envelope. Measurements ranged from 1,590 to 3,816 CFM50.

ACH -- Air changes per hour. The air exchange rate of the interior volume that leaks to the outside in one hour. This can be expressed as ACH natural or as ACH@50 Pascals from the blower door test. Natural air leakage ranged from .36 to 1.35 ACH and ACH50 ranged from 4.6 to 13.6 ACH50.

Table 1: Blower Door Test Results

House ID	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
House Volume (cu.ft.)	21,185	16,065	13,930	13,290	15,035	15,310	16,790	16,255	16,770
Floor Area (sq. ft.)	2,152	1,823	1,544	1,587	1,789	1,750	1,889	1,823	1,889
Height (feet)	21	20	9.5	19	19.5	19.5	19.5	19	19.5
EqLA (sq. in.)	165.5	164.8	262.8	220.4	349.9	174.7	465.5	186.8	180.2
CFM50	1,630	1,590	2,499	2,128	3,033	1,710	3,816	2,031	1,887
ACH50	4.6	5.9	10.8	9.6	12.1	6.7	13.6	7.5	6.8

Natural Air Leakage Flow Rates

Natural air leakage was calculated from blower door depressurization tests. These tests, using Tectite software, calculate the natural air leakage into each house. The natural air leakage estimates ranged from .36 to 1.35 air changes per hour (ACH). See **Table 2**. It is important to note that the model for calculating natural air leakage assumes that the leakage is evenly distributed throughout the house envelope. If the actual house leakage is largely in the crawl space, and the upper portion of the house is reasonably tight, then the natural air leakage will be overestimated by the model. (As an extreme example, a blower door test result on a hot air balloon, with its large hole on the bottom, would distribute this leakage area over the entire balloon surface and estimate air leakage too leaky to fly.) The total effective ventilation, which includes natural air leakage, is likely over-estimated for the houses SC05 and SC07 in this study, which had crawl space vents open. It is especially notable that their 1.07 and 1.35 ACH were much higher than the others and that air leakage estimates from CO₂ decay were much lower than these blower door estimates. This variation in natural air leakage results is addressed further in the discussion section of this report.

Usable Natural Air Leakage

A reduction of the natural air leakage flow rate was made in order to look at the portion that is usable for ventilation. This estimate of the exclusion was made for the portion coming in through the garage and crawl space zones. These may be polluted zones and the air coming through them may not be suitable for ventilation. Moreover, AHFC policy requires the exclusion of air coming through the crawl space and garage in calculating natural air leakage contributions to ventilation airflow rates.

To estimate the zonal exclusion the blower door tests were first taken with the zones closed then re-tested with the zone to house doors open. Six of the nine houses had complete zonal blower door test data that could be used for the zonal exclusion calculations. A range of results was given in the zonal calculations. Averaging the results from this range gave percentages for zonal leakage of 33% from the crawl and 29% from the garage. These percentages are consistent with a recent Municipality of Anchorage study⁸, which analyzed air exchange rates from the garage to

⁸ Investigation of the Influence of Attached Garages on Indoor VOC Concentrations in Anchorage Homes, L.-J. Sally Liu, et al. 2005.

the house with tracer gases. This leaves **38%** of usable natural air leakage for ventilation. The procedure of averaging the range of results to determine the zonal exclusion was thought to be the most reasonable way to treat the variables in the zonal blower door natural air leakage estimates. Finally, since the houses are of similar design by the same builder in the same subdivision and of similar age, the 38 percent of usable natural air leakage was applied to all nine of the houses to give a consistent and equal zonal exclusion.

Table 2: Natural Air Leakage Calculation Results

House ID	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
Avg. Air Changes Per Hour (natural)	0.36	0.44	0.60	0.75	1.07	0.49	1.35	0.45	0.45
Avg. Total CFM (natural)	126	118	139	166	268	124	378	121	126
% Usable CFM (natural)	38%	38%	38%	38%	38%	38%	38%	38%	38%
Avg. Usable CFM (natural)	48	45	53	63	102	47	144	46	48

Mechanical System Contribution

Furnace Fan Supply

The flow box measurements on the Skuttle duct ranged from 50 to 140 CFM into the furnace fan supply, although one Skuttle damper occasionally stuck closed, reducing the flow below 10 CFM. These flows varied widely due to different weights on the Skuttle damper arm, which allowed the various flows into the system when the furnace fan came on. It appears there is not a procedure for commissioning the system and adjusting the damper to provide a specific airflow.

Bathroom Fan Exhaust

The bathroom fan exhaust flows ranged from approximately 15 to 86 CFM. This range came from only two different bath fan models. It was found that 11 of the 24 fans in the nine houses had the back draft damper on the outside weather hood painted closed. This severely reduced airflow and accounted for most of the variation in fan flows. Several bath hoods were opened after the study period and these fans tested close to their rated flow. This appears to reveal a problem with spray painting the house exterior where excess paint seals the bath fan weather hood backdraft flap to its weather stripping. Moreover, it appears no final system commissioning occurs to confirm fan flows before occupancy. The homeowners thought the fans were working properly and the study looked at the houses as the homeowners were operating them.

The chart below shows the summary of the mechanical ventilation calculations. All numbers are in CFM.

These figures show the measured flow rates for the furnace fan Skuttle supply duct and each bath fan. Note that the actual ventilation provided depends on a combination of the flow rates, runtimes, and the proportion of natural air leakage replaced by flow from the mechanical systems. (See *Appendix A* for Total Effective Ventilation calculations.)

Table 3: Fan Flow Measurements.

Fan Flow CFM	House ID	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
	Furnace Skuttle	~10 or 120 **	50	140	120	117	115	93	103	53
Bath Fan Location	BFM (Master)	58	47	50	80	17*	23*	65	34	26*
	BF2 (Second)	60	51	31*	15*	20	48	86	63	25*
	BF3 (Third)	18*	20*	none	none	19*	none	18*	46	19*
Bath Exhaust Fan Total CFM		136	118	81	95	56	71	169	143	70

* Eleven of the 24 bath fans were found with outside weather dampers painted shut, obstructing flow.

**SC01 Skuttle damper occasionally stuck closed, obstructing flow.

RUNTIME RESULTS

Furnace Fan Runtime

The **daily average** of the furnace runtime is a percentage of time each day the furnace fan was on. Runtimes range from 17.8% to 54.7% (**Table 4**). The percent of furnace runtime decreases as outside temperatures warm. The average for the four-month study was 24.6%. The effective ventilation provided by the furnace supply ranged from 6.4 to 40.8 CFM. The daily average of the effective ventilation from the Skuttle furnace fan supply was only 8.3 CFM -- about 5% of the BEES requirement.

One interesting result in the furnace fan runtime data was noted in one house where the furnace fan ran continuously for a five-week period providing continuous supply ventilation. This raised the effective mechanical ventilation rate for this house from an average of 15.3 CFM to 67.6 CFM. This is a significant increase toward the 110 CFM BEES ventilation requirement for this house.

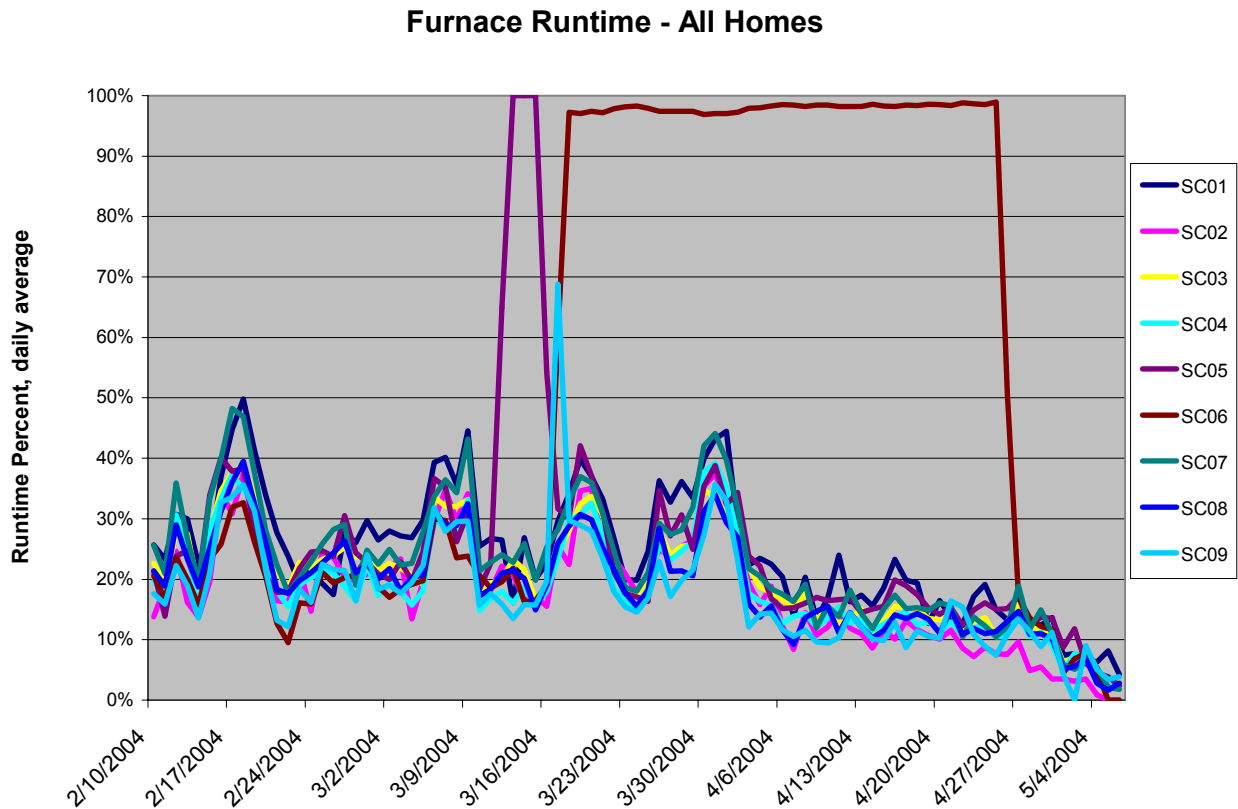


Figure 8: All furnace fan runtimes.

Table 4: Furnace Fan Runtime Results

House ID	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
MIN	4.2%	0.0%	2.7%	2.7%	2.4%	0.0%	1.8%	1.7%	0.0%
MAX	49.8%	37.4%	39.1%	39.2%	100.0%	98.9%	48.2%	39.5%	68.8%
AVERAGE	24.4%	18.0%	20.5%	18.8%	25.3%	54.7%	22.7%	19.1%	17.8%

Bathroom Fan Runtime

The bath fans varied widely in hourly average runtime. However, their overall contribution to ventilation was very small. Although a few fans were run for an hour or more at one time, the average hourly runtime over the four months ranged from 0.3% to 11.2%, contributing 1 CFM or less of effective ventilation. This is less than 1% of the BEES ventilation requirement and not a significant contribution to mechanical ventilation.

Table 5: All Bath Fan Runtime Results by Control

	Control	Timer	Dehumidistat	Manual
All Bath Fans	Average Runtime/Hour	11.2%	2.5%	0.3%

Table 6: All Bath Fan Runtime Results by House

House ID		SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
Bath Fan Control		Timer	Manual	Manual	Dehum.	Timer	Manual	Dehum.	Timer	Dehum.
All Bath Fans	Average Runtime/Hour	10.3%	0.6%	0.02%	2.6%	11.1%	0.15%	1.4%	12.2%	3.4%
	Effective Ventilation CFM	1.0	0.1	0.0	0.3	0.1	0.0	0.1	1.3	0.1

Of the three bath fan controls, the timer provided the highest average hourly runtime at 11.2%. The overall average for all three controls was 4.6% hourly average runtime over the four-month study period, contributing only about 1 CFM to the effective mechanical ventilation. Note that the runtime for the timer control is less than the initial 20 minute per 2 hour programming indicating occupants reduced the runtime settings. Dehumidistats controls were also found with their settings changed to lower the runtime. Four of the six occupants with these controls reported noise as the reason for reducing the runtime.

Combined Mechanical

The combined furnace supply and bath exhaust flow give the mechanical system contribution to ventilation. Unbalanced mechanical ventilation reduces the natural air leakage flows of a home. When combining natural air leakage and unbalanced mechanical ventilation the contribution from mechanical must be calculated using the ASHRAE 136 standard “A Method of Determining Air Change Rates in Detached Dwellings”. This standard is required by AHFC in determining ventilation compliance for these homes. The result of the ASHRAE 136 calculation for the mechanical contribution is defined as effective mechanical ventilation. The effective mechanical contribution ranged from 6 to 48 CFM.

Total Effective Ventilation

The total effective ventilation rate is the combination of natural air leakage, which is determined by ASHRAE 119 “Air Leakage Performance for Detached Single-Family Residential Buildings” and the effective mechanical ventilation rate. Only the usable portions of these flow rates are applied towards the BEES ventilation compliance. For a detailed discussion on the calculation methodology for total effective ventilation, see *Appendix A*. Total effective ventilation rates ranged from 51 to 158 CFM with the zonal exclusions.

Table 7: Average Effective Ventilation Results by House

House ID	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
Avg. Effective Mechanical Ventilation (CFM) - Includes Skuttle & Bath Fans	24	6	24	17	20	48	14	16.4	6.6
Avg. Total Effective Ventilation (CFM)	72	51	77	80	122	95	158	62	54

In the figure below, SC04 is typical of the mechanical system contribution to the effective ventilation. Graphs of all nine houses can be seen in *Appendix E*. The drop in mechanical system contribution reflects seasonal warming and the reduced furnace runtime.

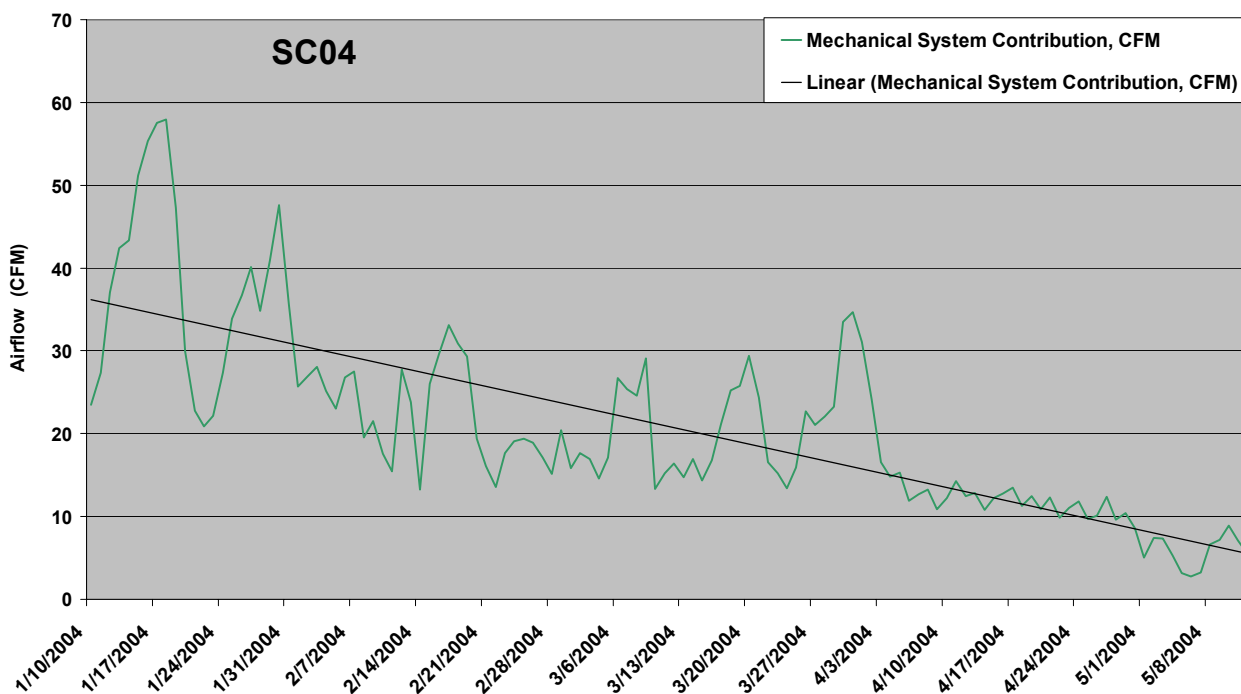


Figure 9: SC04 mechanical system contribution to ventilation.

The daily average of the total effective ventilation rate is compared to the BEES ventilation requirement. These results are summarized and plotted in the table and graphs below. They show that four of the nine houses had no days that met the BEES ventilation requirement. The remaining five houses had a range of 21% to 88% of the days during the study period that met the BEES ventilation requirement. It is notable that SC05 and SC07 with higher percentages of days in compliance include a likely overestimate of the natural air leakage flow. See the discussion section of the report below for supporting evidence of this overestimation.

Summary Tables

Table 8: Summary of days meeting BEES

% days meeting BEES	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
	0%	0%	21%	21%	39%	36%	88%	0%	0%

Table 9: Summary of Skuttle system ventilation

House	SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
Furnace Fan Runtime	24.4%	18.0%	20.5%	18.8%	25.3%	54.7%	22.7%	19.1%	17.8%
Avg. Effective Mechanical Ventilation (CFM)	24	6	24	17	20	48	14	16.4	6.6
Avg. Air Changes Per Hour (natural)	0.36	0.44	0.60	0.75	1.07*	0.49	1.35*	0.45	0.45
Avg. Usable CFM (natural)	48	45	53	63	102*	47	144*	46	48
% days meeting BEES	0%	0%	21%	21%	39%*	36%	88%*	0%	0%

* SC05 and SC07 natural air leakage was likely overestimated.

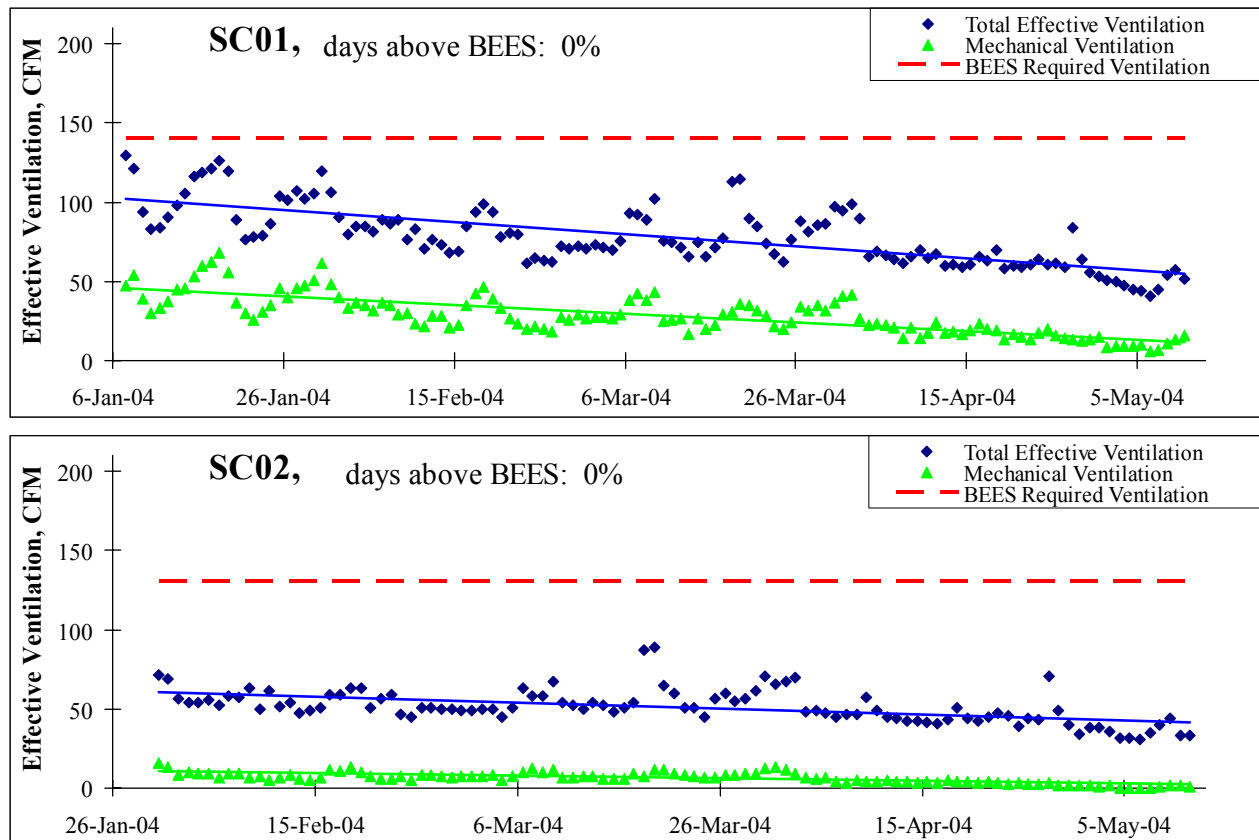


Figure 10: Total effective ventilation for in houses SC01 to SC09.

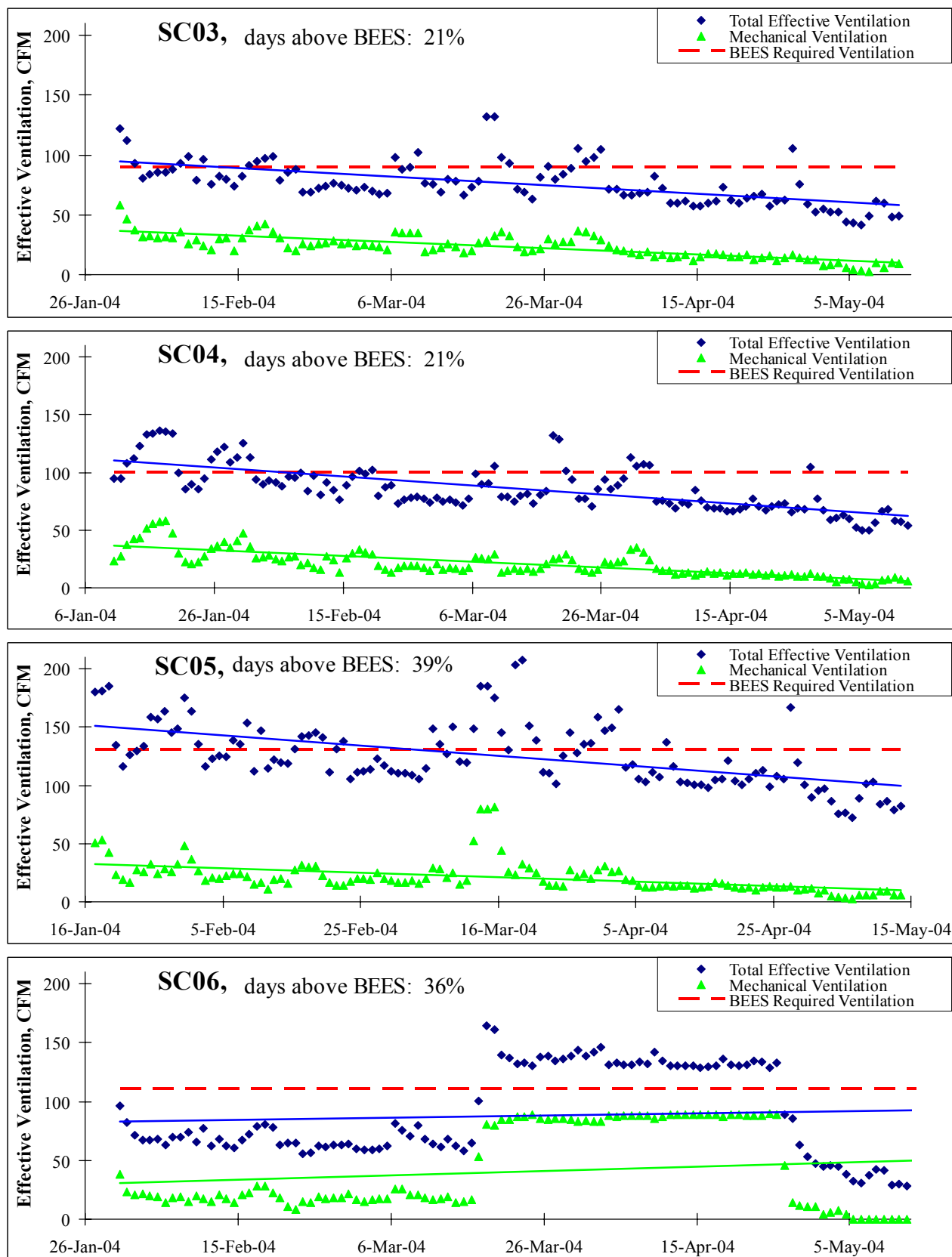


Figure 10: Total effective ventilation for in houses SC01 to SC09.

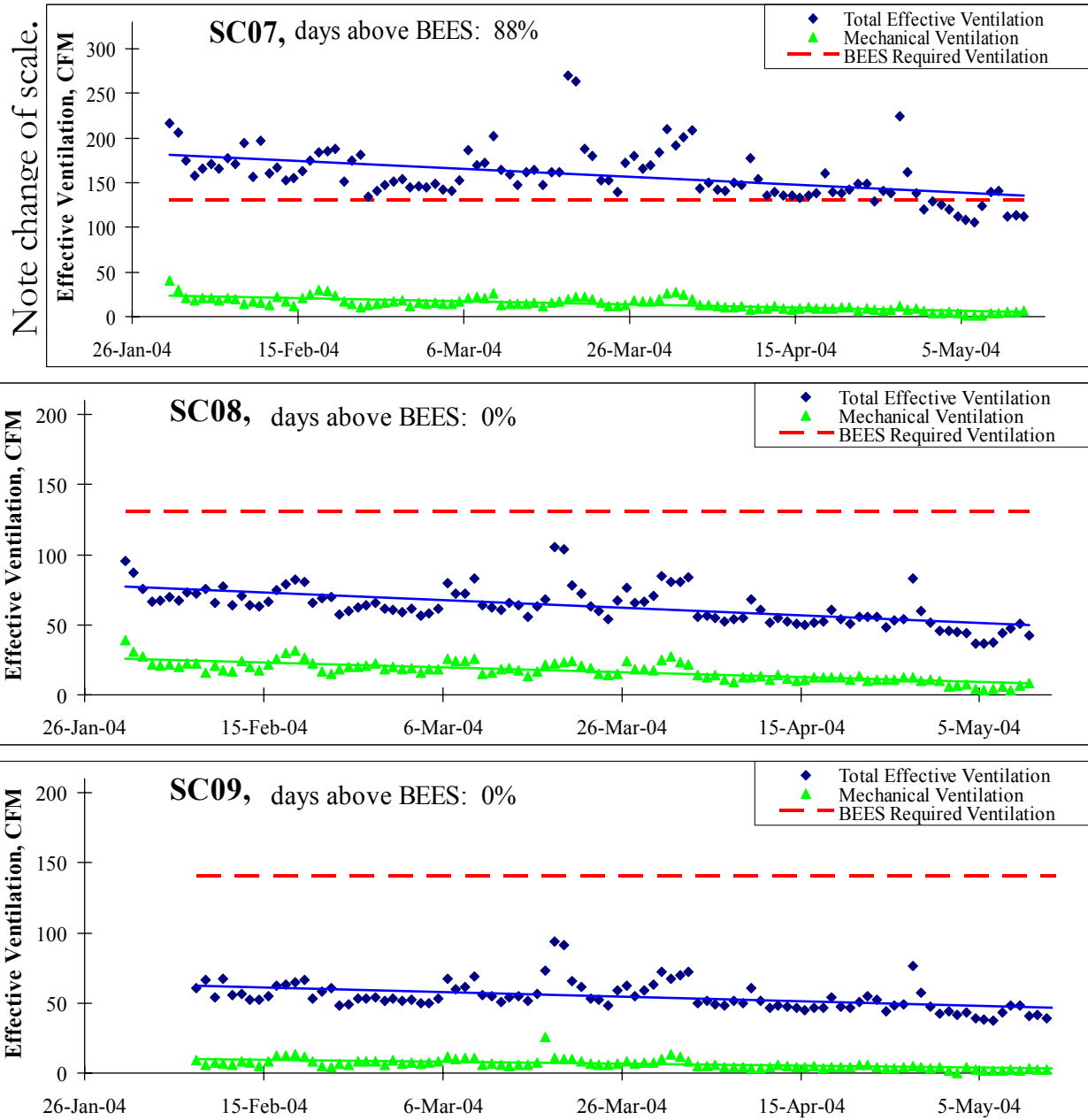


Figure 10: Total effective ventilation for in houses SC01 to SC09.

Discussion

The primary objective of this study was to estimate the effective ventilation rates in homes utilizing the Skuttle ventilation system. In addition to monitoring and measuring airflows, several indoor air quality parameters were monitored and some of the highlights of those results are provided below and in the appendices. The results of the indoor air monitoring lend insight into the flow patterns and air quality in the bedrooms, living areas, crawl spaces and garages. Pressure changes from the Skuttle ventilation system were also monitored demonstrating pressurization and interconnection of zones.

Pressure Tests

Data from the pressure loggers was especially good at showing the pressure increase from the furnace-fan-on cycle as well as the increase with the Skuttle supply duct installation. A pressure increase inside the house with respect to (WRT) outside the house can be clearly seen to occur at regular intervals (**Figure 11**). The pressure increase intervals are consistent with the furnace-fan-on runtime logger and on-site pressure measurements. It is also notable that the furnace-fan-on effect increased after the Skuttle supply duct was added (**Figure 12**) to house SC02 not initially equipped with the duct. The furnace-fan-on pressure effect increased approximately 50% after the Skuttle supply duct was installed.

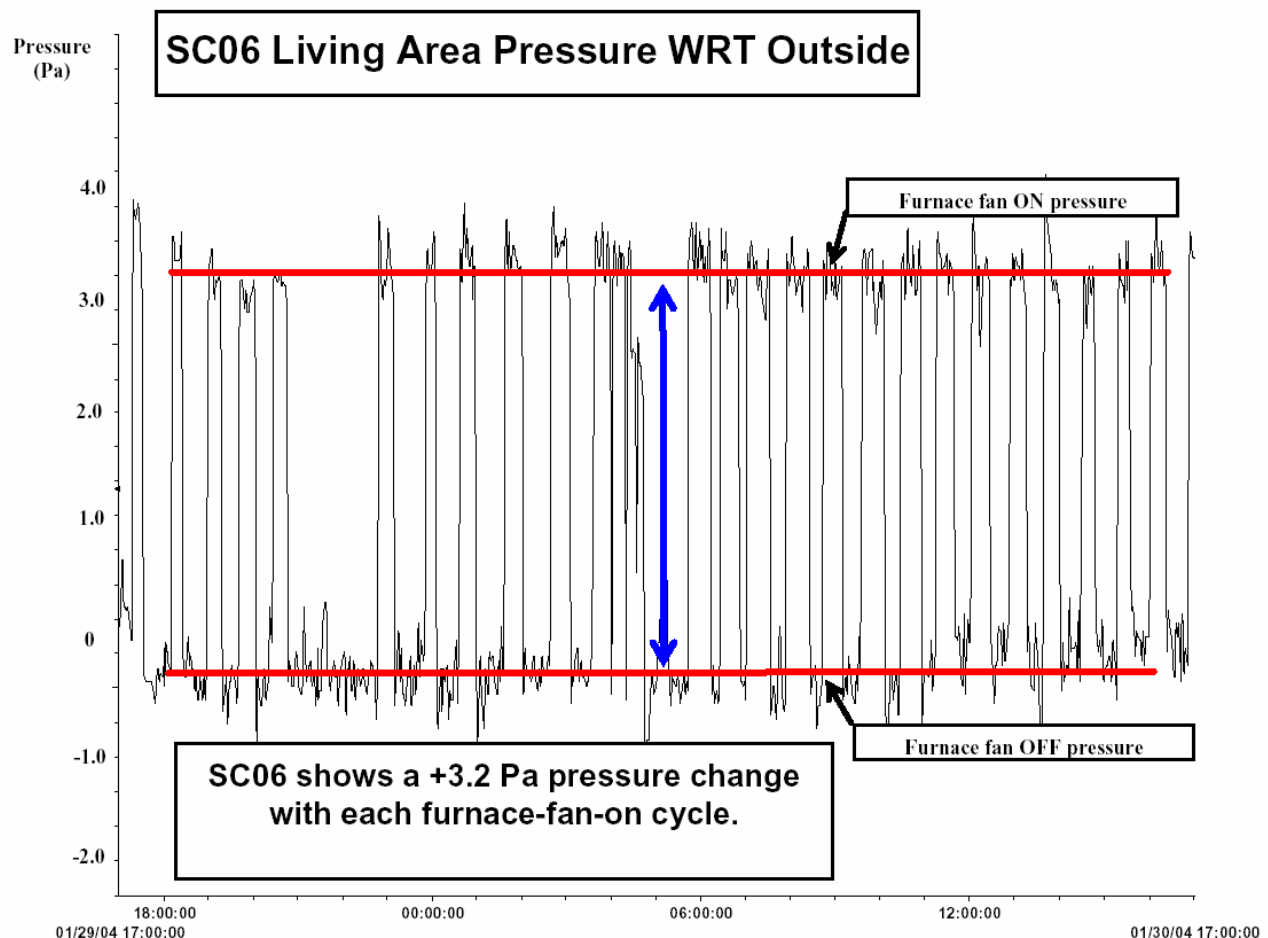


Figure 11: SC06 furnace-fan-on pressure effect.

The added pressure increase with the Skuttle ducts' supply-side airflow demonstrates the pressure imbalance common with supply-only ventilation. This pressurization effect from supply-only ventilation systems raises the concern that moisture at higher pressure inside the house will be driven into the wall and ceiling assemblies, causing moisture-related problems.

Pressure effects from exhaust fans and Skuttle supply can also be used to evaluate the natural air leakage results of the blower door. In less leaky houses, the measured pressure effect from

furnace-fan-on matched the predicted CFM50 for the house based on the CFM50 airflow at various pressures chart⁹. In leakier houses, the fan flow effect did not match what would be predicted. In these cases, the fan flow effect indicated a much lower CFM50 number would be more consistent with the measured fan flows. For instance, in house SC02 (**Figure 12**) the 0.9 Pa pressure effect from the Skuttle supply duct (120 CFM), was consistent with the measurement of 2,128 CFM50, but in the leakier houses the pressure effect was not consistent with the predictions for a high CFM50 house. These pressure effect results further suggest an over estimation of natural air leakage from the blower door test results for SC05 and SC07.

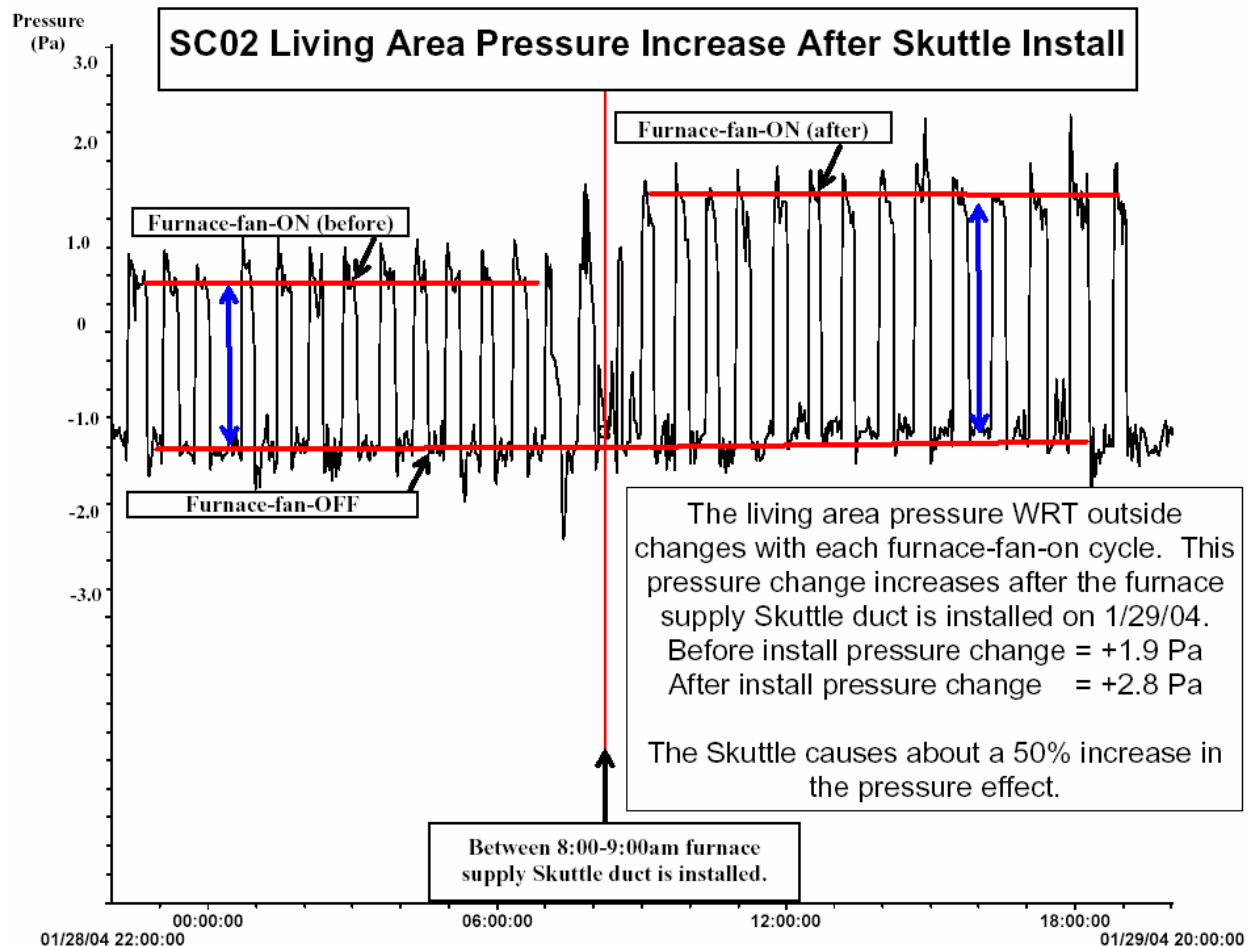


Figure 12: Increase in furnace-fan-on pressure after Skuttle duct installation, house SC02.

The graphs above show the house going positive with each furnace-fan-on cycle. This was typical of all the homes and can be explained by the Skuttle supply air duct drawing in outside air and blowing it into the house through the furnace duct system. Unequal duct leakage to the outside can also contribute to a pressure imbalance in the house when the furnace fan comes on.

⁹CFM-50 Airflow at Various Pressures, NFR, Inc., 1991.

However, in SC02 the change in pressure increase with the furnace-fan-on cycle is immediately observable after the Skuttle supply duct is installed.

Interconnection of Garage and Crawl

Pressure changes WRT outside in different zones were also useful in demonstrating the interconnection of the zones and the air leakage pathways between these zones. In several of the homes, the furnace-fan-on cycle caused the garage to go negative WRT outside (**Figure 13**).

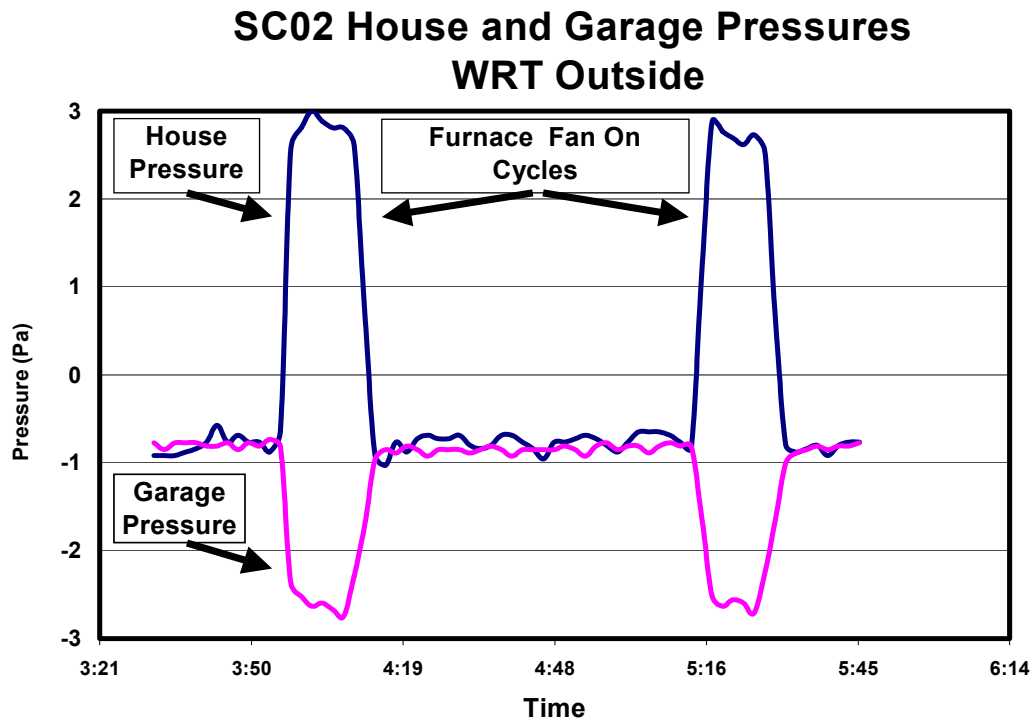


Figure 13: House and garage pressure effect.

Significant duct and furnace cabinet leakage pulling garage air into the furnace ducts contribute to this depressurization. During furnace-fan-off periods, both the house and garage remain slightly negative with respect to outside.

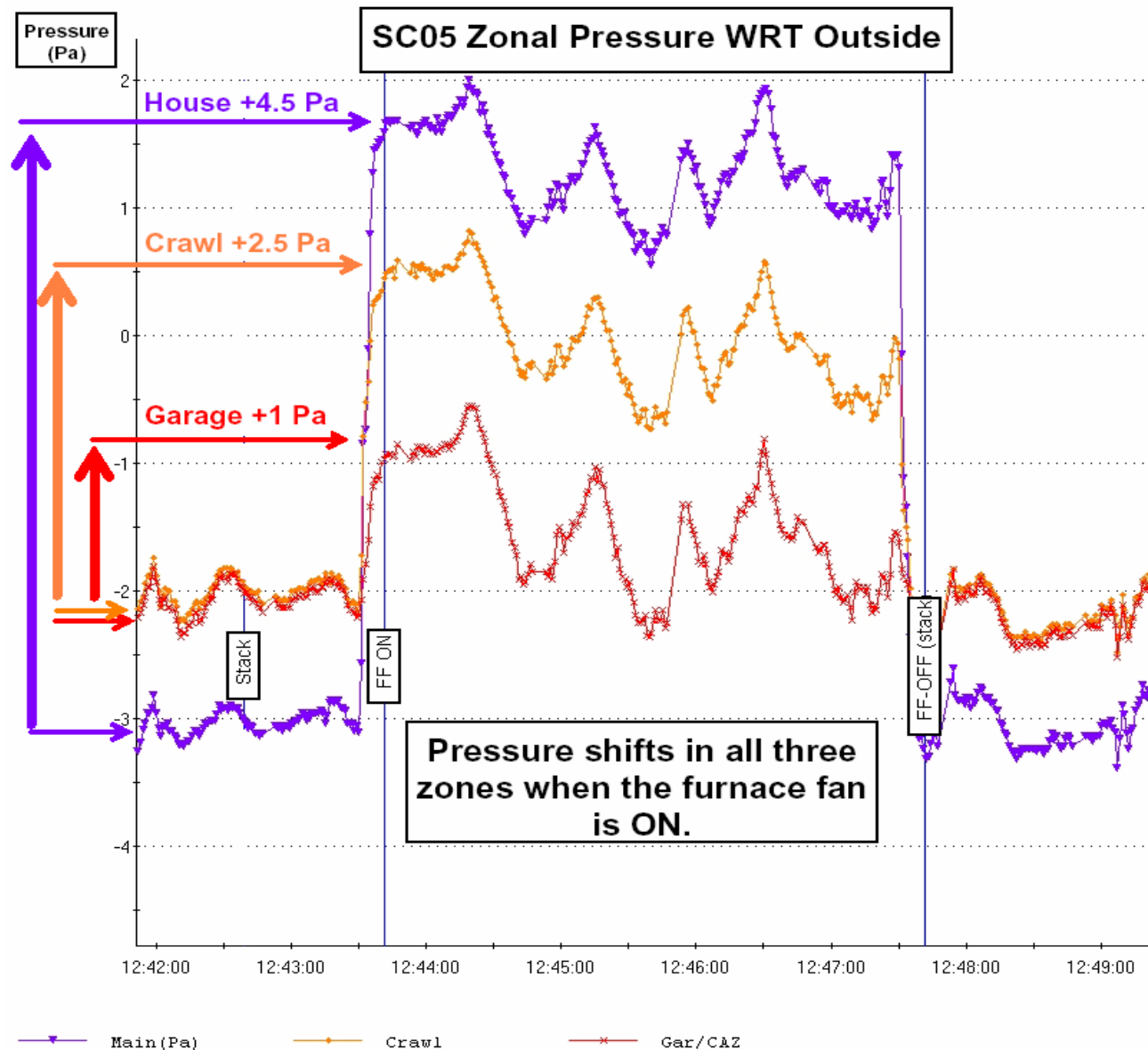


Figure 14: SC05 furnace-fan-on pressure change in three zones.

In the graph above the pressure shift from furnace-fan-off condition to furnace-fan-on shows a positive shift in all three zones. The pressure change in one zone also affecting the pressure in an adjoining zone is attributed to an interconnection between these zones.

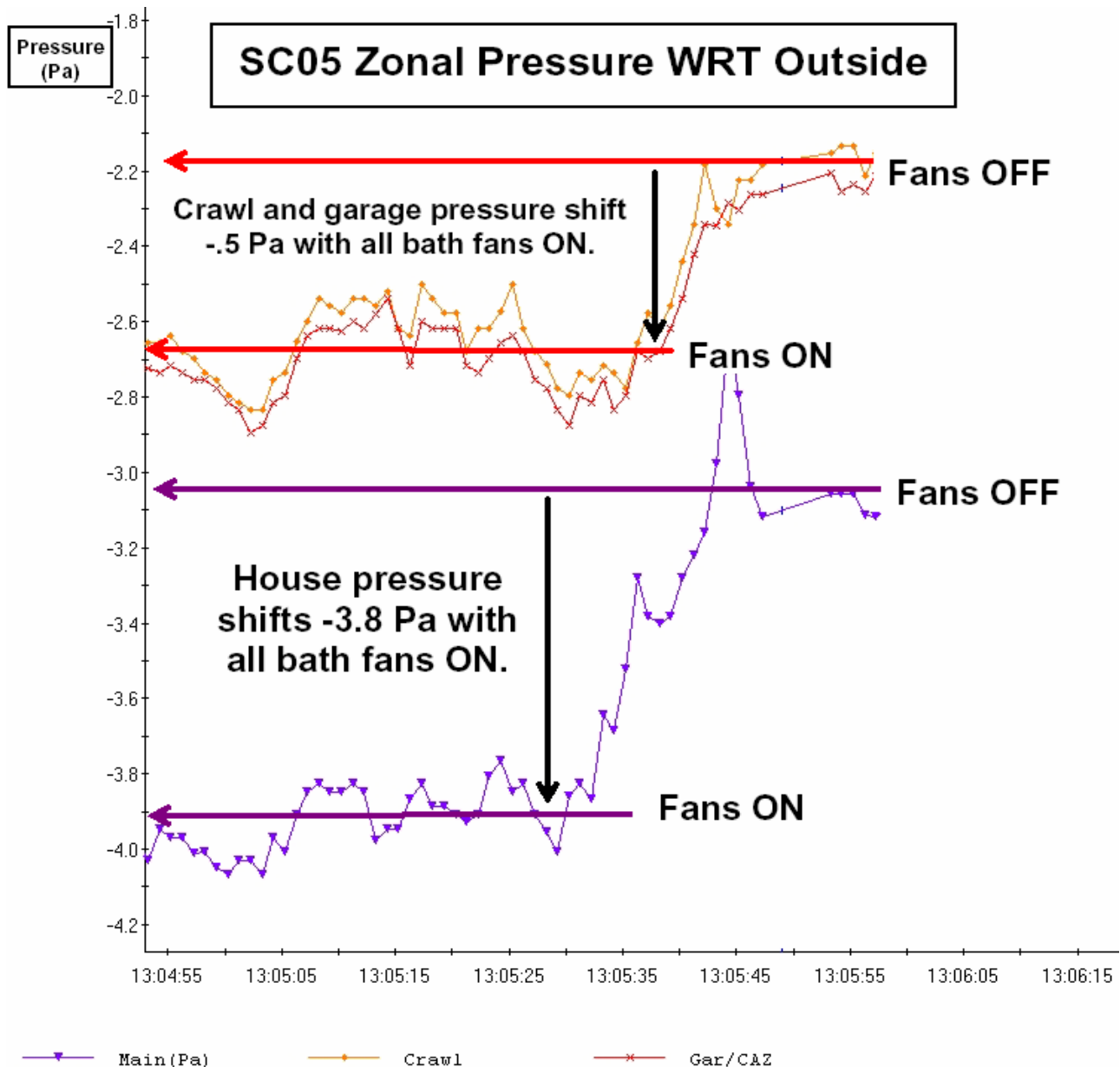


Figure 15: SC05 bath exhaust fan on pressure change in three zones.

The pressure shift in all three zones due to furnace-fan-on is also observed with the bath-fans-on condition. Furthermore, this depressurization of the house placing the house at a lower pressure than the adjacent zones indicates exhaust-only ventilation is pulling air through the crawlspace and garage and into the house.

Additional blower door testing also indicates the amount of interconnection between zones by comparing the pressure shift under different house conditions. The zonal pressures in the garage and crawl space were tested under two different conditions. The first condition shows the pressure differences WRT outside when the crawlspace hatch and garage man door to the house is closed and the house is depressurized to -50 Pa. These pressures in the crawlspace and garage WRT outside indicate how well connected (the leakage areas) the zones are to the

outdoors relative to the indoors. A pressure close to -50 Pa indicates the zone is more inside. A pressure close to zero indicates the zone is more outside. This interconnection can be demonstrated by comparing the results of the zonal blower door tests in (**Figure 16**). In the first test, both the crawlspace hatch and garage door were closed to the house. The crawlspace and garage pressures were -14.5 and -11.9 Pa respectively indicating more leakage to the outdoors than to the inside. In the second test, the garage door to the house is opened, depressurizing the garage to the same pressure as the house. Leakage between the crawlspace and garage is now subjected to the same 50 Pa of pressure as the home. The change in pressure in the crawlspace was substantial, going from -14.5 to -34 Pa WRT outside. This shift moves the crawl space from mostly outside to mostly inside indicating sizable leakage between the crawl and garage.

One of the difficulties in estimating air leakage contribution from the crawlspace and garage to the house is when they themselves are interconnected via air leakage paths. These paths may be leaks through the common wall area of the crawlspace and garage, through duct leakage in the crawlspace and garage, or both. Of the four homes tested, the results demonstrate significant interconnection between the garage and crawlspace. This interconnection provides leakage pathways for the air to move between each zone and enter the house. Later discussion will address the likelihood that this interconnection provides a pollutant transfer pathway. The zonal pressure test results of the other three homes are provided in *Appendix D*.

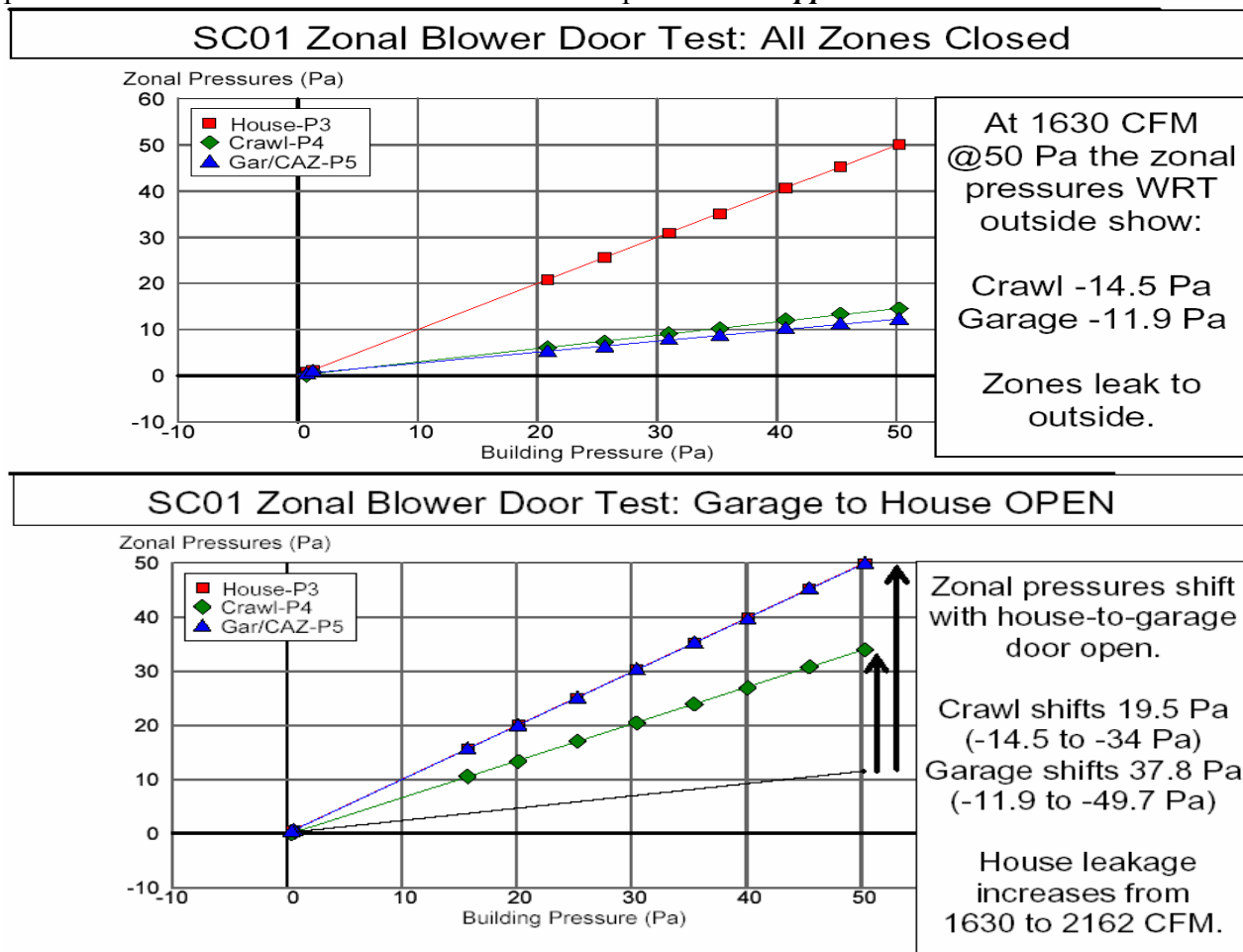


Figure 16: SC01 zonal blower door tests.

Monitoring CO₂ Levels

Monitoring carbon dioxide (CO₂) in the home and bedrooms offered some indication of actual mixing and distribution of ventilation air within the home during the periods of furnace-fan-on and furnace-fan-off cycles. **Figure 17** shows the relationship between CO₂ levels in the bedroom and furnace fan operation. The CO₂ and pressure levels are recorded in voltage and those units have been retained for graphing clarity. The bedroom CO₂ level rose quickly and exceeded the 2000 ppm limit of the sensor for many hours each evening while the nighttime setback thermostat reduced furnace fan operation. The small variations in the bedroom pressure were due to the furnace fan operation with Skuttle supply air pressurizing the house. During periods of little or no furnace fan operation CO₂ levels remained high until the furnace fan came on. Though the evening setback thermostat generated this worst case for elevated CO₂, other homes in the study also exhibited high CO₂ in the master bedroom during evening hours. The furnace fan operation is evident from the pressure changes in the room. **Figure 18** shows the living area CO₂ over the same time period. There is no mixing or distribution of ventilation air until the furnace fan comes on. This demonstrates the importance of the mechanical system in distributing ventilation air.

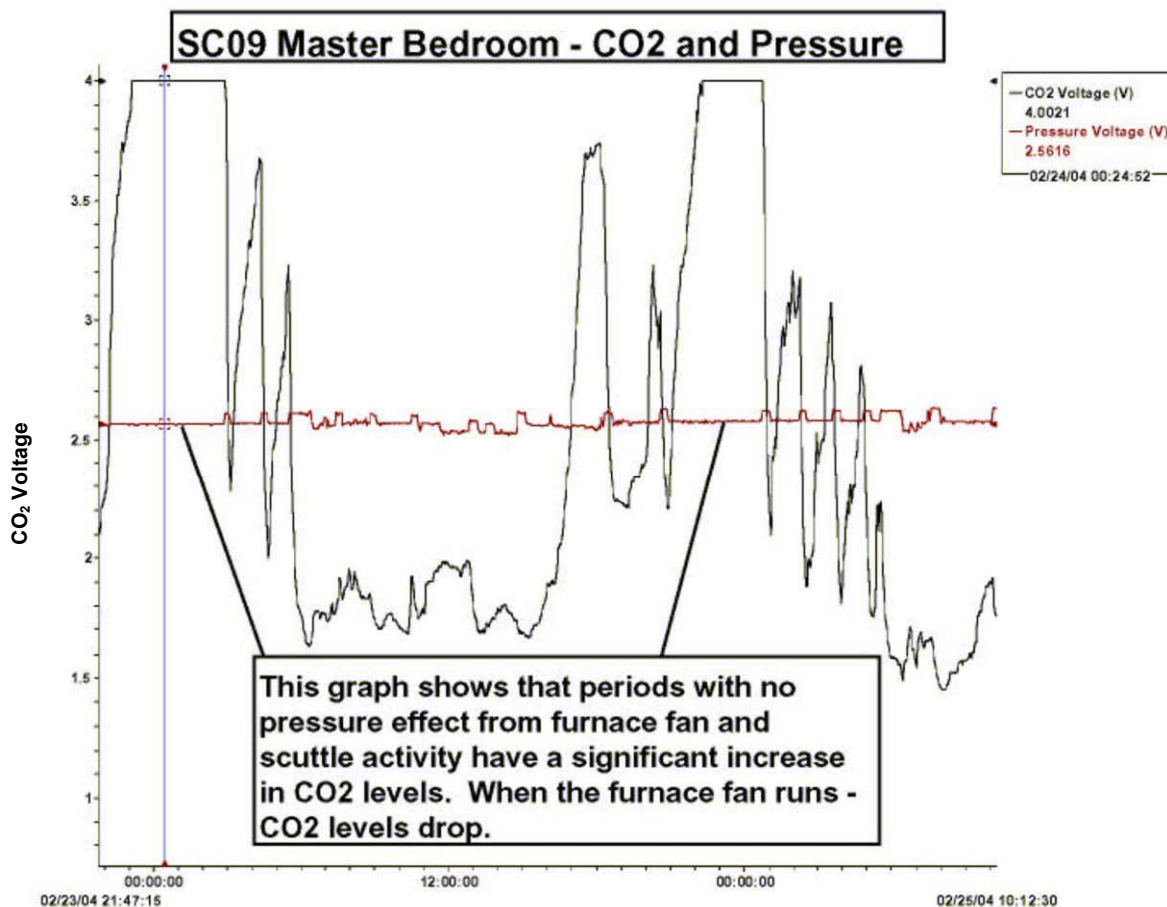


Figure 17: Carbon dioxide levels in house SC09 master bedroom.

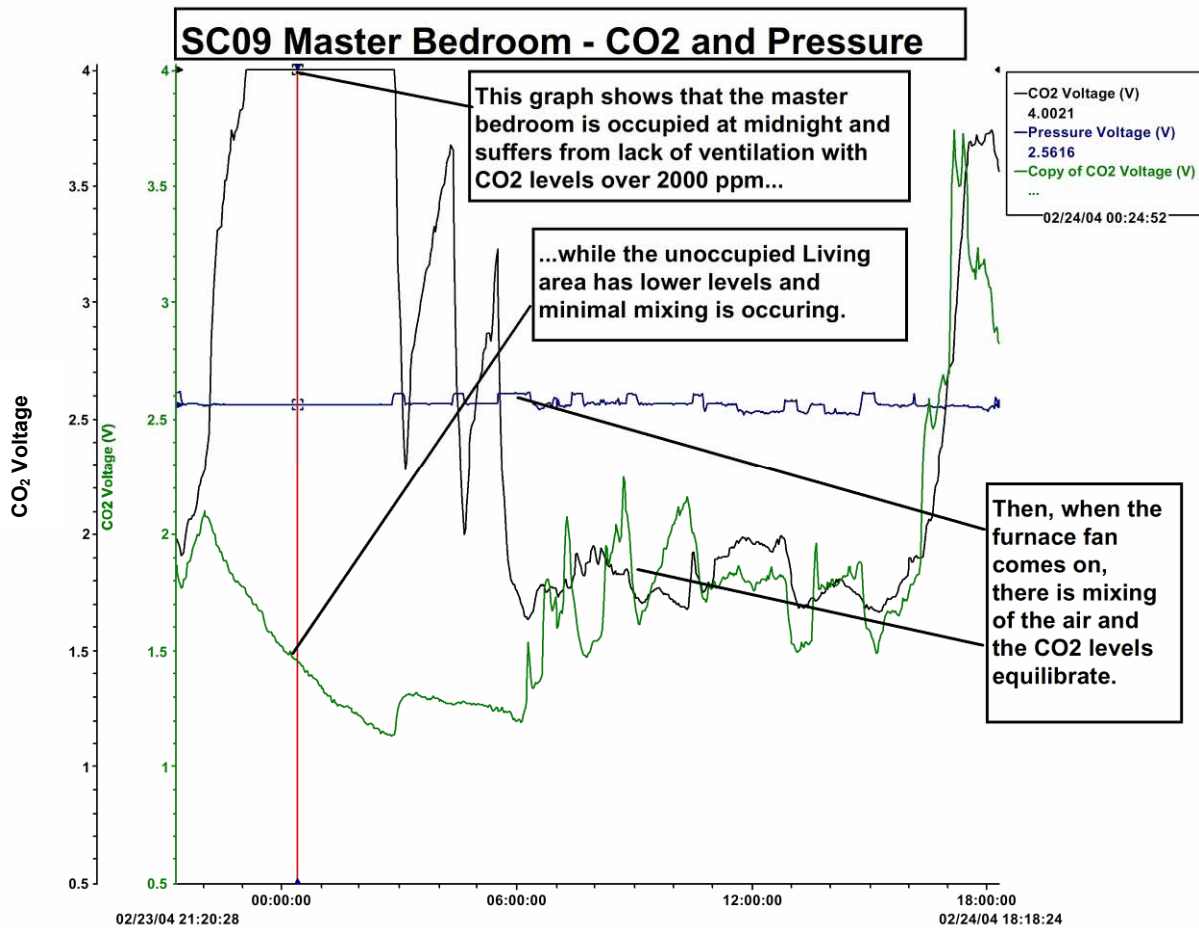


Figure 18: Carbon dioxide levels and pressure in house SC09 master bedroom.

Though CO₂ at the levels found in these homes is not considered to pose any health risks, ASHRAE 62 “Ventilation for Acceptable Air”¹⁰ recommends maintaining CO₂ levels of less than 1000 ppm as an indicator of indoor air quality. An adult sleeping requires approximately 7½ CFM of outside air to maintain CO₂ levels below 1000 ppm (ASHRAE 62). Fifteen CFM of ventilation will maintain CO₂ levels at about 1000 ppm with two sleeping adults in a bedroom. For CO₂ levels to rise well above 2000 ppm as was measured in this bedroom, it is calculated that less than 8 CFM of air was flowing into and out of the bedroom from the main living area or from natural air leakage while the furnace fan was off and the bedroom door closed. The blower door test results estimated an average natural air leakage rate of 126 CFM for this house. From the measured CO₂ levels, it seems little natural air leakage was entering the master bedroom and indicates the blower door test is over-estimating the amount of natural air leakage that is occurring in these houses. In the homes where the master bedroom door is closed during the evening, the operation of the furnace fan to provide uniform mixing and air circulation into those rooms appears essential.

¹⁰ ASHRAE 62-1989 Ventilation for Acceptable Indoor Air Quality.

CO₂ Decay Analysis

As previously noted in the report, there is uncertainty about the accuracy of the natural air leakage rates for those homes with open crawlspace vents. The blower door test software that estimates natural air leakage from the blower door test data assumes the leakage areas are distributed equally through the house. The open crawlspace vents created a significant disproportion of leakage areas on the lower portion of the house, resulting in an over-estimate of natural air leakage. House SC05 and SC07 blower door tests calculated an average annual natural air leakage rate of 1.07 and 1.35 air changes per hour respectively. Homes with closed crawlspace vents had estimated natural air leakage rates of .36 to .60 ACH. (**Table 9**).

Natural air leakage rates can also be estimated by analyzing the decay rate of CO₂ during times when the home is unoccupied. House SC07 was analyzed for CO₂ decay on four different days in January and February. The average air change rate from the CO₂ decay analysis was 0.39 ACH. This rate is three and one-half times less than the 1.35 ACH blower door estimate for natural air leakage. The lower ACH estimates for SC07 from CO₂ decay rate analysis appear to be more in line with the blower door test estimates of the other homes with closed crawl space vents. This further indicates the over-estimation of natural air leakage from the blower door testing. The figure below is a graph showing one CO₂ decay analysis in house SC07 giving a .41 ACH result.

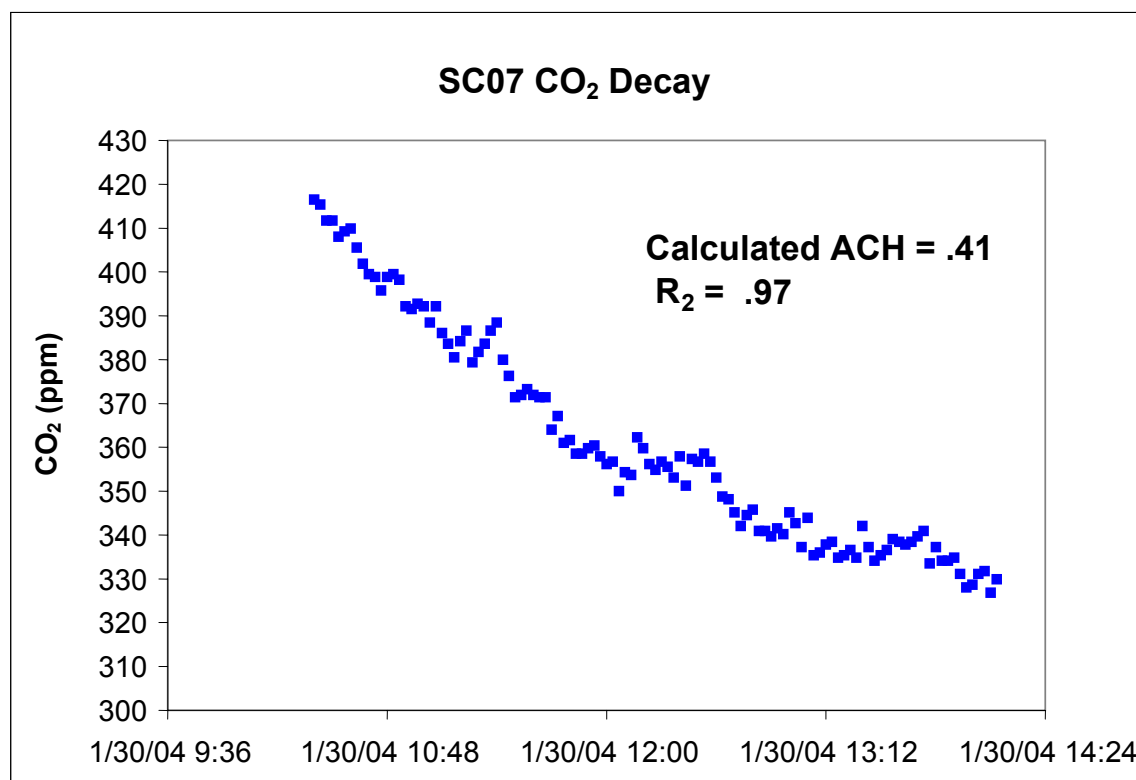


Figure 19: Carbon dioxide decay analysis calculation of 0.41 ACH.

Applying a lower natural air leakage rate to the total effective ventilation contribution has a significant impact. The figures below show the reduction in natural air leakage contribution

when the blower door estimated ACH of 1.35 has been lowered to 0.7ACH. The 0.7ACH was chosen as an upper limit of the other homes in the study. The second graph simulates the results on the ventilation from a reduced estimation of natural air leakage. The adjusted ventilation reduces the days that are above the BEES requirement from 88% to 3%.

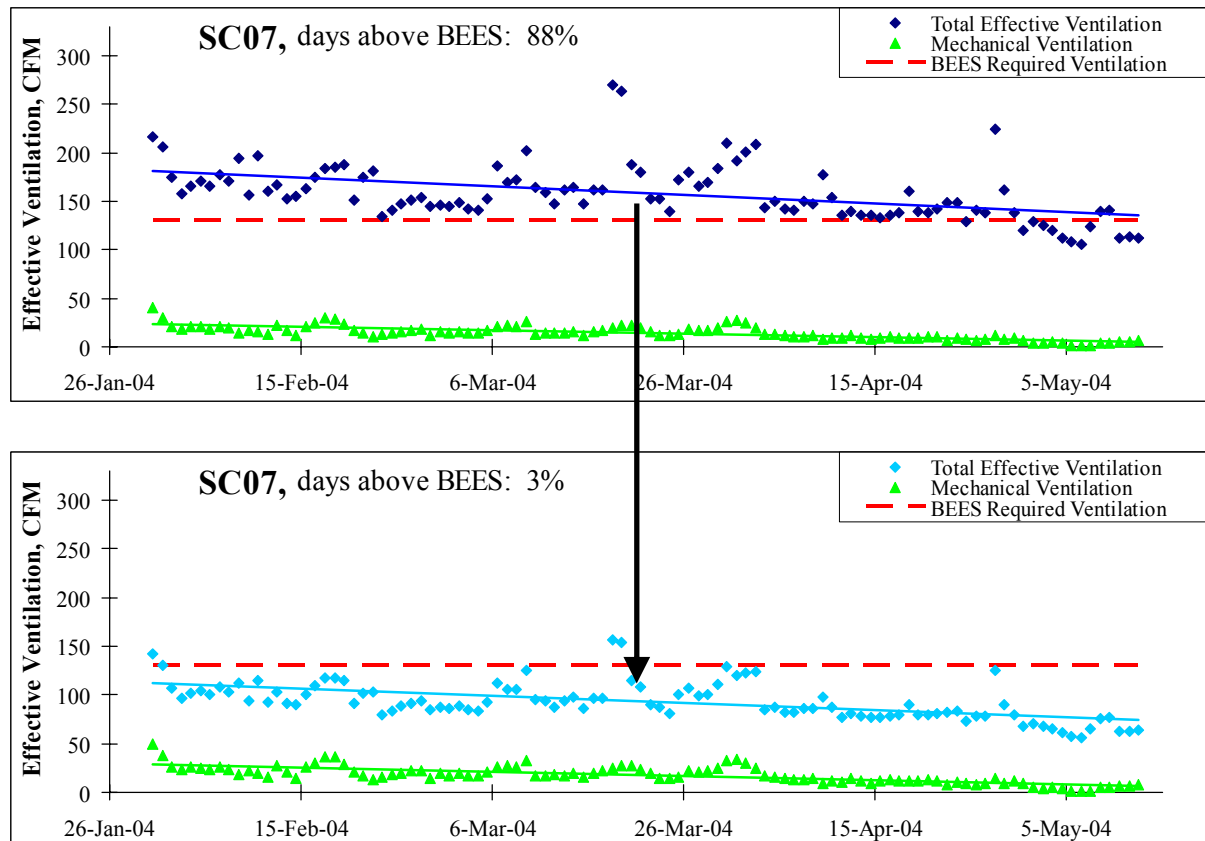


Figure 20: SC07 total effective ventilation with adjusted from 1.35 to 0.7 ACH natural air leakage rate.

Source and Quality of Ventilation Air

A good deal of effort in this study was made in estimating the zonal exclusion of natural air leakage passing through the garage and crawlspace and into the home. The uncertainty of the quality of this air, now or in the future, is the primary reason for AHFC requiring it be excluded from ventilation calculations. The following discussion provides support for the exclusion policy. The photos in Figure 21 show a flooded crawl space in one of the homes in the study. The long-term affects on the quality of air in this crawl space are unknown, but the potential for mold and other indoor air quality issues is significant.



Figure 21: SC06 flooded crawl space during monitoring period.

One home in the study provided the opportunity to use CO as a tracer gas, using several Draeger CO loggers, provided by the Municipality of Anchorage, to monitor the CO concentrations in the garage, house, and crawlspace for a 24-hour period. The home was unoccupied during the day.

Figure 22 shows the CO movement from the garage into the crawlspace and house just following a morning car start. CO levels in the garage peaked at 140 ppm. As shown in this single car start event, the CO levels increased in the crawlspace much quicker than the house, indicating a significant flow of garage air into the crawlspace. The crawlspace CO levels remained higher than the house for approximately 3 hours, then leveling off to the house CO concentration for the remaining several hours of the monitoring period.

This was only one home and one test. However, the results support the interconnection between the garage and crawlspace and potential movement of garage air into the crawlspace and subsequently into the home. This migration of garage pollutants into home via the crawlspace further supports the notion that crawlspace air may not be suitable for BEES compliance ventilation.

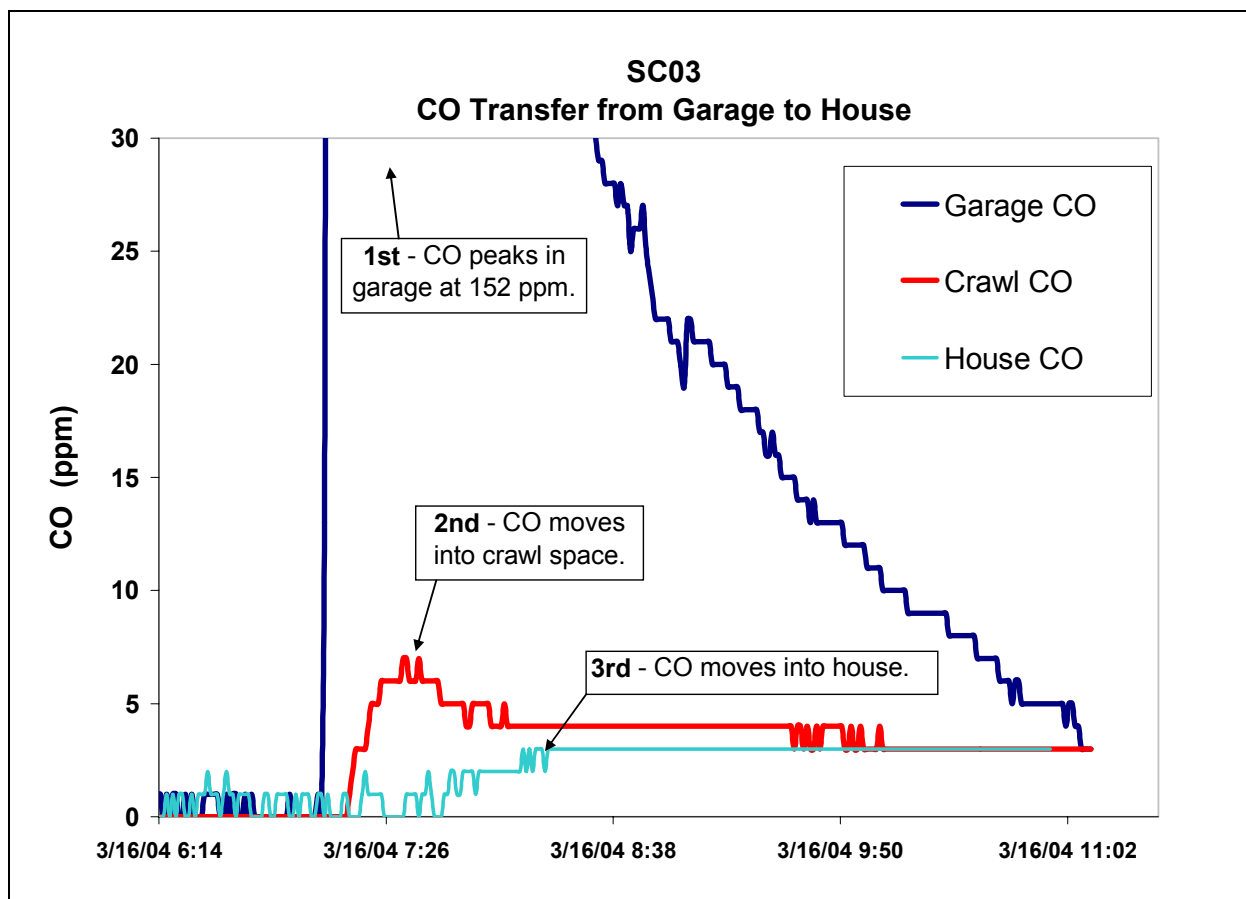


Figure 22: CO transfer from garage into house via the crawl space.

Carbon Monoxide Monitoring

CO was monitored in the garage, main living area, and master bedroom. The ability to monitor CO levels provides an opportunity to use CO as a tracer gas to observe the transfer of other potential pollutants throughout the home. The results indicate a pattern of pollutant transfer from the garage to the house as seen in **Figures 23 and 24**. This pattern was consistent with all eight homes with cars in the garage. Each time a CO event occurs in the garage, the CO levels increase in the house. This pattern indicates significant connection between the garage and the house.

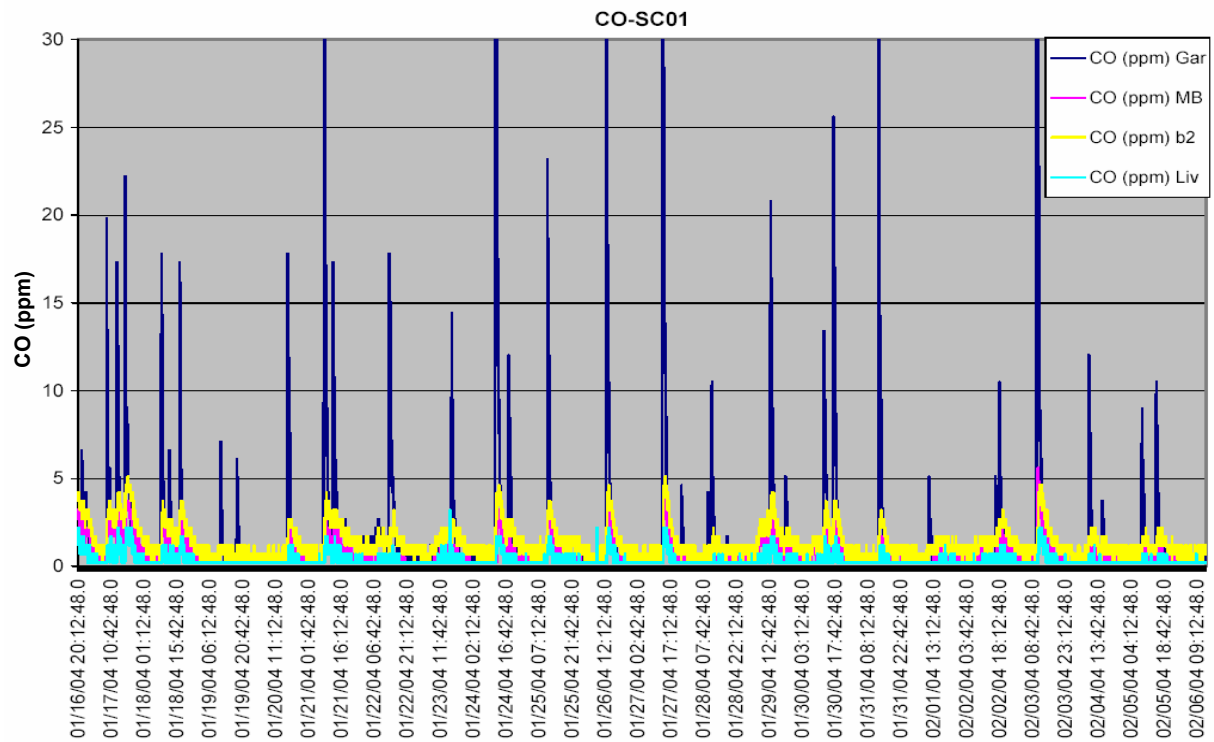


Figure 23: SC01 carbon monoxide levels in ppm.

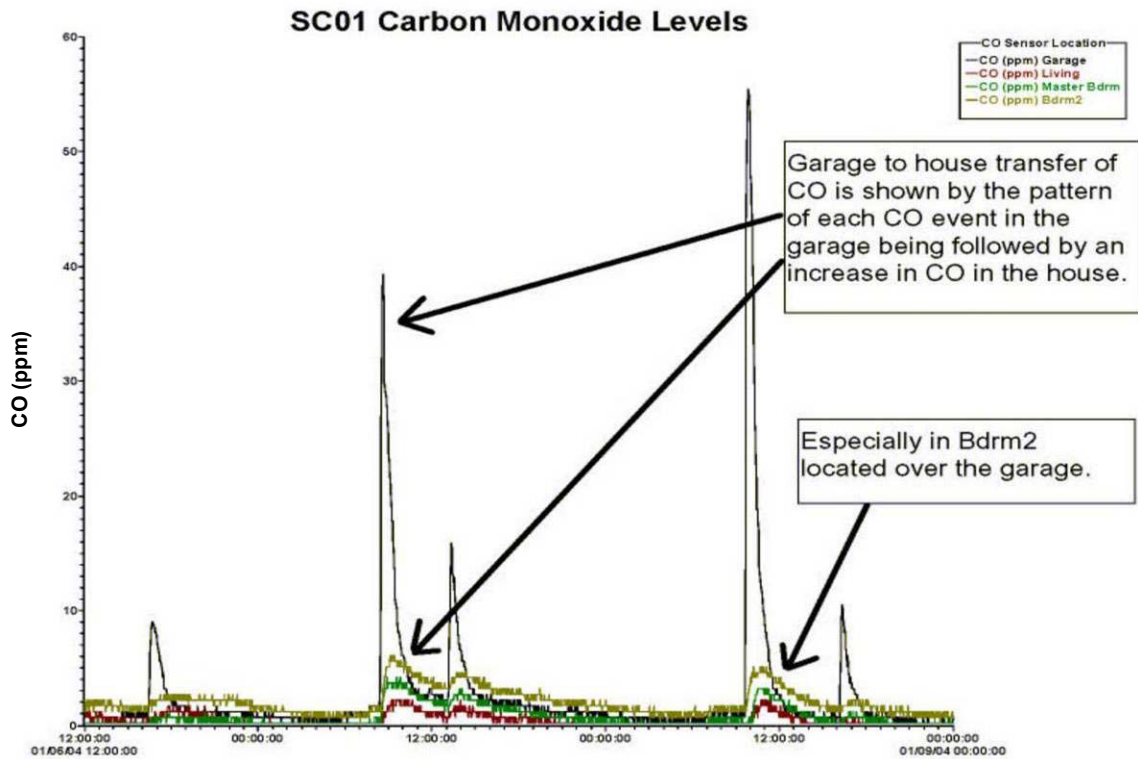


Figure 24: SC01 carbon monoxide levels in ppm.

Carbon Monoxide Exposure Levels

Garage source of CO ppm –CO level in parts per million (ppm) was measured by a sensor in the garage. The levels were logged at two-minute intervals and are averaged for one hour. The hour average of the peak CO levels in the garage ranged from 5 ppm (where garage was used as woodshop with no car present) to 105 ppm.

House CO ppm – CO level in ppm was taken from the average of two or three CO sensors located throughout the house. Peak CO levels in the house, averaged over an hour, ranged from 5.3 ppm to 15 ppm. The bedroom levels were typically higher than the house average.

No recommended CO exposure limits have been established for indoor air in homes. As an indoor air pollutant, the elderly, the very young, those with cardiovascular and pulmonary diseases are all particularly sensitive to elevated CO levels. The Environmental Protection Agency (EPA) recommends an exposure limit of no more than 9 ppm over an eight-hour period for outdoor air. No homes exceeded this EPA limit of 9 ppm over an eight-hour period. Sources of CO were found in the garage from car starts and to a lesser degree, gas cook stoves in the home.

Benzene Monitoring

The purpose of monitoring benzene levels in these homes was to determine if the Skuttle ventilation system significantly affected benzene exposure in homes and to add to the growing database of benzene levels found in Alaskan homes. The monitoring period of 10 to 31 days in this study provided for a detection limit of less than 2 ppb using the passive 3M badges.

The Alaska Department of Environmental Conservation ranks benzene #3 in Alaska's top ten hazardous air pollutants. The EPA has classified benzene as a Group A human carcinogen. Recent studies conducted by the Municipality of Anchorage¹¹ and Alaska Building Science Network¹² report elevated benzene levels in Alaskan homes with attached garages. Automobiles, small gas engines, and gasoline storage have all been identified as likely sources of benzene within the garage. Outdoor benzene and cigarette smokers were found not to be a significant source of benzene in these study homes.

Benzene Exposure Results

The table of results of the benzene levels shows that similar concentrations were found in the bedroom and living area indicating consistent distribution throughout the house with slightly higher concentrations in the location closest to the garage. Six out of the nine houses had levels at or above the 4 ppb minimum risk level * (MRL) for benzene. The house levels were approximately a third to a half of the level in the garage.

¹¹ Investigation of the Influence of Attached Garages on Indoor VOC Concentrations in Anchorage Homes, 2005.

¹² Indoor Air Quality & Ventilation Strategies in New Homes in Alaska, 2002.

Table 10: Benzene Level Results*

House #		SC01	SC02	SC03	SC04	SC05	SC06	SC07	SC08	SC09
<i>parts per Billion</i>		<i>ppb</i>	<i>ppb</i>	<i>ppb</i>	<i>ppb</i>	<i>ppb</i>	<i>ppb</i>	<i>ppb</i>	<i>ppb</i>	<i>ppb</i>
Benzene badge location	Master Bed	5	4	5	6	2	11	< 2	9	4
	Living	5	3	7	6	2	11	< 2	8	4
	Garage	12	11	17	17	6	35	4	16	11
Total days of exposure		31	33	31	32	21	21	11	11	10
% Garage level inside		41.7%	31.8%	35.3%	35.3%	33.3%	31.4%	43%	53.1%	36.4%

*The U.S. Agency for Toxic Substances and Disease Registry (ATSDR) has developed minimal risk levels (MRLs) for human exposure to hazardous substances in the environment. An MRL is “an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure.” ASTDR’s MRL for inhaled benzene is 50 ppb over a 1 to 14-day exposure range and 4 ppb at a 14 to 364-day exposure range.

Four of the homes in the South Central study also had additional benzene monitoring as part of the Municipality of Anchorage study *Investigation of the Influence of Attached Garages on Indoor VOC Concentrations in Anchorage Homes 2005*¹³. This study monitored benzene levels for 24 hours using collection adsorptive tubes (CATs). **Table 11** shows the comparison of results.

Table 11: MOA Study and SC Study Benzene Results.

House #		SC01		SC02		SC03		SC04	
Study (badges vs. CATs)		SC	MOA	SC	MOA	SC	MOA	SC	MOA
Benzene sample location	Master. Bed (ppb)	5		4		5		6	
	Living (ppb)	5	8.64	3	6.01	7	8.85	6	12.88
	Garage (ppb)	12	28.44	11	33.43	17	38.62	17	59.62
Total days of exposure		31	1	33	1	31	1	32	1
% Garage level inside		41.2%	30.4%	31.8%	18.0%	35.3%	22.9%	35.3%	21.6%

The MOA study found significantly higher levels of benzene in the garage and somewhat higher levels in the house. Thus, the percentage of the garage level inside the house is lower. The benzene levels of the homes in this study are consistent with the benzene levels found in other homes from the MOA study with different ventilation strategies. The Skuttle ventilation strategy does not appear to significantly change the levels of pollutants entering the home from the garage.

Effective Ventilation and Source Control

The definition of “Total Effective Ventilation” used in this report is the amount of incoming airflow, from both natural and mechanical sources, that does not pass through a polluted space.

¹³ Investigation of the Influence of Attached Garages on Indoor VOC Concentrations in Anchorage Homes, 2005.

An expanded definition of total Effective Ventilation should include an assurance of acceptable indoor air quality. In order to achieve acceptable indoor air quality, homes with attached crawlspaces and garages that may contain pollutants of a known health risk (i.e. mold, benzene) need to address the flow of air from these zones into the home. A pollutant that is potentially harmful at extremely low levels, such as benzene or radon, cannot be controlled easily through whole house ventilation. Some exhaust only ventilation strategies may in fact pull more pollutants from the garage or crawlspace than they are effectively removing. Source control ventilation is needed to prevent the migration and buildup of potentially harmful contaminants from entering the home through polluted connected spaces. Source control can be achieved through proper air sealing and separate exhaust ventilation of the polluted zones. Pressure management can be used to control the flow of air through unavoidable leakage paths between those zones and the home. Previous studies on Anchorage homes have reported the furnace in the garage as a significant cause of garage air entering the home. In the most recent study done by the Municipality of Anchorage: *Investigation of the Influence of Attached Garages on Indoor VOC Concentrations in Anchorage Homes 2005*, the data indicates furnaces in garages more than double the percent of house air infiltration that enters via the garage. See **Figure 25** below.

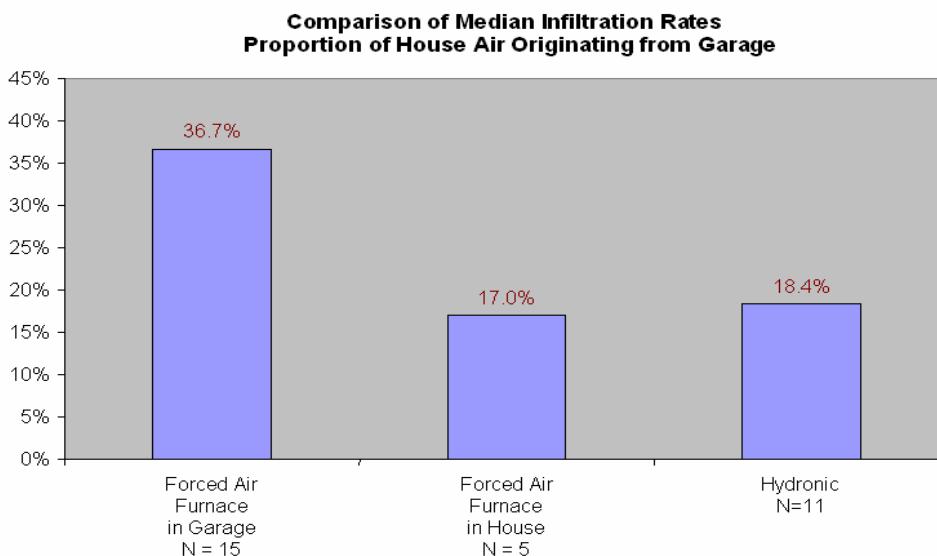


Figure 25: MOA study comparison of infiltration rates from the garage.

The new ASHRAE 62.2 Ventilation standard for residential buildings strongly discourages furnaces in the garage. This standard requires performance testing on furnace duct leakage when the furnace is located in the garage and limits total duct leakage to less than 6%. Duct leakage testing on one study home revealed approximately 40% duct leakage of the total furnace flow. The duct leakage reduction to meet the new standard is substantial and may be difficult to achieve without removing the furnace from the garage.

By removing the furnace and non-direct vent appliances from the garage a small exhaust fan in the garage can provide the mechanical ventilation and pressure management needed to significantly reduce the amount of garage air entering the home. Crawl spaces can also be vented directly to the outdoors using an exhaust fan to reduce the risk of crawl space pollutants

entering the home. Quiet bathroom and kitchen range hood fans are also required in the new ASHRAE. This requirement assumes that they will be used more often and therefore provide better source control of pollutants generated within the home. Improved source control reduces the whole house ventilation rates needed to attain acceptable indoor air.

The new ASHRAE 62.2 requires approximately 50% lower ventilation rates than the BEES option II currently being used. These lower rates are easily achieved using the Skuttle ventilation system and may be acceptable given the appropriate source control from polluted zones.

Seasonal Changes in Effective Ventilation

The natural air leakage of a home is dependent upon the leakage distribution in the home, wind speed, building height, and outdoor temperature. As the outdoor temperature rises, the natural air leakage decreases in the building. The reduction of natural air leakage from warmer outdoor temperatures, and the reduced heating demand on the home, results in less furnace runtime. The mechanical contribution of the effective ventilation via the Skuttle is also reduced. The straight trend lines provided in the following graphs show this reduction in mechanical and total effective ventilation over the monitoring period (**Figure 26**). This indicates the importance of a mechanical ventilation control that is independent of heating demands.

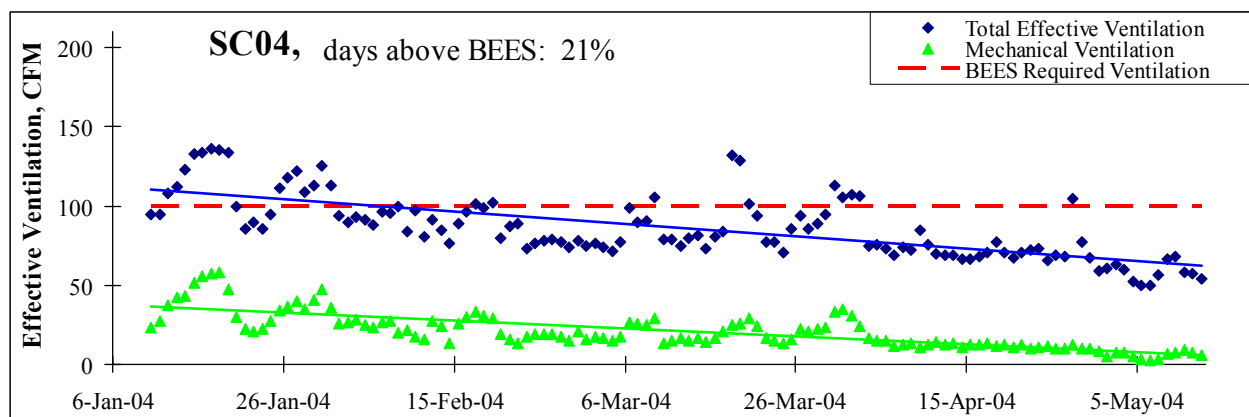


Figure 26: SC04 total effective ventilation shows seasonal drop in ventilation rate.

Improving the Furnace Skuttle System

The furnace Skuttle design used in these homes was identified to have the following shortcomings:

- Minimal mechanical contribution to the effective ventilation rates due to limited runtime of the furnace, especially during warmer outdoor conditions and during evening temperature setback.
- Lower effective mechanical contribution due to imbalanced supply only airflow.
- The supply only strategy pressurizes the home, increasing the potential for moisture damage in the building assembly and ice damming on the roof.
- Lack of commissioning of the system to confirm the airflow rates.

A more effective strategy, utilizing the furnace ductwork for distribution of fresh air, is to incorporate a furnace fan controller, such as the AirCycler, that will operate the furnace fan independently of the thermostat's call for heat. The potential advantages of the AirCycler are:

- It provides for longer occupant controlled Skuttle system runtime cycles when needed.
- The fan controller can be interconnected to a quiet bathroom exhaust fan to operate at the same time as the furnace Skuttle supply air providing balanced airflow. This will increase the total effective ventilation from the system.
- The weighted damper in the existing Skuttle system should be replaced with a 24 volt motorized damper and operated in conjunction with the AirCycler's call for ventilation. This controls when outdoor air is introduced into the home thereby reducing excessive ventilation during cold outdoor conditions. The control also allows adjustment of ventilation for vacation or changes in occupant load.
- The AirCycler fan controller optimizes the runtime of the furnace fan by taking advantage of those periods when there is a call for heat, and only after a set time is the furnace fan operated independently of a call for heat. This optimizing feature can reduce furnace fan runtimes during non-heating periods.

Another recommended improvement to the Skuttle ventilation strategy, still incorporating the AirCycler, is to reduce the size of the furnace or install a multi-stage furnace to provide for longer heating mode furnace fan runtimes and less non-heating furnace fan operation. It should be noted that increased runtime of the furnace fan when the furnace is installed in the garage may increase one of the primary methods of pollutant transfer from the garage.

CONCLUSIONS

1. The daily average of the effective mechanical ventilation rate from the Skuttle system was a minor contribution (less than 15%) to the BEES ventilation requirement as operated by the participants in this study.
2. The daily average of the total effective ventilation rate never reached the BEES ventilation rate requirement in four of the nine houses. The remaining five houses had a range of 21% to 88% of the days during the study period that met the BEES ventilation rate requirement.
3. The furnace fan supply was the biggest contributor to the mechanical ventilation flow rate.
4. None of the three exhaust fan controls provided a major portion of the mechanical ventilation.
5. Timer-controlled fans had the highest hourly average runtime, running 11.2% of the time. They provided more mechanical ventilation than dehumidistats, which ran 2.5% of the time on average, or manual controls, which averaged 0.3% runtime. Several factors limited bath fan usage:
 - Occupants shortened runtime settings on dehumidistats and timers. Manual switches had very limited runtime.
 - Occupants reported that they avoided using bathroom exhaust fans because they were noisy. Fans controlled by timers and dehumidistats drew the most complaints.

- Eleven of the 24 exhaust hoods from the bathroom fans were painted shut, drastically reducing airflow. Proper commissioning would verify ventilation flows after construction, including exterior painting, is completed.
6. The Skuttle furnace supply duct creates a measurable positive pressure in the house when the furnace fan comes on. A positive pressure inside the house is typically not desirable in a heating climate because it can drive warm moist air into wall and ceiling assemblies. This can cause condensation and moisture problems, including ice damming. Increased runtime of the Skuttle system as a supply-only system would increase the positive pressure conditions and the risk of these problems. Increasing the runtime of any unbalanced system is not recommended.
 7. Several problems exist for considering natural air leakage as part of ventilation:
 - Most natural air leakage comes through polluted zones. Ventilating with air from polluted zones may increase the need for additional ventilation.
 - In some instances, blower door tests may significantly overestimate the natural air leakage contribution to ventilation.
 - Natural air leakage did not adequately ventilate bedrooms at night, particularly where bedroom doors were closed. Bedroom ventilation is most important because occupants spend much of their time in the bedrooms. It is especially important to have mechanical distribution to adequately ventilate bedrooms at night.
 8. Carbon monoxide, released when cars start in the garage, disperses easily throughout the house. This demonstrates pollutant transfer from garage to house. The increased exposure levels to CO in these houses were small during the study period; the health risks were not evaluated.
 9. One house showed movement of CO from the garage through the crawl space into the house, suggesting a pollutant pathway into the house includes the crawl space.
 10. Results from zonal pressure diagnostics, furnace-fan-on pressure effect tests, CO and benzene transfer from the garage to the house, and the CO transfer through the crawl space confirmed the connection of garage and crawl space zones to the house. All indicate a significant interconnection of the zones and are consistent with other studies showing garage and crawl space connection to the house.
 11. Benzene also moves from the garage into the house. The benzene exposure levels in six of the nine homes measured for 10 to 31 days were at or above the ATSDR minimum risk level of 4 ppb for exposures of 14 to 365 days.
 12. Based on the risk of garage pollutants moving into the crawl space and the uncertainty of crawl space air quality (e.g. soil gases, mold, flooding, and exposed fiberglass), the AHFC exclusion of garage and crawl space air for ventilation appears justified.
 13. The current Skuttle ventilation system design relies on the thermostat to turn on the furnace that provides the ventilation supply air. Thus, as the outside temperatures warm, both natural air leakage and the furnace supply ventilation rates decrease and reduce shoulder season ventilation rates.
 14. The system has the potential to provide the BEES ventilation requirement if the furnace fan supply and the bath fan exhaust operate at the same time, as a balanced ventilation system.

An interlocked fan controller, such as the AirCycler, could provide balanced ventilation throughout the year.

15. The recommended improvements for the Skuttle system in this study are:

- Provide interlocked control on the furnace supply, on the bathroom exhaust fan, and on a motorized damper to the furnace supply duct.
- Switch to low-noise bathroom exhaust fans.
- Verify proper airflows and operation after completion.
- Provide homeowners adequate information to assure proper operation during occupancy.
- Remove the furnace from the garage. This will reduce transfer of garage pollutants through the duct system into the home.
- Reduce furnace over-sizing for greater furnace runtime. Ventilation air delivered during heating is warmer and more comfortable.

These changes would increase the effective ventilation flow rates, improve distribution to bedrooms, and provide balanced ventilation with cleaner source air.

APPENDIX A: Ventilation Model Calculation Methodology

The purpose of this appendix is to explain the methodology used to calculate “Total Effective Ventilation Rate” and “Mechanical System Contribution”, as displayed in columns Q and R of the “Effective Ventilation Model” spreadsheet. In addition, the meaning of the other columns in that spreadsheet will be explained.

To start, two simplified examples will be presented, followed later by a more detailed explanation of the model spreadsheet. The first example will calculate the Total Effective Ventilation and Mechanical System Contribution of a home with an exhaust fan that runs continuously. The second example will address a home with a supply fan (or Furnace Skuttle) that runs continuously.

The definition of “Total Effective Ventilation Rate” is the amount of incoming airflow, both from natural and mechanical sources, that does not pass through a space that pollutes the incoming air. The spaces that can potentially pollute the incoming air are the garage and the crawl space. The actual ventilation model allows the user to control whether either of those spaces is considered to pollute incoming air. For these two simplified examples, 25% of the incoming air not passing through a supply fan is assumed to flow through the garage, and that air is considered polluted and not useful for ventilation.

The definition of “Mechanical System Contribution” is the additional amount of Total Effective Ventilation that occurs due to use of the mechanical ventilation system. To actually calculate Mechanical System Contribution it is therefore necessary to first determine the amount of Total Effective Ventilation of the home with the mechanical system off and then reevaluate Total Effective Ventilation assuming normal use of the mechanical system. The difference between these Total Effective Ventilation rates is defined to be the Mechanical System Contribution.

Given these definitions, let us move on to the first example. In this example, a home has 100 CFM of natural infiltration (when *no* fans are running), 25% of which comes in through the garage. Present in the home is a 100 CFM exhaust fan that is assumed to run continuously. The goal of the example is to calculate the Total Effective Ventilation in the home and determine the Mechanical System Contribution (the mechanical system in this case is the exhaust fan). In order to calculate the Mechanical System Contribution, it is necessary to analyze the home assuming *no* operation of the mechanical system. Figure 1 below shows the airflow present when the home is in that state.

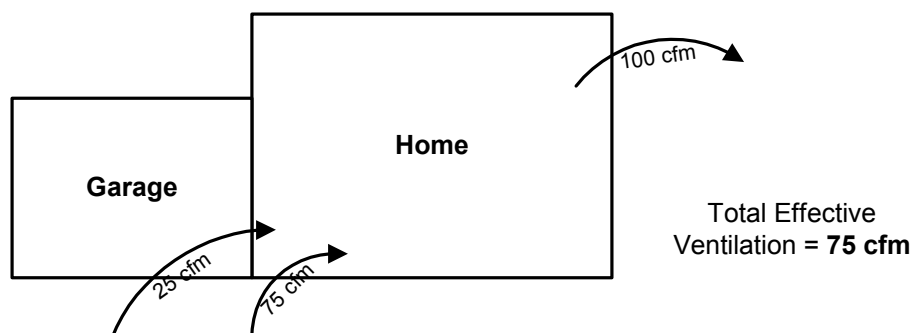


Figure 1

APPENDIX A: Ventilation Model Calculation Methodology

The Total Effective Ventilation in this scenario with no exhaust fan running is 75 CFM, because the 25 CFM of natural infiltration air coming through the garage is assumed unsuitable for ventilation purposes.

Figure 2 below shows the airflows in the home with the 100 CFM exhaust fan running. The total flow of air through the home is 141 CFM, as determined by the procedures in ASHRAE 136. The ASHRAE 136 procedure states that the total flow in a home with unbalanced ventilation can be determined by taking the square root of the sum of the squares of the natural infiltration rate and the unbalanced mechanical ventilation rate:

$$\text{Total Airflow through home} = \text{square-root}((100 \text{ CFM})^2 + (100 \text{ CFM})^2) = 141 \text{ CFM}$$

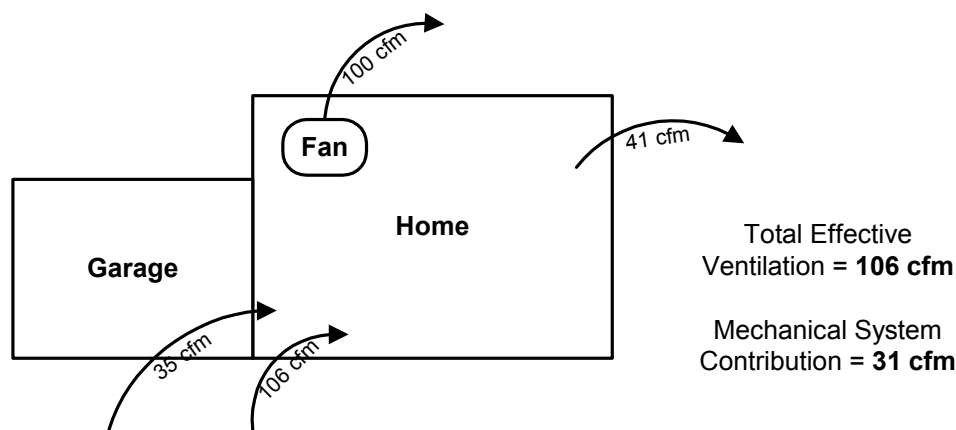


Figure 2

Since we know the total flow through the home is 141 CFM and the exhaust flow through the fan is 100 CFM, which leaves 41 CFM that must be exfiltrating through leaks in the home's shell. As to the infiltration air, the total must again be 141 CFM. We maintain the assumption that 25% of this airflows through the garage and 75% flows directly into the home.¹⁴ Those ratios result in flows of 35 CFM into the garage (and then into the home) and 106 CFM directly into the home. Since the flow of air through the garage is considered unsuitable for ventilation, the Total Effective Ventilation in this scenario is 106 CFM, the clean air infiltration directly into the home.

By comparing Figure 1 to Figure 2, we see that the Total Effective Ventilation increased from 75 CFM in Figure 1 to 106 CFM in Figure 2. That 31 CFM increase in ventilation is defined as the Mechanical System Contribution. Use of the mechanical ventilation system in this home caused an increase of 31 CFM of usable ventilation air. The fan served to increase the total flow

¹⁴ In fact, when the exhaust fan runs, the neutral pressure plane in the home rises, changing the distribution of the incoming air. Therefore, it is likely that the percentage of the incoming air passing through the garage does change but it is difficult to predict the magnitude of that change. The opposite is true for the supply fan, which would likely increase the percentage of air leakage from the lower leakage paths such as the crawlspace.

APPENDIX A: Ventilation Model Calculation Methodology

of air through the home by 41 CFM, but only 31 CFM of that increased flow was useable ventilation air.

The second example uses a home with the same natural characteristics but assumes that a 100 CFM **supply** fan is run continuously (which could be a furnace Skuttle controlled to run continuously). Again, to determine the Mechanical System Contribution, we need to analyze the home with the supply fan not operating. We have already performed that analysis in Figure 1 above, showing Total Effective Ventilation of 75 CFM.

Figure 3 below shows the airflows in the home with the 100 CFM supply fan operating:

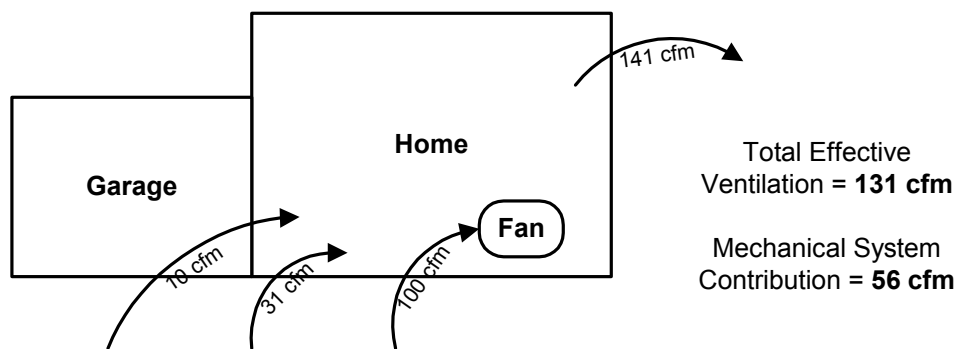


Figure 3

The ASHRAE 136 calculation to determine the total airflow through the home is the same as before; there is still 100 CFM of natural air leakage and 100 CFM of unbalanced mechanical ventilation. These characteristics result in 141 CFM of total airflow through the home. Total exfiltration through the shell therefore equals 141 CFM, as there are no exhaust fans to remove air. Since 100 CFM of the incoming airflows through the supply fan, 41 CFM of air must infiltrate through the building shell. We maintain the same assumption that 25% of this infiltration air comes through the garage, resulting in 10 CFM through the garage and 31 CFM directly into the home. The useable ventilation air consists of the 31 CFM of infiltration directly into the home and the 100 CFM of clean supply air flowing through the supply fan. Thus, Total Effective Ventilation is 131 CFM. Comparing this ventilation rate to that in Figure 1 (75 CFM) shows that the supply only Mechanical System Contribution is 56 CFM, the difference between the two effective ventilation flows.

Now let us look at balanced mechanical contribution.

Figure 4 below shows the airflow with a balanced system of 100 CFM supply and a 100 CFM exhaust.

APPENDIX A: Ventilation Model Calculation Methodology

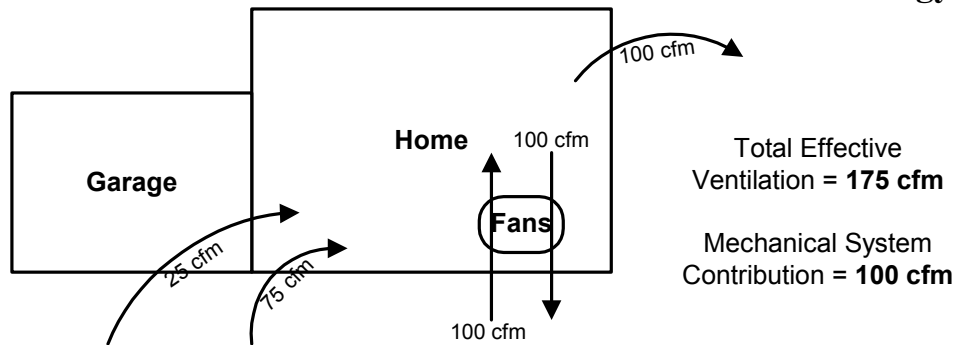


Figure 4

Balanced ventilation does not affect the pressures in the home thus does not change the natural air leakage contribution to the home or percentage of flow through the garage. One can add the balanced 100 CFM mechanical with the 75 CFM effective natural for a total effective ventilation rate of 175 CFM.

The supply only fan contributed more effective ventilation (56 CFM) than the exhaust only fan (31 CFM). The reason is that the supply air fan diverts some of the unsuitable infiltration air that normally flows through the garage. The disadvantage to supply only ventilation in cold climates is the concern of increased pressurization within the home relative to the outside, on the upper portion of the home and increasing the air leakage into building assembly and attic, and potentially causing moisture and ice damming problems.

With this general background on the approach to calculating Total Effective Ventilation and Mechanical System Contribution, we can look in more detail at the Effective Ventilation Model spreadsheet. First, it is important to know that a number of the calculations are not performed on that spreadsheet but are instead performed by Python programming scripts.¹⁵ The portion of that programming code that performs the ventilation calculations is attached.¹⁶ Columns A through N, (the column “Date” through the column “Bath 3 Runtime”) are calculated by the Python programming code and are inserted into the Effective Ventilation Model spreadsheets as data inputs. Columns O (“Contribution to Eff. Vent. during Furnace Off”) and beyond are calculated in the spreadsheet. Following are explanations of each of the columns:

A - Date: The spreadsheet presents and analyzes the home on a daily average basis. The Python calculations that feed the spreadsheet deal with data collected hourly or more frequently in some cases. The natural infiltration and ASHRAE 136 effective ventilation calculations performed in

¹⁵ Python is a high-level programming language well suited for processing data and performing engineering and scientific calculations. See <http://www.python.org>.

¹⁶ While the programming syntax may be foreign to the reader, some of the comments and calculations in the code should be understandable.

APPENDIX A: Ventilation Model Calculation Methodology

the Python code is done on an hour-by-hour basis, and those values are summarized into daily averages for use in the spreadsheet.

B - Required Ventilation, CFM: This is the calculated flow requirement based upon the Alaska Building Energy Efficiency Standards, Option II, Room Count Method.

C - Outside Temp., deg F: Anchorage International Airport weather data was used in the analysis. This column is the average outdoor temperature for the day.

D - Average Wind Speed, mph: This is the average wind speed for the day. This value has not been adjusted yet for wind shielding and terrain present at the home. Those adjustments are done in the natural infiltration calculation described next.

E - Natural Infiltration, CFM: This is the estimated average natural infiltration for the home, assuming none of the fans are operating. It is determined using the LBL natural infiltration algorithm, which is the same algorithm used in the AkWarm Home Energy Rating software. For the actual calculation, see lines 29-48, and 76-79 in the attached Python code.

F - Furnace Effective Vent. CFM: This ventilation flow is the increased airflow through the house due to operation of the furnace Skuttle during the day. This ventilation amount accounts for the fact that the Skuttle does not operate continuously during the day. The ventilation amount also accounts for the ASHRAE 136 effect, i.e. 1 CFM of unbalanced fan flow results in less than 1 CFM of increased airflow through the house. There is one important factor that is not accounted for in this ventilation figure: this ventilation figure does not consider the unsuitability of garage and crawlspace air for ventilation purposes. That factor is addressed in the calculations performed in columns O and beyond. This ventilation amount is calculated in lines 83 through 89 in the attached Python code. The code performs this calculation for every hour, and the hourly amounts are averaged into daily averages before inserting into the Ventilation Model spreadsheet.

G - Furnace Flow Rate, CFM: This is the total flow rate of the furnace Skuttle when the furnace Skuttle is operating. No ASHRAE 136 effects or cycling (partial use) effects are considered.

H - Furnace Runtime: This is the fraction of the day that the furnace fan operated.

I through N - Effective Ventilations and Runtimes for the 3 bathroom fans: These are the effective ventilations and runtimes for the three bathroom fans in the home. The ventilation flows shown are defined exactly as they were in column F, the furnace effective ventilation; ASHRAE 136 effects and fan runtime are considered. Garage and crawlspace airflow issues are not considered. The effective ventilation flow calculations were simplified (with some loss of accuracy) by assuming that no two fans (including the furnace fan) operate simultaneously.

O through Q - Total Effective Ventilation Calculations: These three columns implement the Total Effective Ventilation calculation, which was described in the two introductory examples.

APPENDIX A: Ventilation Model Calculation Methodology

The column O calculation determines the effective ventilation during the period when the furnace fan is off; only bath fans are assumed to run during this period. Thus, the calculation follows the exhaust fan example presented at the beginning of this appendix. The column P calculation analyzes the period when the furnace fan and Skuttle are operating; this calculation is patterned after the supply fan example presented at the beginning of the appendix. Column Q sums columns O and P and is the Total Effective Ventilation for the home during that day.

R - Mechanical System Contribution, CFM: As in the introductory examples, this column calculates the contribution that all the fans had to the Total Effective Ventilation, above and beyond the useful ventilation provided by natural infiltration alone.

S - Meets BEES?: If the Total Effective Ventilation for the Home (column Q) exceeds the Required Ventilation (column B), a 1 is shown in this column; otherwise, a 0 shows.

APPENDIX B: Effective Ventilation Model spreadsheet

Effective Ventilation Model

Select Home:

SC01

% of Shell Infiltration thru This Component Ventilation

Crawl Space

Garage

33% 29% 0% 0%

Overall Usable Fraction of Infiltration Air:

38%

Start date End date
7-Jan-04 10-May-04

% of days above BEES: 0%
% of days below BEES: 100%

Home ID:

SC01

Calculated Values										Calculated Values											
Date	Required Ventilation, cfm	Outside Temp., deg F	Average Wind Speed, mph	Natural Infiltration, n, cfm	Furnace Effective Flow		Furnace		Master Bath		Bath 2 Eff. Vent,		Bath 3 Eff. Vent,		Bath 3 Runtime		Total Effective Ventilati on		Mechanical System Contribution		Meets BEES?
					Rate, cfm	Run Time	Furnace Flow	Furnace Run Time	Master Bath Eff. Vent, cfm	Master Bath Runtime	Bath 2 Eff. Vent, cfm	Bath 2 Runtime	Bath 3 Eff. Vent, cfm	Bath 3 Runtime	Contribution during Furnace	Contribution during Furnace	Contribution during Furnace	Contribution during Furnace			
7-Jan-04	140	12.7	20.1	215.7	17.1	120	0.548	0	0	0	0	0	0	0	0	0	37.0	92.2	129.2	47.3	0
8-Jan-04	140	5.4	12.8	174.9	22.9	120	0.613	0	0	0	0	0	0	0	0	0	25.7	95.1	120.8	54.3	0
9-Jan-04	140	17.7	7.5	141.5	19	120	0.433	0	0	0	0	0	0	0	0	0	30.5	62.7	93.2	39.4	0
10-Jan-04	140	26.9	8.3	137.4	15	120	0.33	0	0	0	0	0	0	0	0	0	35.0	47.5	82.5	30.3	0
11-Jan-04	140	20.6	4.8	130.7	17.1	120	0.365	0	0	0	0	0	0	0	0	0	31.5	51.8	83.3	33.7	0
12-Jan-04	140	12.3	4.8	138.7	18.5	120	0.412	0	0	0	0	0	0	0	0	0	31.0	59.4	90.4	37.7	0
13-Jan-04	140	12	4.6	139.1	22	120	0.494	0	0	0	0	0	0	0	0	0	26.7	71.2	98.0	45.1	0
14-Jan-04	140	8.5	9.2	157.2	20.6	120	0.508	0	0	0	0	0	0	0	0	0	29.4	76.0	105.4	45.6	0
15-Jan-04	140	3.4	9.6	163.6	23.5	120	0.598	0	0	0	0	0	0	0	0	0	25.0	90.6	115.6	53.4	0
16-Jan-04	140	-6.1	4.2	154.6	26.6	120	0.647	4.4	0.425	0	0	0	0	0	0	0	22.4	96.3	118.7	59.9	0
17-Jan-04	140	-10.1	2.2	153.3	28.7	120	0.695	0	0.004	0	0	0	0	0	0	0	17.8	103.1	120.9	62.6	0
18-Jan-04	140	-9.2	1.1	151.5	31.6	120	0.756	0	0	0	0	0	0	0	0	0	14.0	111.8	125.8	68.3	0
19-Jan-04	140	1.2	10.4	168.4	24.2	120	0.625	0	0	0	0	0	0	0	0	0	24.0	95.7	119.7	55.7	0
20-Jan-04	140	22.7	7.8	136.5	18.3	120	0.402	0	0	0	0	0	0	0	0	0	31.0	57.7	88.7	36.9	0

APPENDIX C: Python Code

```
1  """
2  Script to generate a hourly infiltration and ventilation files for each house.  Uses the
3  natural infiltration
4  routine from AKWarm, but allows for a variable flow exponent instead of a 0.67 exponent
5  assumption.
6  Uses ASHRAE 136 formulae to determine effective ventilation due to unbalanced fan flow.
7  """
8  import os, time
9  from os.path import join
10 from ConfigParser import ConfigParser
11 from Numeric import *
12 from TimeSeries import getSeriesDict, TimeSeries
13 from constants import *      # holds the general constants for this script and others
14
15 # make temperature and wind series and create dictionaries from those
16 # series as well
17 outTempDict = getSeriesDict(TEMP_FILE)
18 windDict = getSeriesDict(WIND_FILE)
19
20 for dir in os.listdir(DATA_OUT):
21     print 'Processing %s . . .' % dir
22
23     # make most of the output file name
24     outFname = join(DATA_OUT, dir, '%s-' % dir)
25
26     # read the config file for the house
27     cfg = ConfigParser()
28     cfg.read(join(DATA_IN, dir, 'CONFIG-%s.txt' % dir))
29
30     # calculate the stack and wind multipliers by adjusting AKWarm multipliers
31     exponent = cfg.getfloat('GENERAL', 'EXPONENT')
32     exp_adj = (0.08**exponent/0.08**0.67)**2
33     stack_mult = 0.00000497899 * exp_adj
34     wind_mult = 0.000067228 * exp_adj
35
36     # calculate stack and wind coefficients using quantities that don't change with weather
37
38     # multiplier to convert PANC wind speed to site wind speed. Assumed average
39     # shiedling. These are from AKWarm
40     height = cfg.getfloat('GENERAL', 'HEIGHT')      # house height
41     site_mult = 0.678 * (height / 32.8)**0.2
42
43     cfm50 = cfg.getfloat('GENERAL', 'CFM50')
44     cfm50sqd = cfm50 * cfm50
45     stack_coeff = stack_mult * cfm50sqd * height
46     wind_coeff = wind_mult * cfm50sqd * site_mult * site_mult
47
48     # get the indoor temperatures from the living room
49     inTempDict = getSeriesDict(outFname + 'Liv-TE.txt', 3600)
50
51     # read the furnace fan file to find out the time interval
52     ser = TimeSeries(filename=outFname + 'Fur-RT.txt', silent=1)
53     minTime = int(min(ser.time))
54     maxTime = int(max(ser.time))
55     # make an array of times spanning this interval with hourly steps
56     finalTimes = range(minTime, maxTime + 1, 3600)
57
58     # make a list of the fans present in the home, for which effective ventilation flows
59     # need to be calculated. Each item in the list is a tuple containing:
60     # ID of fan, fan flow rate, empty list to contain times, empty list to contain
61     # effective
62     # flow rate series, and dictionary of runtimes for the fan
63     fans = []
64     if cfg.has_option('GENERAL', 'FAN-FF CFM'):
65         fans.append( ('Fur', cfg.getfloat('GENERAL', 'FAN-FF CFM'), [], [],
66             getSeriesDict(outFname + 'Fur-RT.txt') ) )
67     if cfg.has_option('GENERAL', 'FAN-BFM CFM'):
68         fans.append( ('BathM', cfg.getfloat('GENERAL', 'FAN-BFM CFM'), [], [],
69             getSeriesDict(outFname + 'BathM-RT.txt') ) )
70     if cfg.has_option('GENERAL', 'FAN-BF2 CFM'):
```

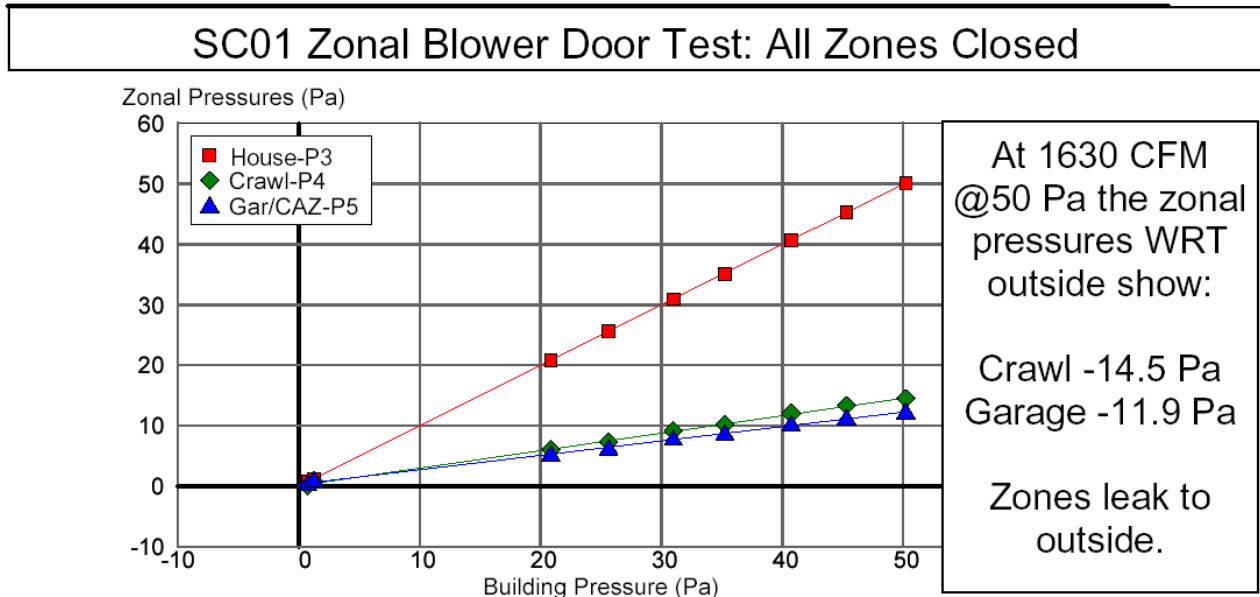
APPENDIX C: Python Code

```
67     fans.append( ('Bath2', cfg.getfloat('GENERAL', 'FAN-BF2 CFM'), [], [] ,
68                 getSeriesDict(outFname + 'Bath2-RT.txt') ) )
69     if cfg.has_option('GENERAL', 'FAN-BF3 CFM'):
70         fans.append( ('Bath3', cfg.getfloat('GENERAL', 'FAN-BF3 CFM'), [], [] ,
71                     getSeriesDict(outFname + 'Bath3-RT.txt') ) )
72
73     # calculate the infiltration values and the effective ventilation for each fan
74     infil = []
75     times = []
76     for t in finalTimes:
77         try:
78             outTemp = outTempDict[t]
79             wind = windDict[t]
80             inTemp = inTempDict.get(t, 70.0)      # if no inside temp, use 70 deg F
81             infilFlow = (stack_coeff * abs(inTemp - outTemp) + wind_coeff * wind *
82                         wind)**0.5
83             infil.append( infilFlow )
84             times.append(t)
85             for nm, flow, tms, effFlows, rt in fans:
86                 # using ASHRAE 136 formula, calculate total ventilation flow and then
87                 # subtract
88                 # out natural to determine effective flow of the fan when it is on.
89                 effFlow = (infilFlow * infilFlow + flow * flow)**0.5 - infilFlow
90                 if rt.has_key(t):
91                     tms.append(t)
92                     # multiply the runtime of the fan against the effective flow
93                     effFlows.append( effFlow * rt[t] )
94                     #if len(effFlows)<10:
95                     #print 'eff-flow', effFlow, rt[t]
96
97             #if len(infil)<10:
98             #print 'infil', outTemp, wind, inTemp, infil[-1]
99
100     except KeyError:
101         print 'missing value for time: %s' % time.ctime(t)
102         continue
103
104     # save the natural infiltration to a file
105     infilSer = TimeSeries(times=times, values=infil)
106     infilFile = outFname + 'Tot-IN.txt'
107     infilSer.saveToFile(infilFile, timeLabel='Time', valueLabel='cfm', valueFormat='%.1f')
108
109     # save the effective fan flow rates to files
110     for nm, flow, tms, effFlows, rt in fans:
111         ser = TimeSeries(times=tms, values=effFlows)
112         fname = outFname + ('%s-EF.txt' % nm)
113         ser.saveToFile(fname, timeLabel='Time', valueLabel='cfm', valueFormat='%.1f')
```

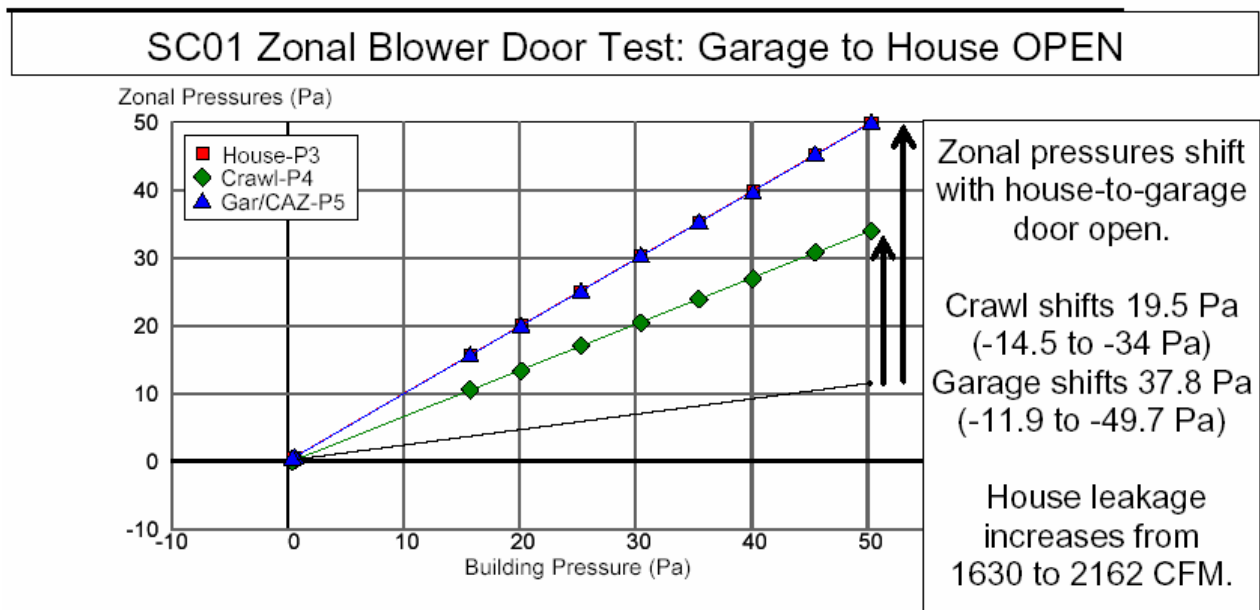
APPENDIX D: Zonal Blower Door Tests

The range of pressure changes in the crawlspace depends upon where the zonal pressure started from and how leaky the crawlspace is to the outdoors. The leakier the crawlspace is to the outdoors the less the pressure will change between the two tests if the leakage between the crawlspace and garage remains the same. For example, a small pressure change between tests, with a very leaky crawlspace to outside, may still indicate a significant interconnection between the crawlspace and garage. The zonal pressure changes in the four homes that were tested all showed substantial leakage between the crawlspace and garage.

SC01 All Zones Closed

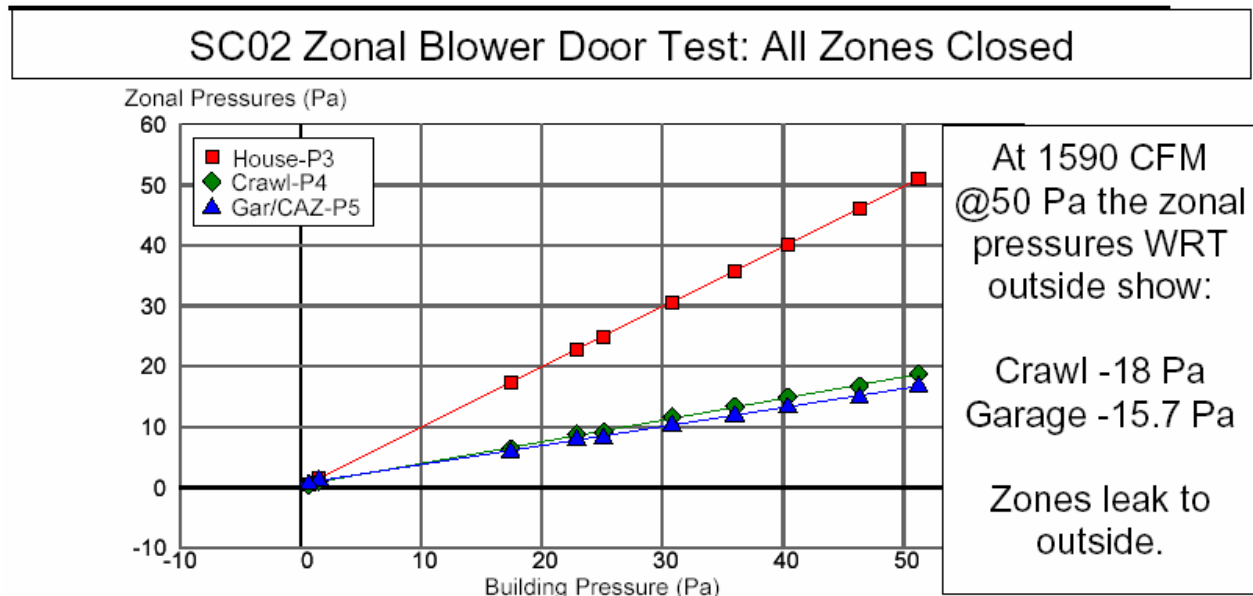


SC01 Crawl Closed – Garage Open

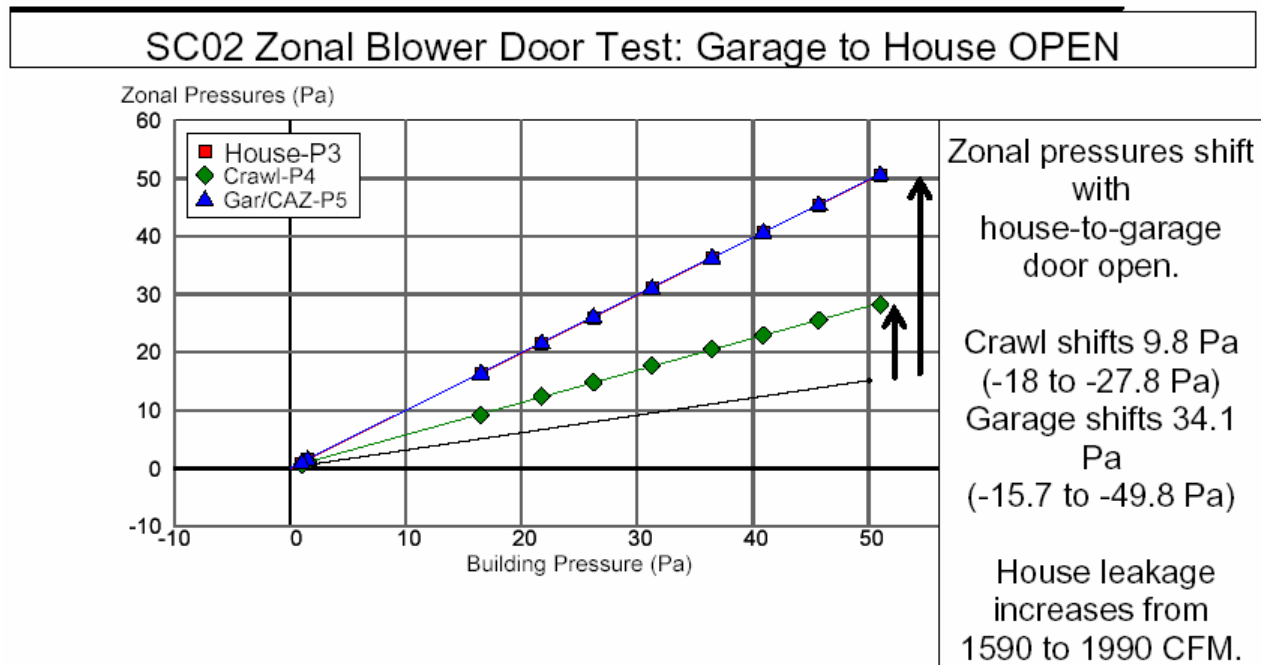


APPENDIX D: Zonal Blower Door Tests

SC02 All Zones Closed

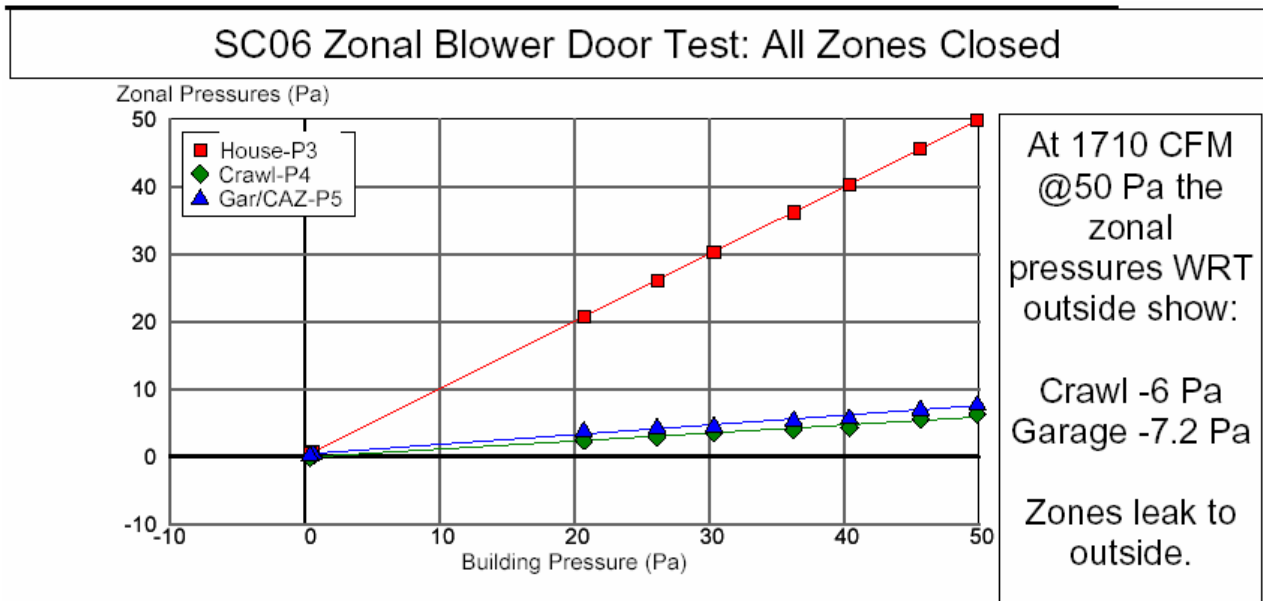


SC02 Crawl Closed – Garage Open

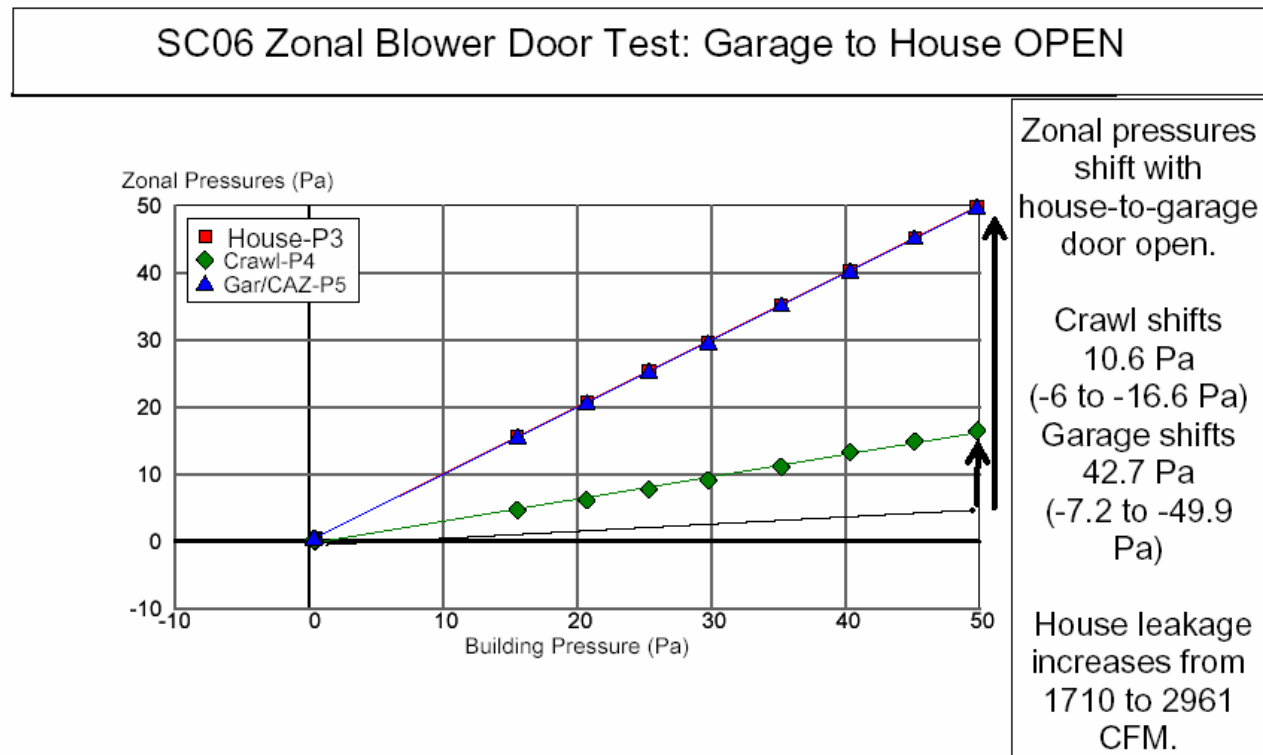


APPENDIX D: Zonal Blower Door Tests

SC06 All Zones Closed

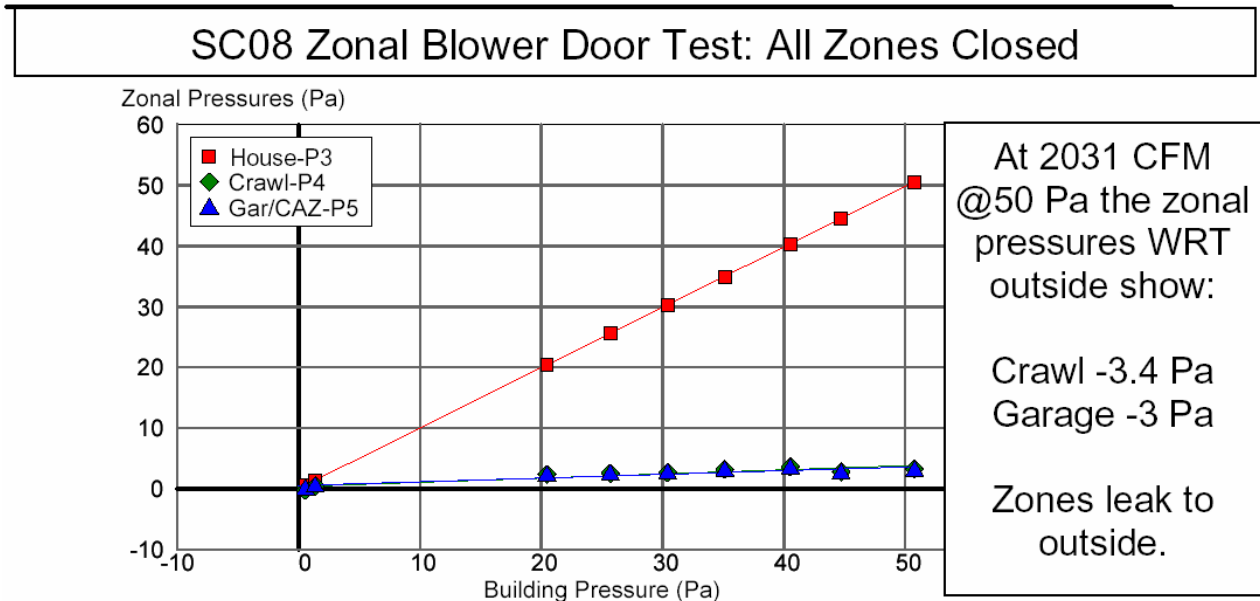


SC06 Crawl Closed – Garage Open

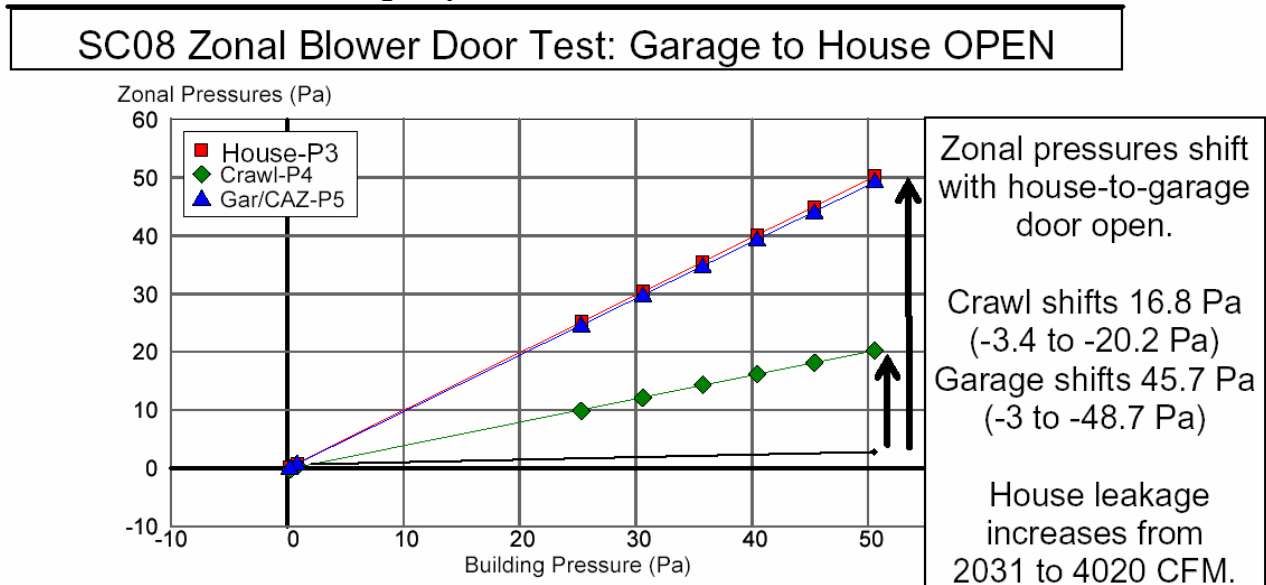


APPENDIX D: Zonal Blower Door Tests

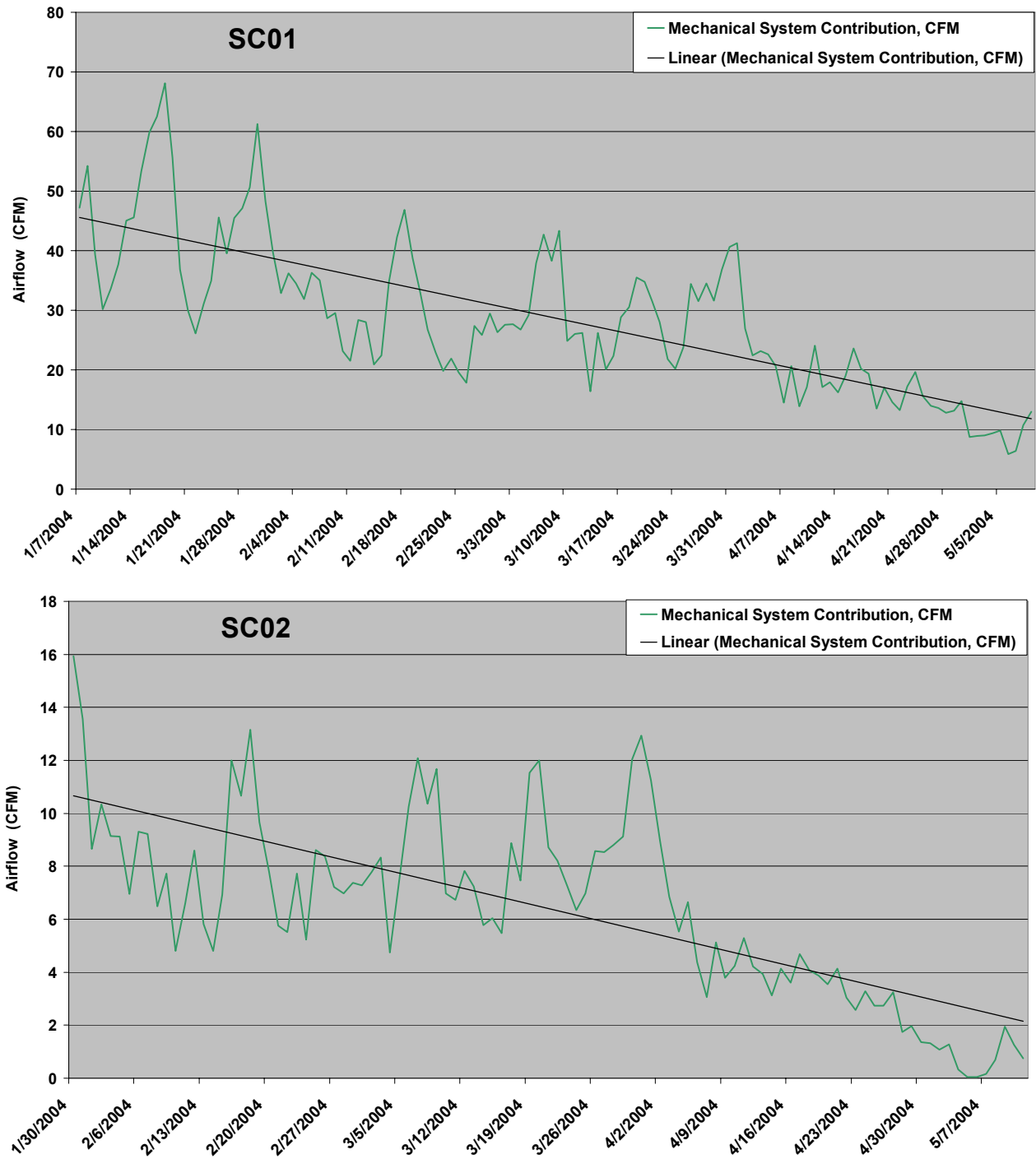
SC08 All Zones Closed



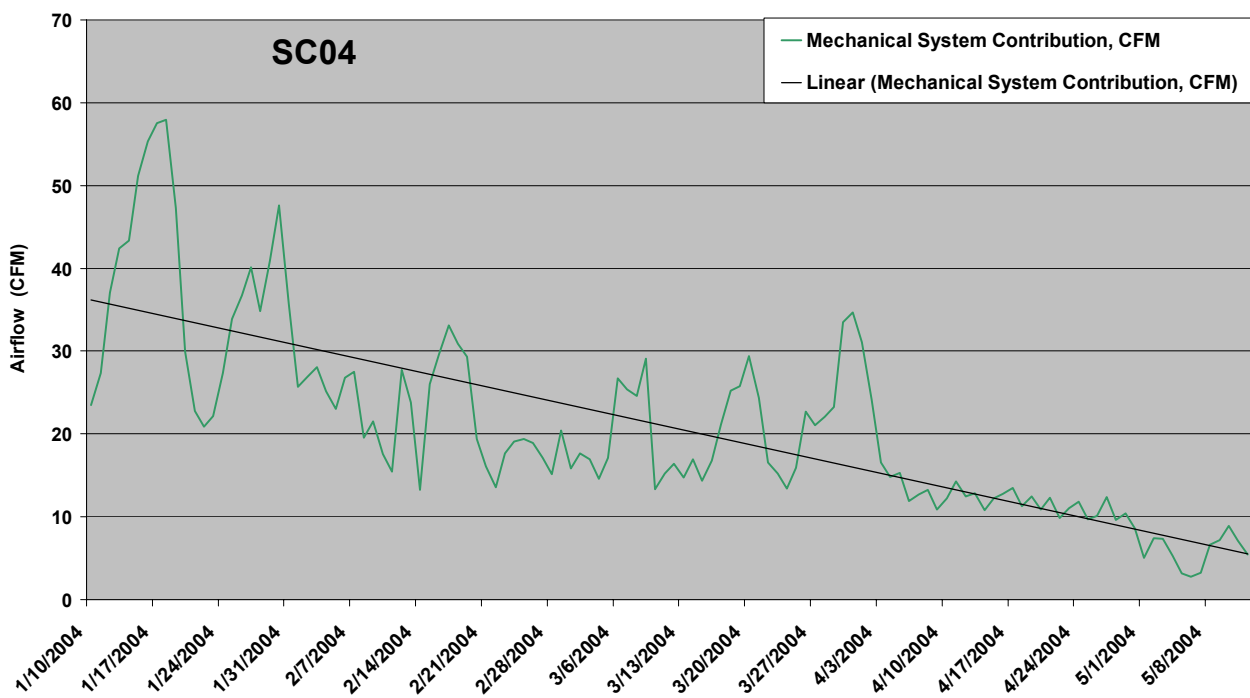
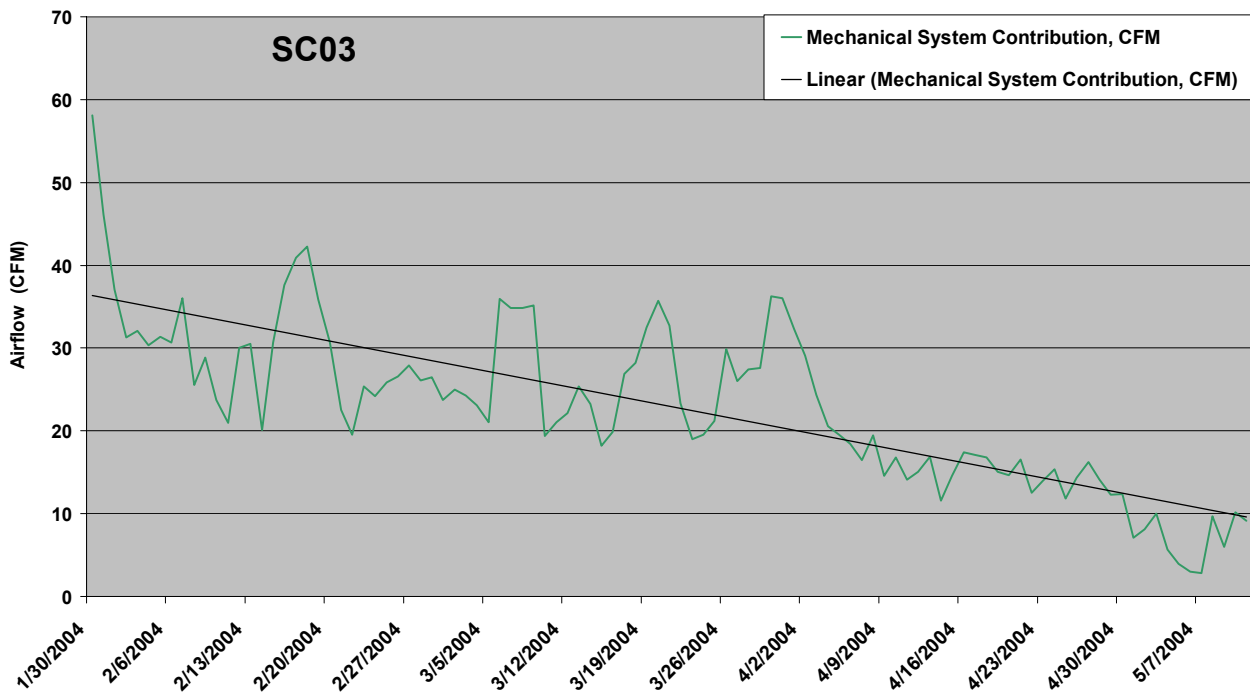
SC08 Crawl Closed – Garage Open



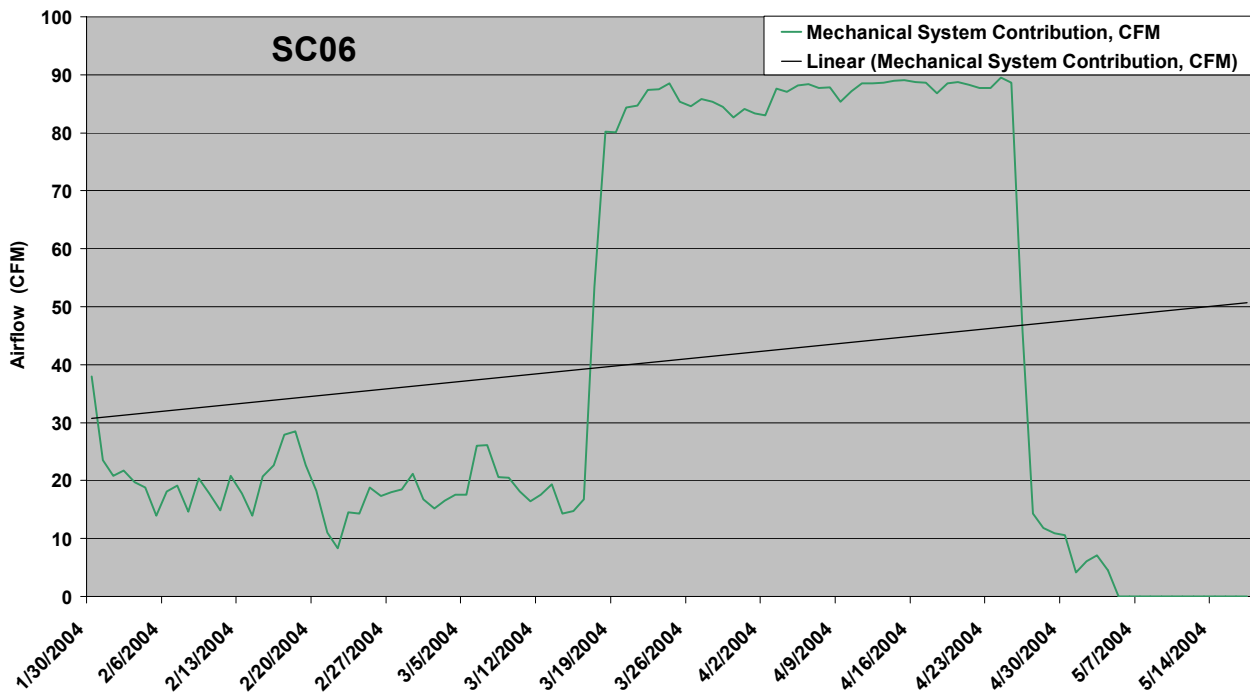
APPENDIX E: Mechanical System Contribution



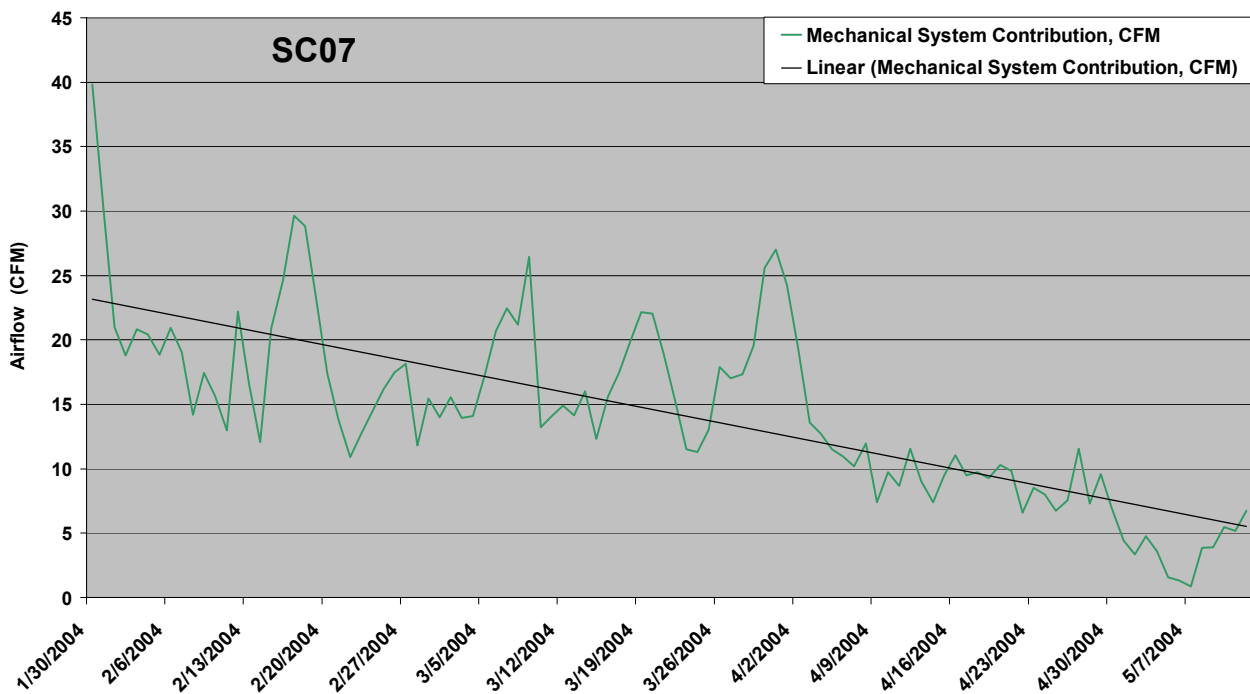
APPENDIX E: Mechanical System Contribution



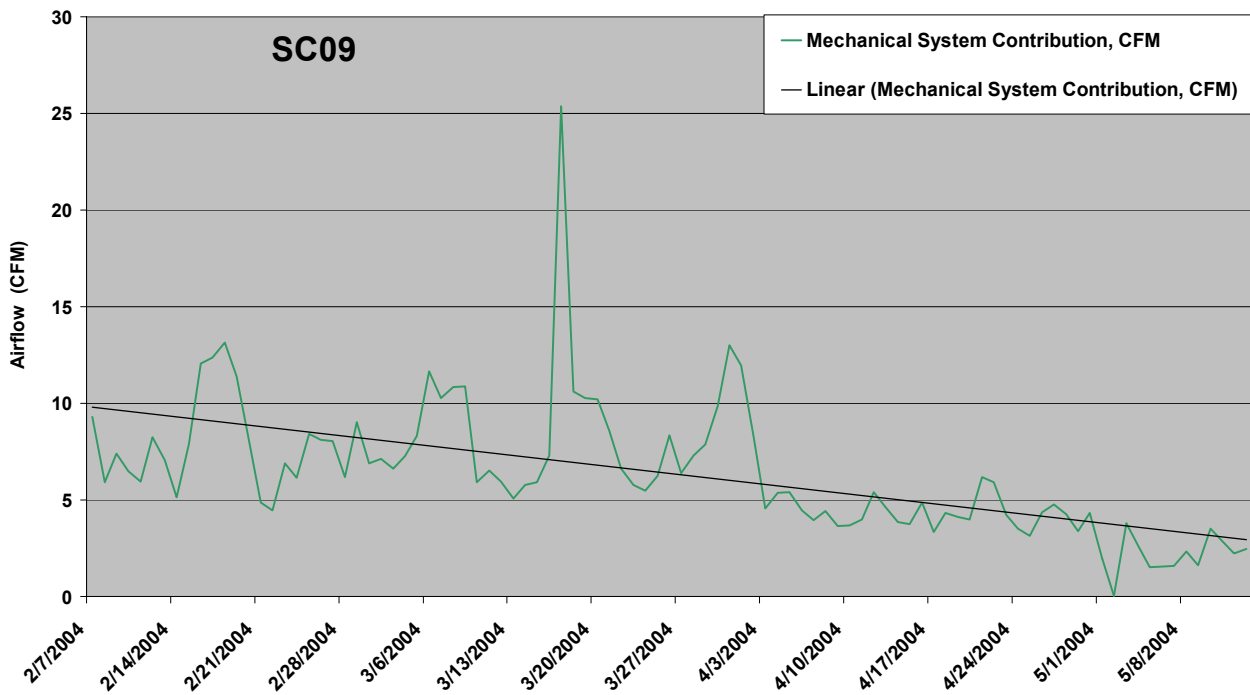
APPENDIX E: Mechanical System Contribution



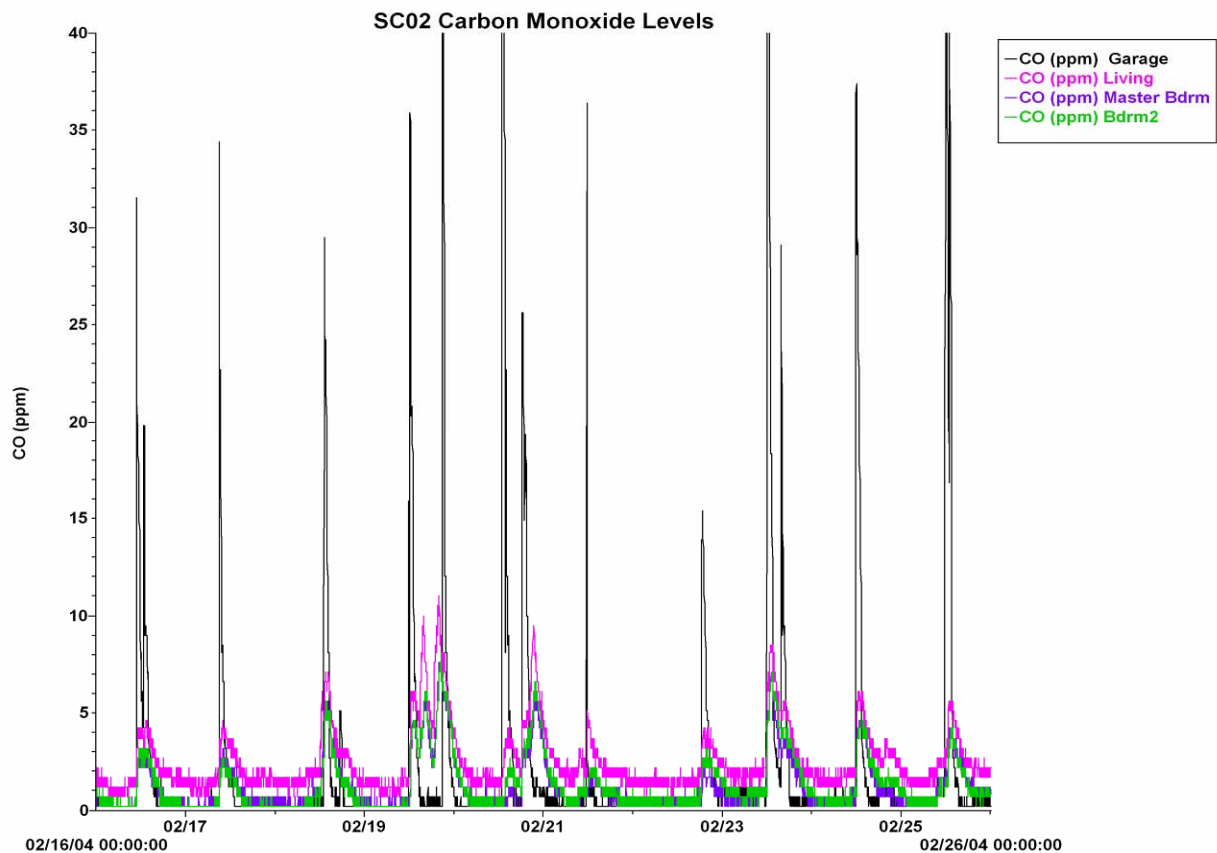
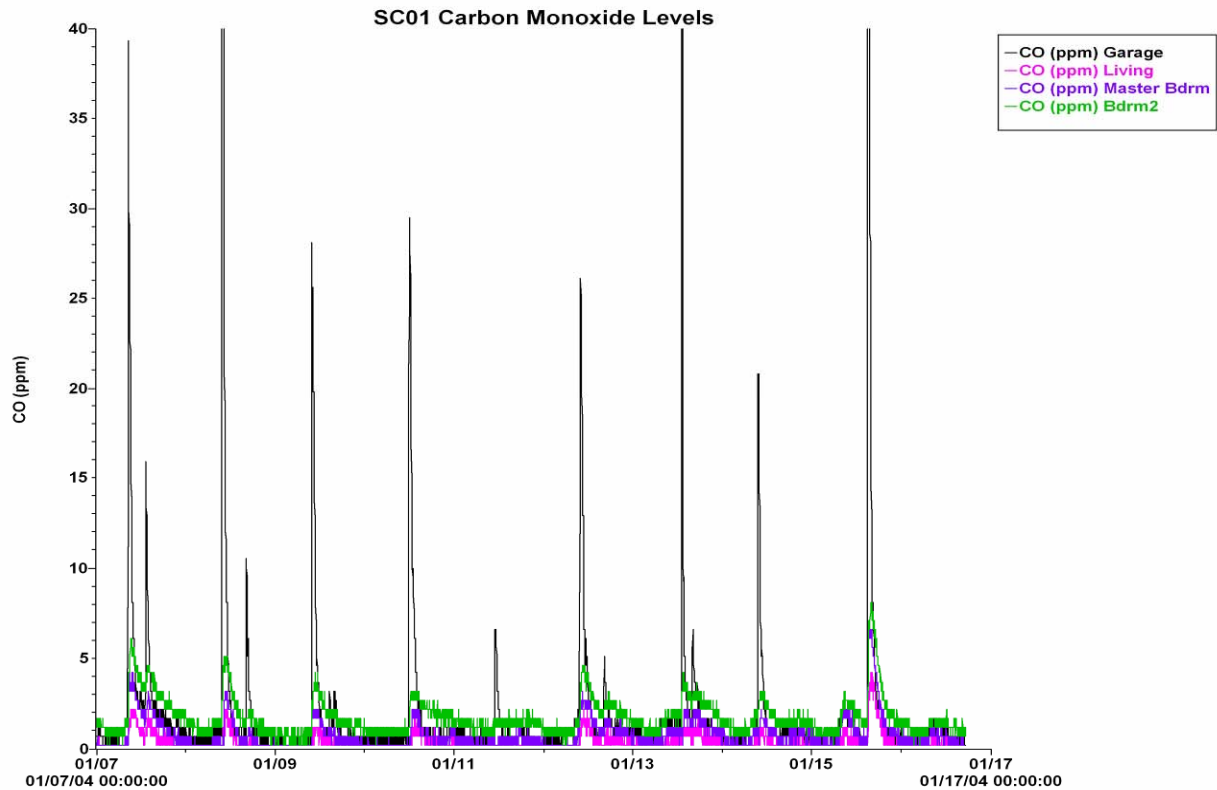
<< N.B. SC06 furnace fan was left on continuously from 3/17/04 to 4/26/04.>>



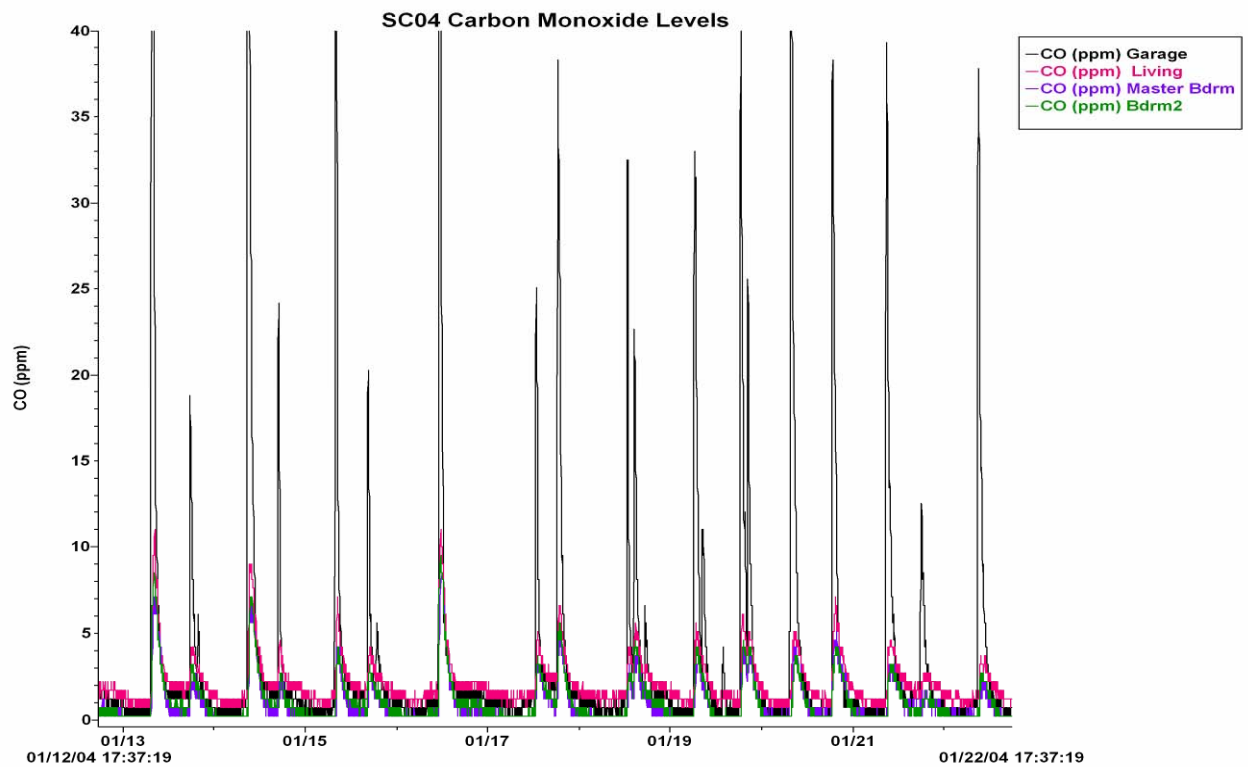
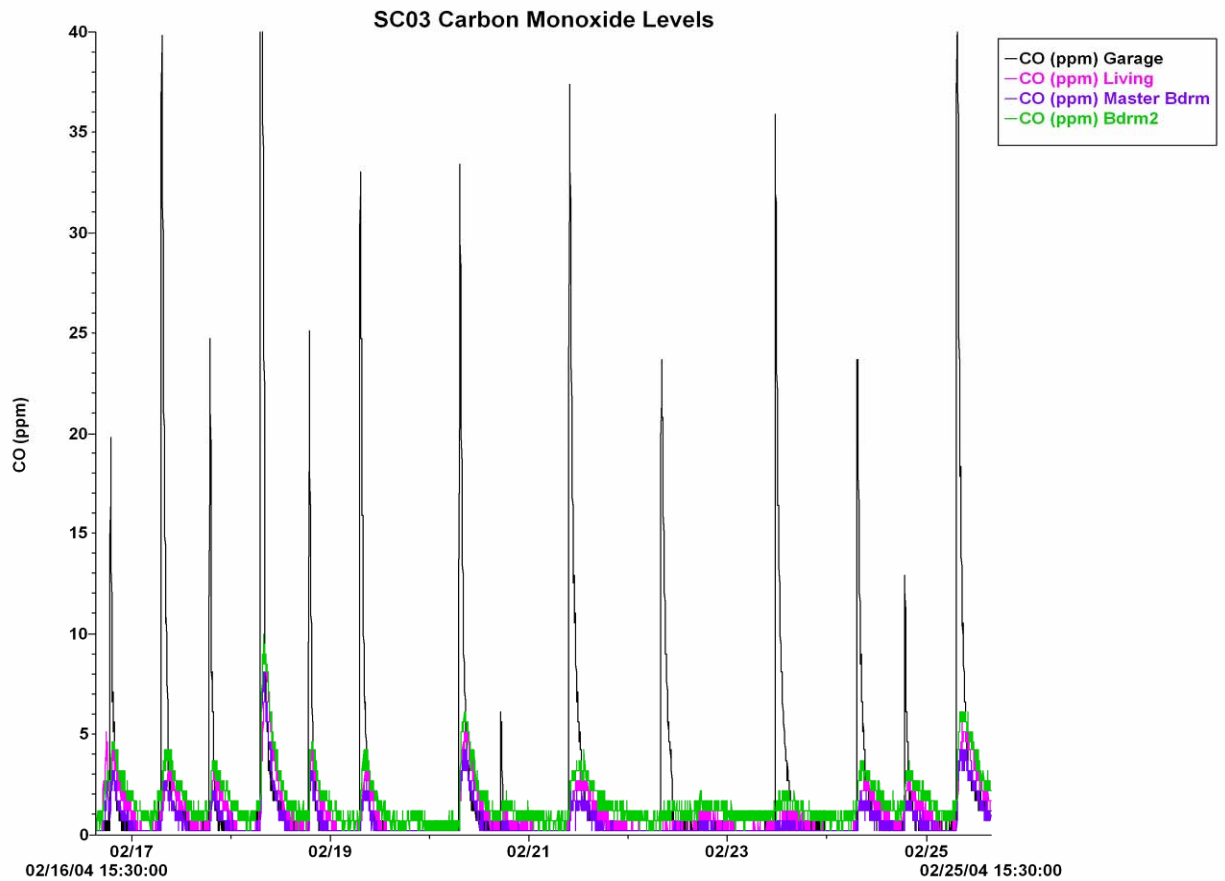
APPENDIX E: Mechanical System Contribution



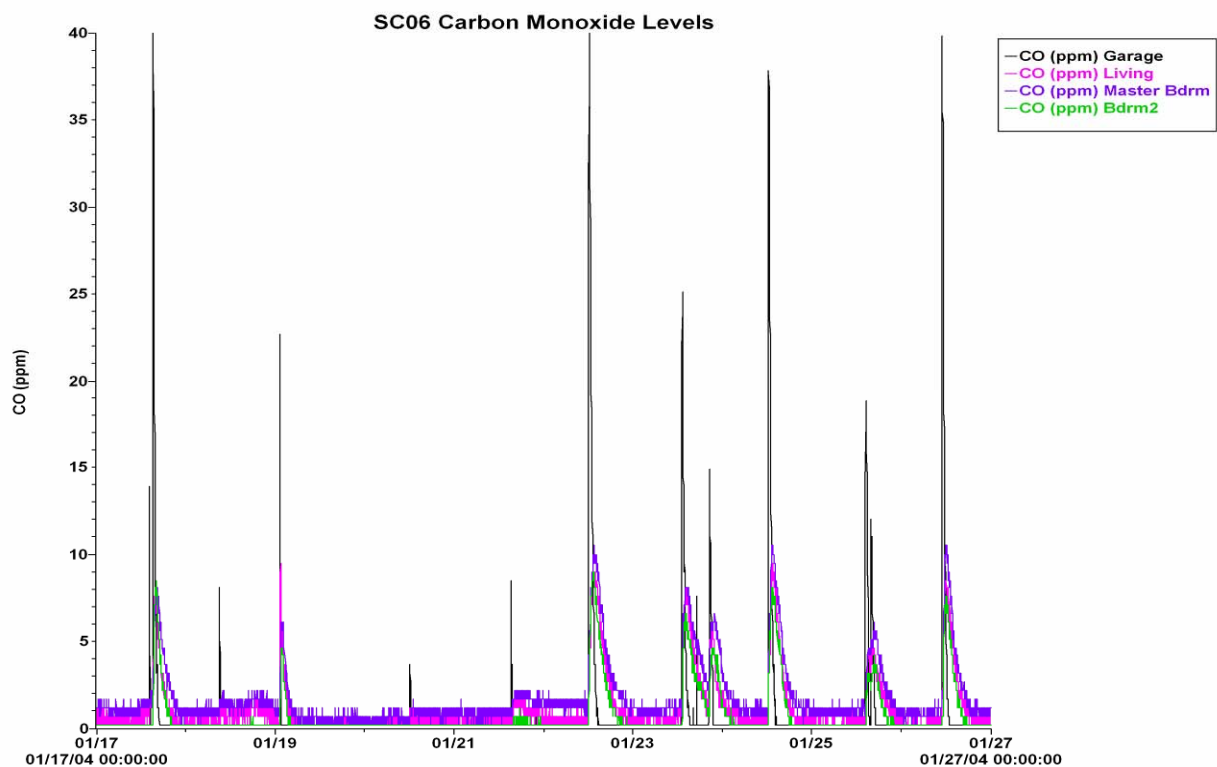
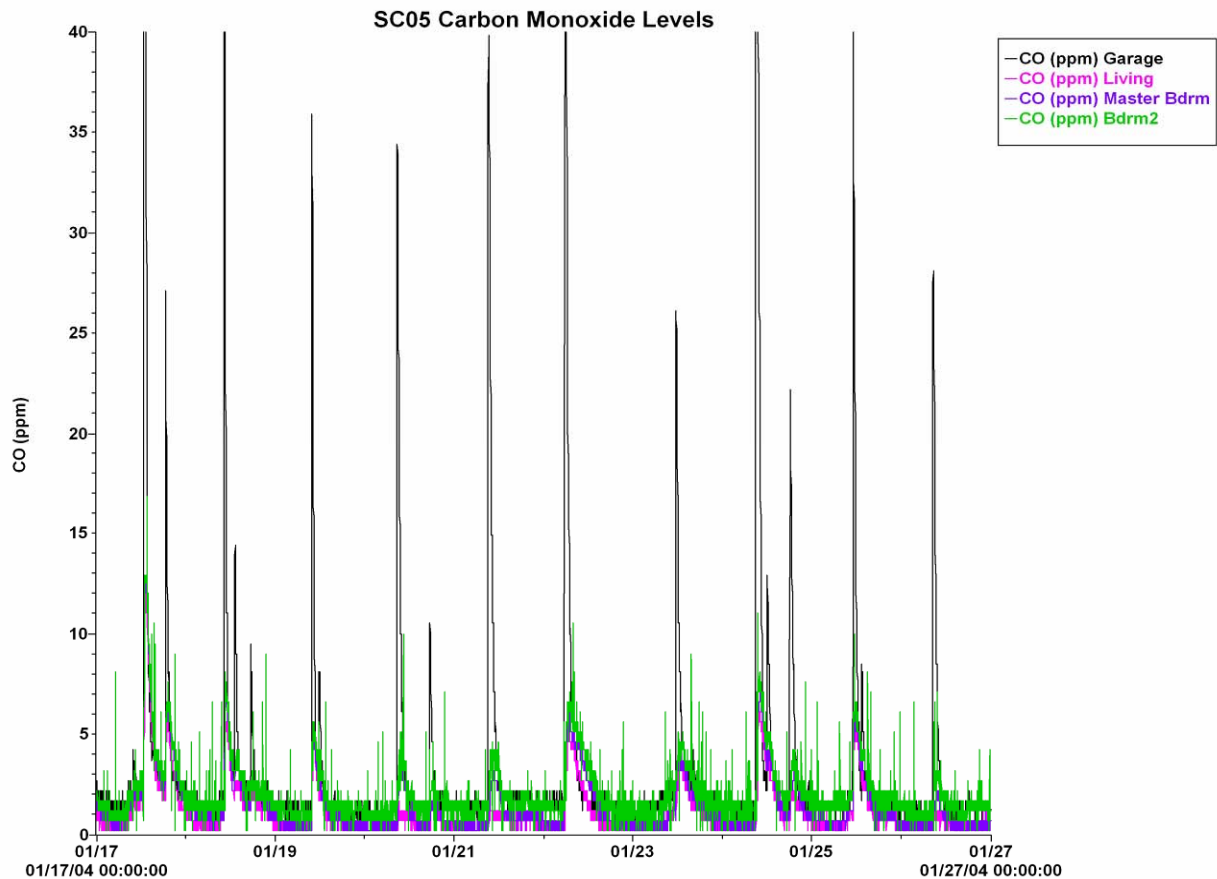
APPENDIX F: Carbon Monoxide Levels



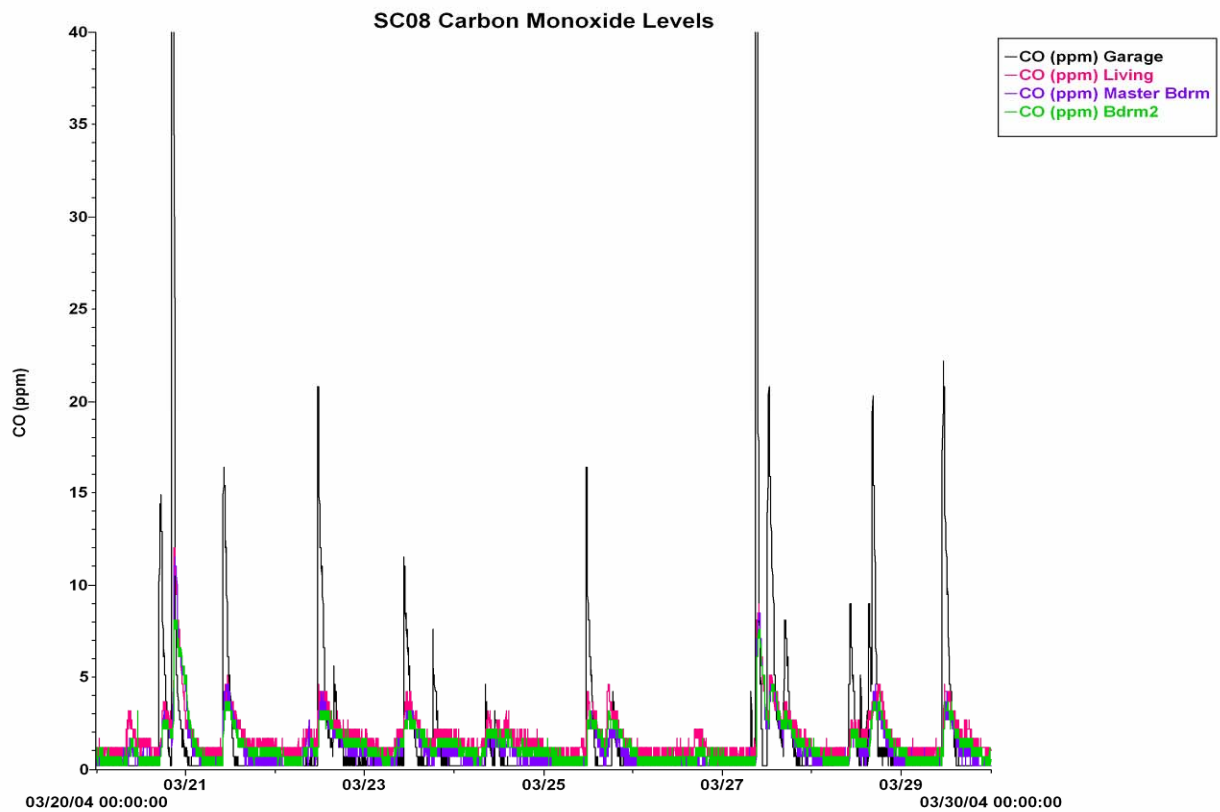
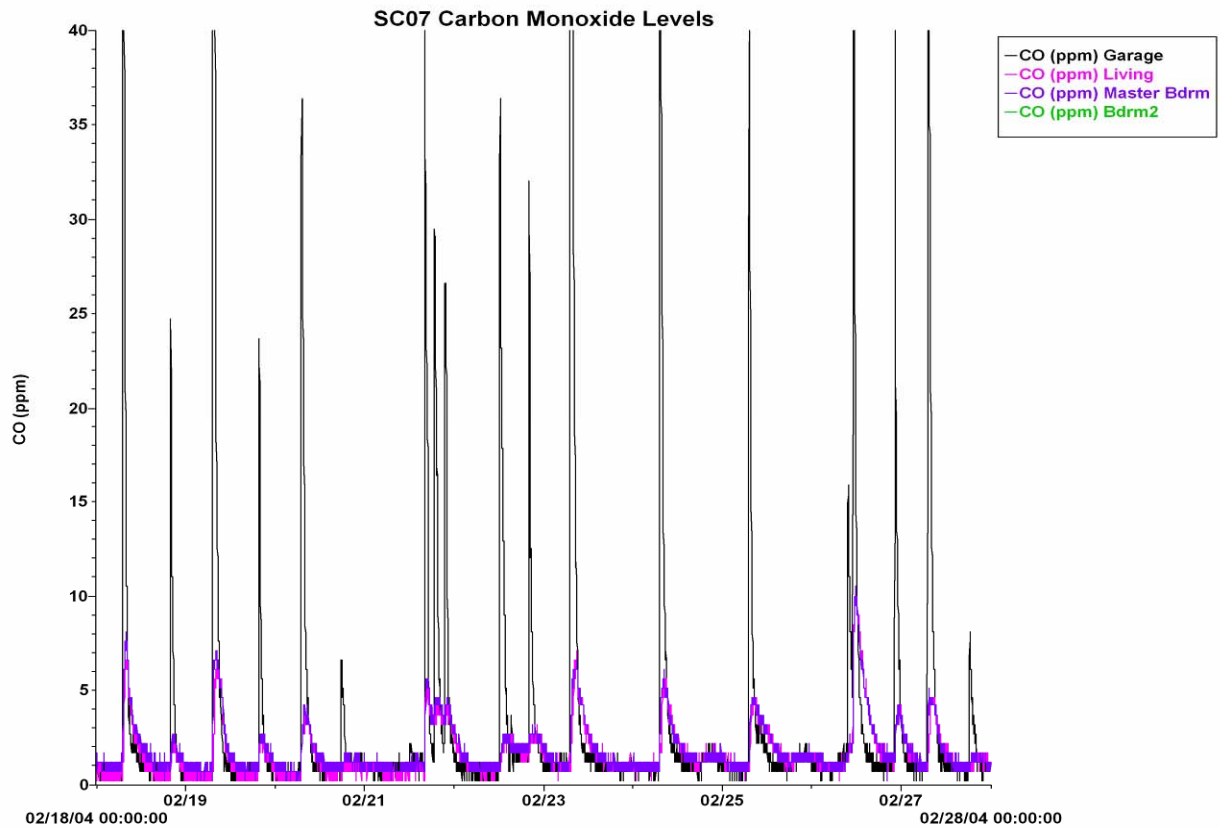
APPENDIX F: Carbon Monoxide Levels



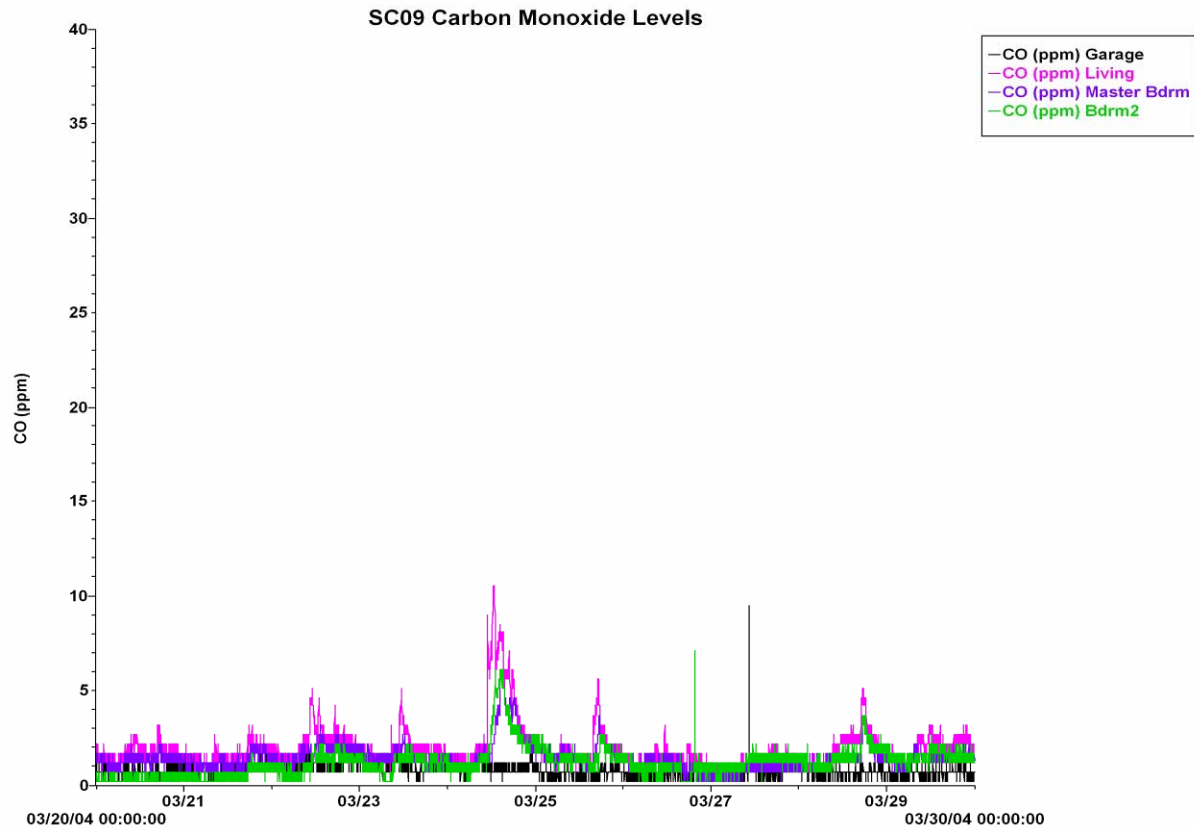
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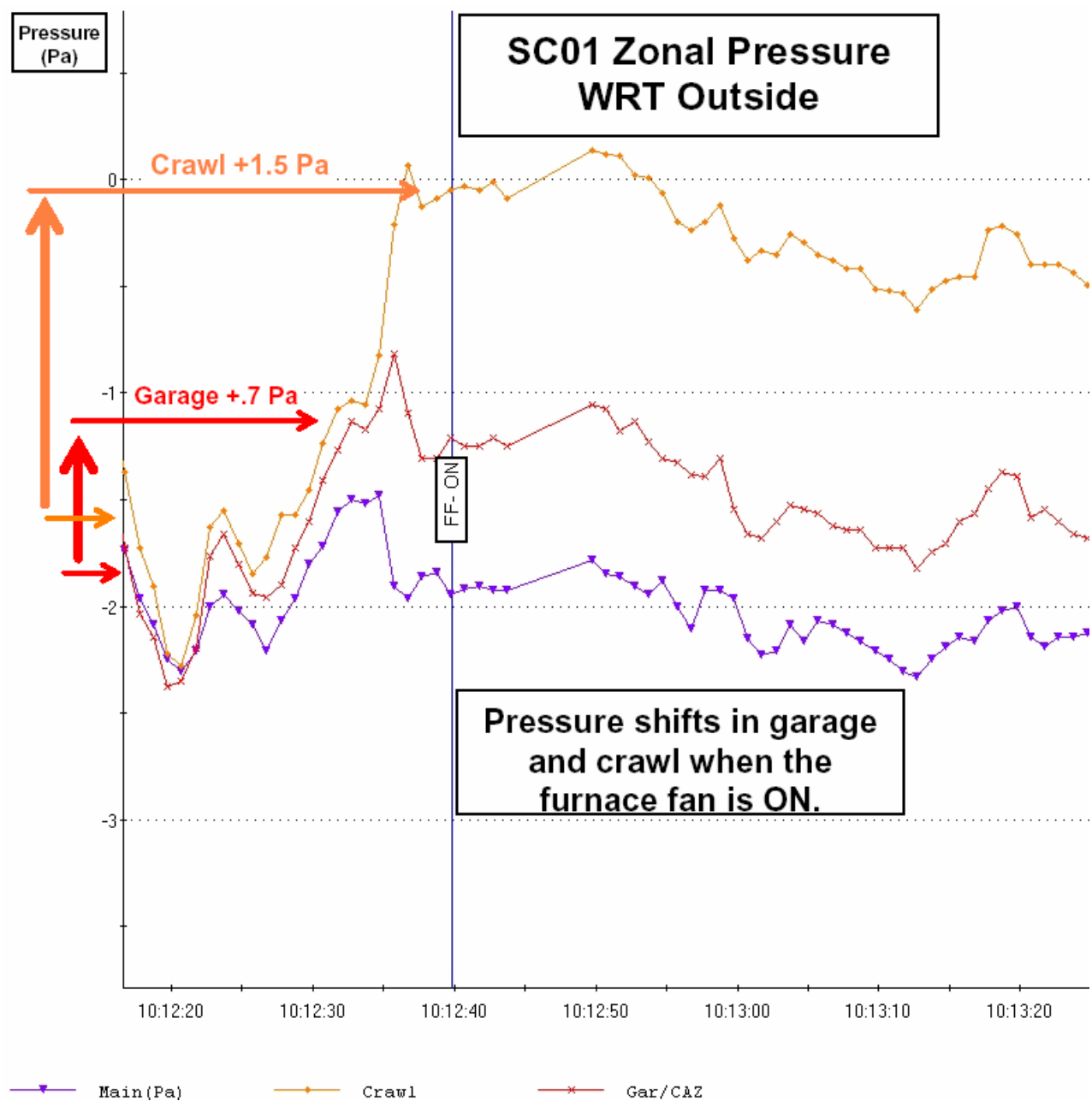


APPENDIX F: Carbon Monoxide Levels

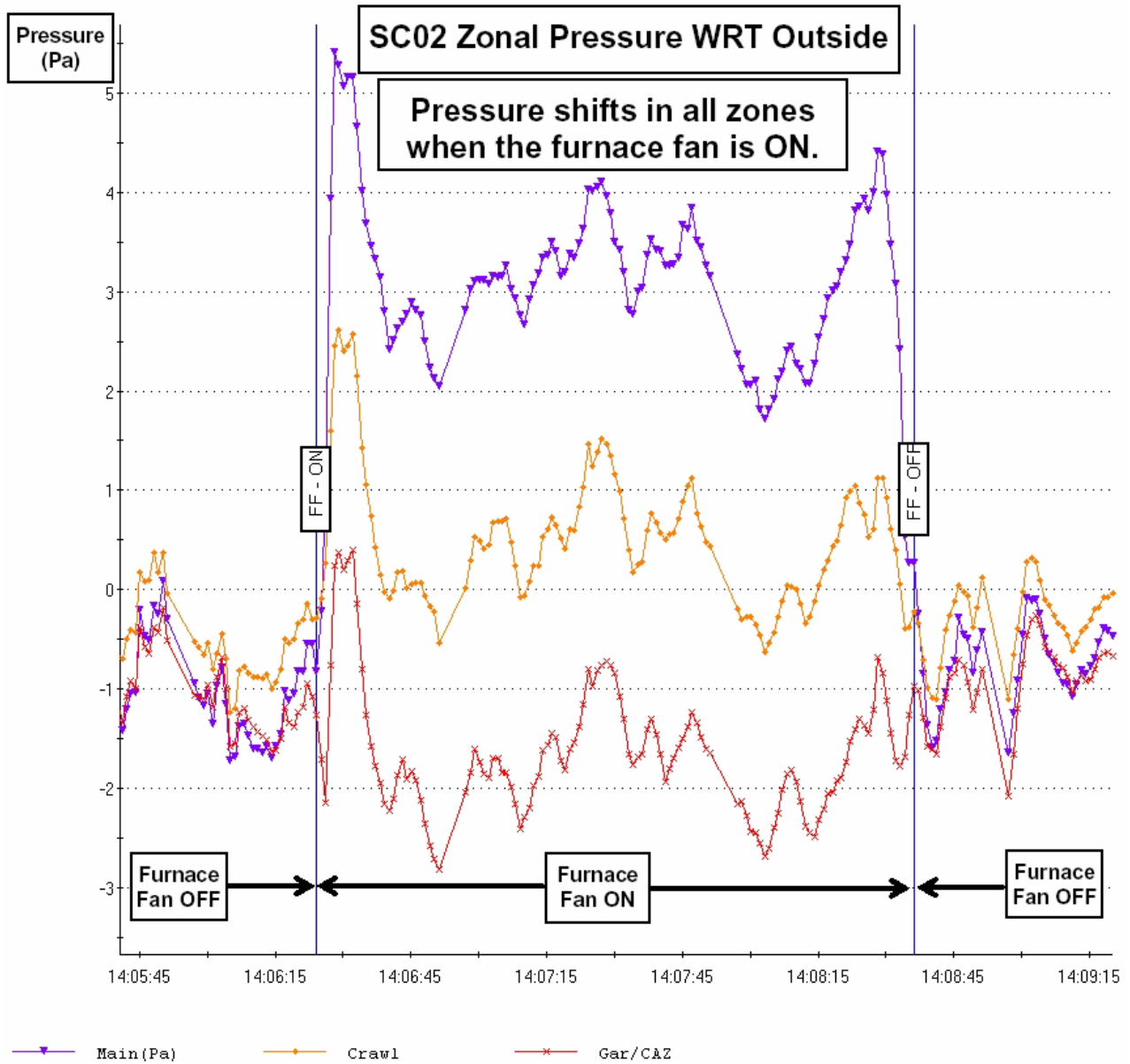


N.B. SC09 garage had NO cars in it during the study period. An occasional CO event appears to be from cooking on the gas range.

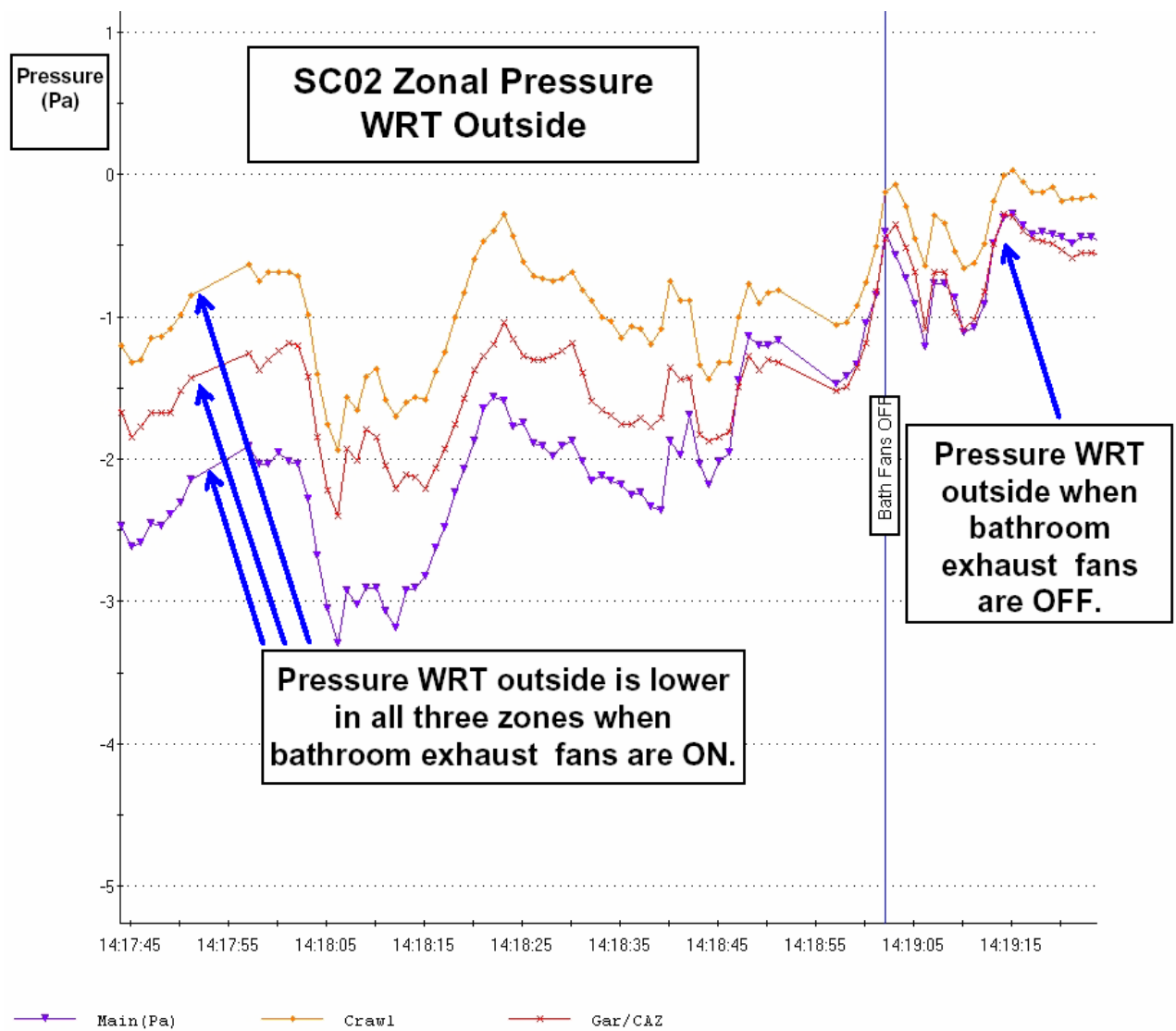
APPENDIX G: Zonal Interconnection Pressure Shift



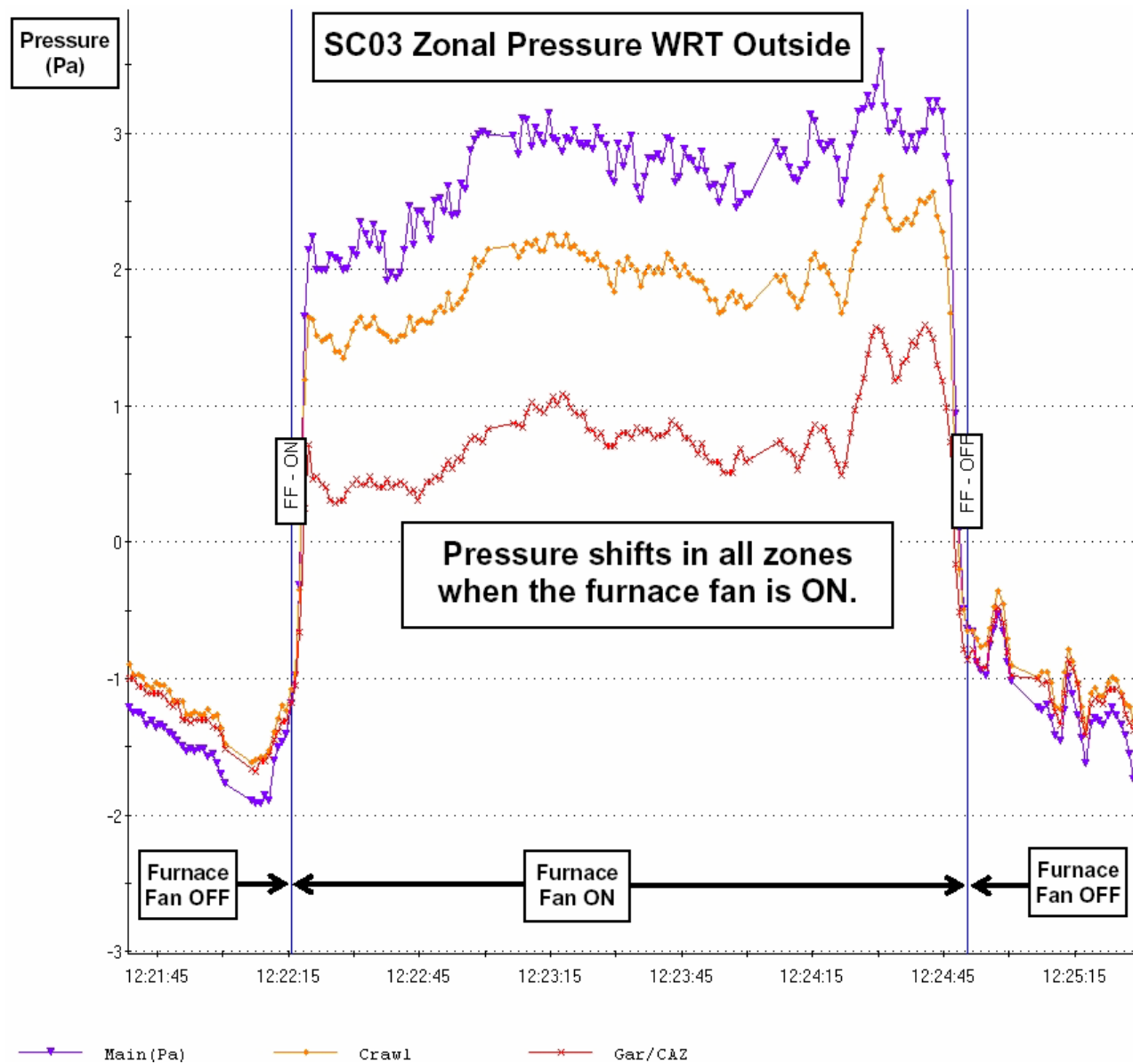
APPENDIX G: Zonal Interconnection Pressure Shift



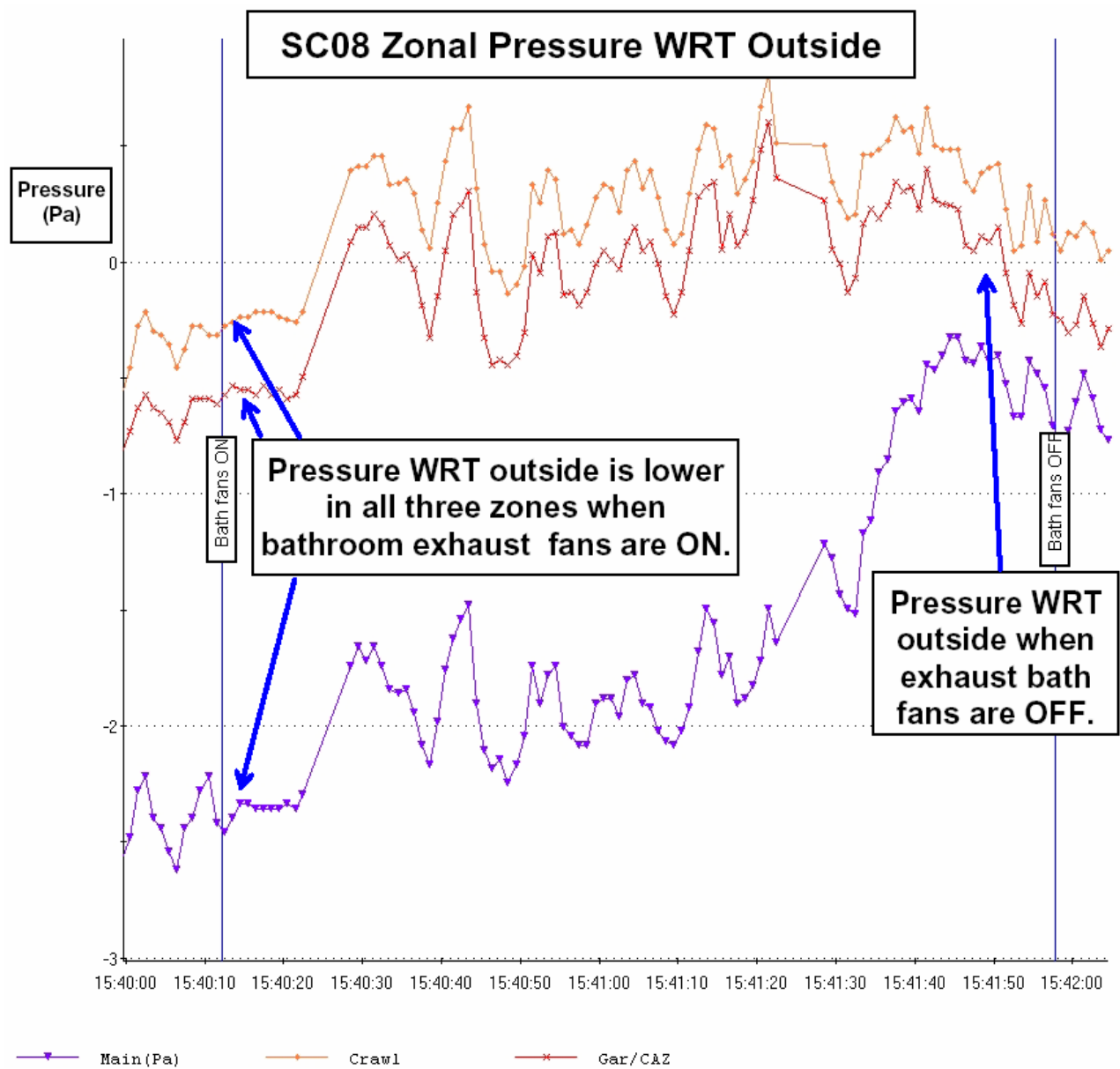
APPENDIX G: Zonal Interconnection Pressure Shift



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APPENDIX G: Zonal Interconnection Pressure Shift



REFERENCES

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