Final White Paper

Residential Kitchen and Bathroom Ventilation as Compared to the Whole House

Prepared for:

C. Richard Titus, Executive Vice President

Kitchen Cabinet Manufacturers Association (KCMA)

1899 Preston White Drive

Reston, VA 20191-5435

P: 703-264-1690

www.kcma.org

Prepared by:

Armin Rudd, Principal

ABT Systems, LLC

726 East Maple Street

Annville, PA 17003

P: 717.867.0123

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Executive Summary

This project was directed at evaluating a premise that residential kitchens and bathrooms are the best ventilated rooms in a house. In general, residential mechanical ventilation consists of local exhaust ventilation and whole-building dilution ventilation. Local exhaust ventilation is important for removing air contaminants at the point of contaminant generation. Whole-building ventilation is important for diluting air contaminants that are remote from locations having local exhaust (Rudd 2011). Air change rates in houses without mechanical whole-house dilution ventilation can be quite low – well below 0.1 air changes per hour (ach), however, use of whole-house dilution ventilation can provide a consistent air change rate of 0.2 ach or higher (Rudd and Bergey 2013). Building codes and standards typically require local exhaust ventilation in kitchens and bathrooms. Analysis compared calculated air change rates in kitchens and bathrooms, under different scenarios of local exhaust use, to typical air change in the rest of the house with and without whole-house dilution ventilation in operation. This analysis showed that kitchens and bathrooms are indeed the best ventilated rooms in the house when local exhaust ventilation is used at code levels or higher in those spaces. The kitchen ventilation rate is two times the whole-house ventilation rate when the kitchen exhaust fan is operated for 1 hour/day in a small kitchen or 4 hours/day in a large kitchen. The bathroom ventilation rate is more than two times the whole-house ventilation rate when the bathroom exhaust fan is operated for 1 hour/day in a small bathroom or 3 hours/day in a large bathroom. These facts, combined with attention to environmental stewardship directed at reducing contaminant emission levels from cabinet materials and finishes should clearly alleviate concerns that some may have about kitchen and bathroom cabinets being a detriment to residential indoor air quality.

Introduction

In general, residential mechanical ventilation consists of local exhaust ventilation and whole-building dilution ventilation. Local exhaust ventilation is important for removing air contaminants at the point of contaminant generation. Whole-building ventilation is important for diluting air contaminants that are remote from locations having local exhaust (Rudd 2011). Figure 1 is a schematic representation of typical residential local exhaust and whole-house dilution ventilation systems.

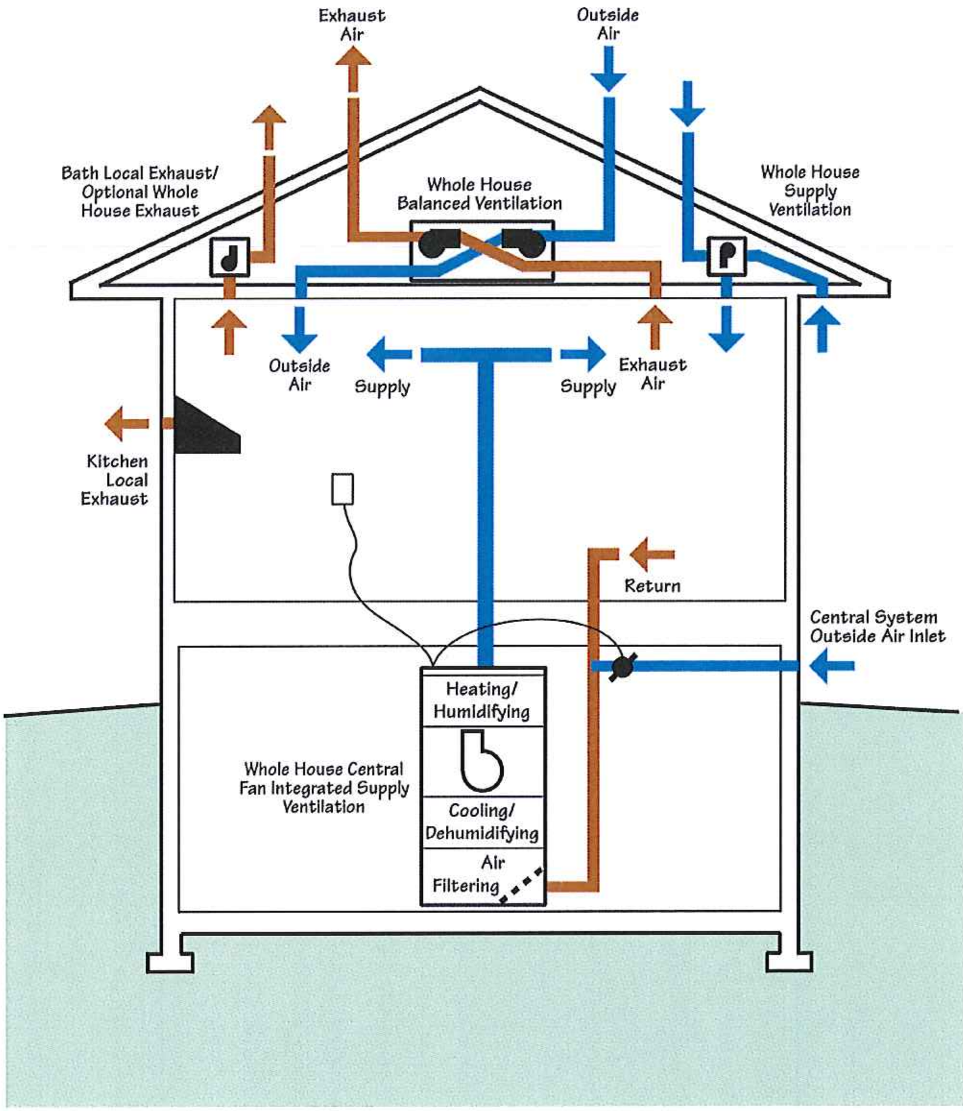

Figure 1. Schematic overview of typical residential ventilation equipment

Neither local exhaust nor whole-house dilution ventilation will be adequate if the contaminant source generation rate and the contaminant species risk is very high. That is one reason why we do not store fuels, solvents, pesticides, etc. inside homes. Thinking about contaminant sources of lower risk and generation rate, such as construction materials that involve adhesives, plastics, and paint or other finishes that off-gas, it is still always good to limit the quantity or existence of those materials in the home, especially if they are not specifically made to have low emission rates. That purposeful limiting is called source control – i.e. the contaminant is not controlled by exhaust or dilution ventilation but by not putting the contaminant source in the building in the first place, or by limiting its quantity. Programs such as the Kitchen Cabinet Manufacturers Association (KCMA) Environmental Stewardship Program encourage the use of materials and finishes that reduce the emission of indoor air contaminants.

Most new and existing homes today have provisions for window opening or local exhaust ventilation in kitchens, bathrooms and toilet rooms (commonly referred to as half baths). While kitchen exhaust ventilation should be standard for the best air quality, it is sometimes substituted for recirculation hoods with a grease filter and/or a charcoal filter. Most people instinctively understand the usefulness of local exhaust in those spaces because of obvious odor and moisture, or airborne particle contaminants such as those generated from cooking. Some studies have shown that while people understand the usefulness of local exhaust, they do not always use it in their homes on a routine basis. Where local exhaust in kitchens and bathrooms is used on a routine basis, it should be reasonable that those rooms would be the best ventilated rooms in the house.

Research Question

This project is directed at evaluating a premise that residential kitchens and bathrooms are the best ventilated rooms in a house.

Research Approach

The research approach includes:

1. A summary of prior publication for reference, including measurement of residential multi-zone air change rates, and formaldehyde and volatile organic compound contaminant levels in kitchen and bathroom spaces.
2. An overview of what building codes and standards require in terms of kitchen and bathroom local exhaust ventilation.
3. Analysis comparing calculated air change rates in kitchens and bathrooms, under different scenarios of local exhaust use, to typical air change in the rest of the house with and without whole-house dilution ventilation in operation.

Prior Publication

Rudd and Bergey (2013)

Rudd and Bergey (2013) measured air change rates in multiple zones of two houses in Tyler, Texas using perfluorocarbon tracer gas. One of the zones included the kitchen which was open to the dining and living areas. Another zone was the master bedroom which was open to the master bathroom. In both of those zones, formaldehyde and volatile organic compounds (VOC) concentrations were also measured. Air change rates were measured in two other bedroom zones but VOCs and formaldehyde were not.

These measurements were made with and without operation of whole-house dilution ventilation. Local exhaust was not used since the study was focused on the performance differences of whole-house dilution ventilation systems. Table 1 shows the measured air changes per hour (ach) in each zone of each house, with no whole-house dilution ventilation and with operation of the three different whole-house ventilation systems. Air change rates in houses without mechanical whole-house dilution ventilation can be quite low – they ranged from 0.02 to 0.08 ach for these two houses, depending on the zone. Exhaust from the master bathroom had little effect on the secondary bedrooms. That problem was eliminated by adding whole-house air mixing via the central system fan operating 10 minutes per hour. Supply ventilation via the central system fan showed fairly consistent results near 0.20 ach. Balanced ventilation using an energy recovery ventilator, independently ducted from the central system, supplying ventilation air to the bedrooms and exhausting air from the main zone, showed high air change rates in the bedrooms (0.4 to 0.8 ach) and low air change in the main zone (0.07 to 0.14 ach).

Table 1. Measured air changes per hour (ach) from two houses, with operation of three different whole-house dilution ventilation systems

	Measured Air Changes per Hour (1/h)				
HOUSE 1	No vent.	Exhaust	Exhaust w/central mixing	Central supply	Balanced
ZONE					
Main w/kitchen	0.07	0.17	0.18	0.19	0.07
Master bedroom, w/bathroom	0.02	0.11	0.14	0.20	0.40
Middle bedroom	0.02	0.08	0.28	0.27	0.79
Front bedroom	0.05	0:08	0.19	0.20	0.65
HOUSE 2					
ZONE					
Main w/kitchen	0.05	0.18	0.21	0.20	0.14
Master bedroom, w/bathroom	0.05	0.16	0.14	0.10	0.38
Middle bedroom	0.05	0.08	0.14	0.15	0.61
Front bedroom	0.08	0.10	0.23	0.19	0.42

Figure 2 and Figure 3 show measured formaldehyde and total organic compounds (TVOC) concentrations in the two houses, respectively. Formaldehyde and VOC concentration was measured only in the main zone near the kitchen and in the master bedroom zone near the master bathroom. The complete set of kitchen and bathroom cabinets were installed, but no furniture or carpet was in the house. Unfortunately, this data set does not provide us with measurements of formaldehyde and VOC concentration in the secondary bedrooms (which had no cabinets) for comparison to the zones with cabinets. However, the data do show that the central supply ventilation and balanced ventilation systems lowered formaldehyde and TVOC concentrations the most.

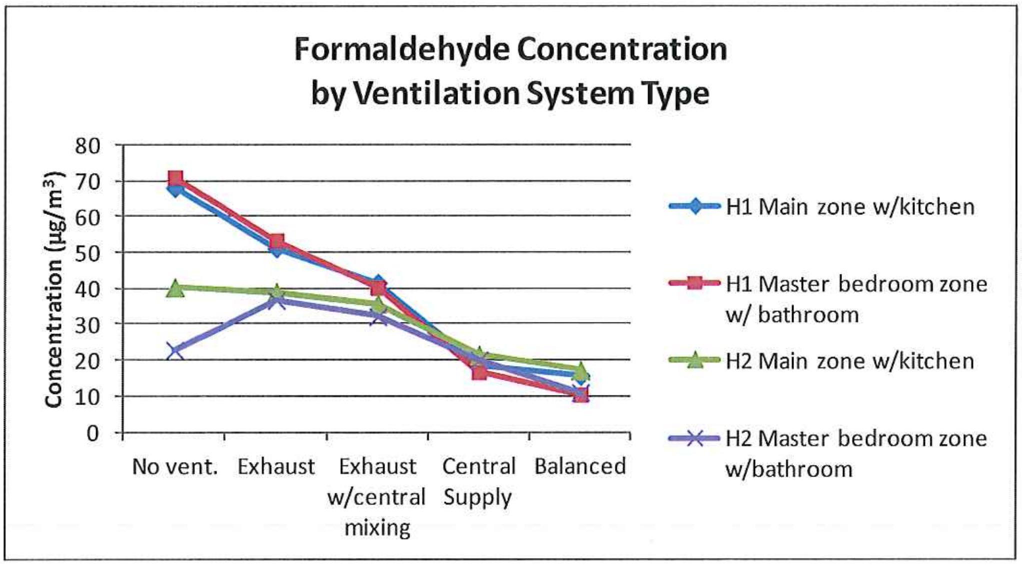

Figure 2. Formaldehyde concentration measurements in two houses, with operation of three different whole-house dilution ventilation systems

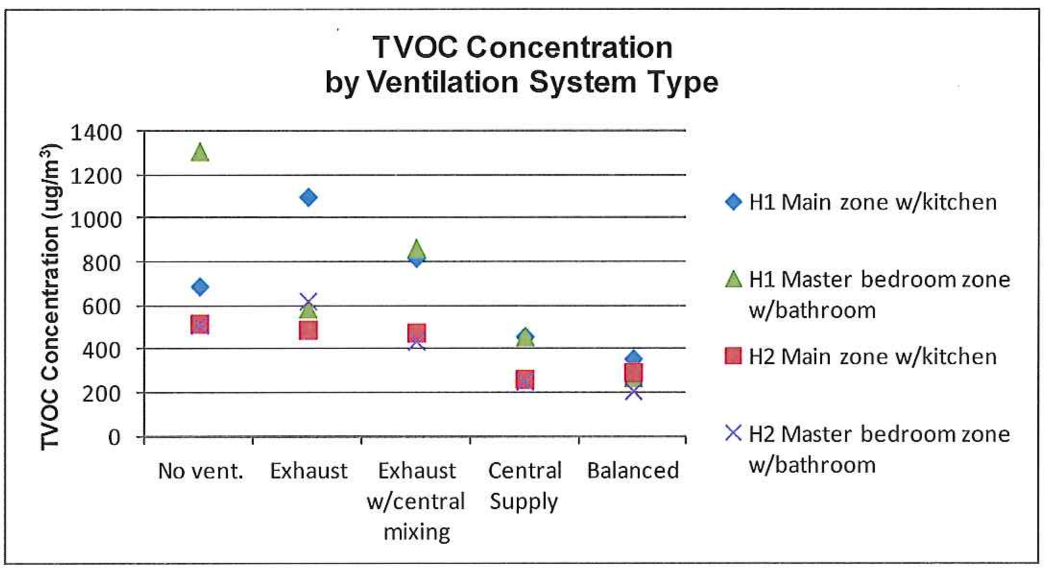

Figure 3. Total Volatile Organic Compound (TVOC) concentration measurements in two houses, with operation of three different whole-house dilution ventilation systems

Building Codes and Standards

Most new and existing homes today have provisions for window opening or local exhaust ventilation in kitchens, bathrooms and toilet rooms (commonly referred to as half baths). Here is what a sampling of current building codes and standards require.

Kitchen

The 2012 International Residential Code (IRC), the 2012 International Mechanical Code (IMC), the Minnesota Building Code (which points to the IRC), the Washington State Ventilation and Indoor Air Quality (VIAQ) Code, and ASHRAE 62.2-2013 require 100 cfm exhaust to outside intermittently on demand, or 25 cfm exhaust to outside continuously in a kitchen. The U.S. Housing and Urban Development (HUD) Code and the National Building Code of Canada require rated exhaust to outside capacity of 100 cfm in a kitchen.

Bathroom

The 2012 IRC, the 2012 IMC, the Minnesota Building Code, the Washington State VIAQ Code, and ASHRAE 62.2-2013 require 50 cfm to outside intermittently on demand, or 20 cfm exhaust to outside continuously in a bathroom. The HUD Code and the National Building Code of Canada require rated exhaust to outside capacity of 50 cfm in a bathroom.

The 2012 IRC, the 2012 IMC, the Minnesota Building Code, and the Washington State VIAQ Code, require 50 cfm to outside intermittently on demand, or 20 cfm continuously in a toilet room. The HUD Code and the National Building Code of Canada require rated exhaust to outside capacity of 50 cfm in a toilet room. ASHRAE 62.2-2013 does not require mechanical ventilation for toilet rooms if there is a window.

Analysis of Kitchen Air Change Rates

The dimensions of a kitchen are sometimes hard to define. Older homes typically had four walls that defined the kitchen footprint, and vaulted ceilings above kitchens were not common. Newer homes typically have more open plans where the kitchen may be defined by one, two, or three floor-to-ceiling walls, but rarely by four floor-to-ceiling walls. Kitchens may also be open to a vaulted ceiling at the top, which makes it hard to define the "kitchen" volume. The volume of a kitchen is important to this analysis because a volume calculation is required in order to calculate an air change rate.

The National Kitchen and Bath Association considers a small kitchen to be less than 150 ft^2, a medium kitchen to be 150-350 ft^2, and a large kitchen to be more than 350 ft^2 (NKBA 2012). Table 2 shows the area of kitchens in two groups: those defined by walls, and those open to eating and/or living areas. These are only general groupings for help in viewing this data. The kitchen air change rates shown in Table 2 are based on kitchen size and operation of a 100 cfm kitchen exhaust fan (the code amount) for the listed hours per day. The results in Table 2 assume that a whole-house dilution ventilation system is providing an air exchange rate of 0.3 air changes per hour (ach) when the kitchen exhaust fan is off. That air exchange rate could be due to controlled whole-house dilution mechanical ventilation in tighter homes or due to uncontrolled infiltration in leakier homes. As shown in Table 2, the kitchen ventilation rate is two times the whole-house ventilation rate when the kitchen exhaust fan is operated for 1 hour/day in a small kitchen or 4 hours/day in a large kitchen.

Table 2. Kitchen air change rate calculations based on kitchen size and operation of a 100 cfm kitchen exhaust fan for the hours per day listed; these results assume whole-house dilution ventilation of 0.3 air changes per hour when the exhaust fan is off

Kitchen Area (ft²)	Kitchen Height (ft)	Kitchen Volume (ft³)	Exhaust Airflow (ft³/min)	Kitchen air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
Defined by walls										
100	8	800	100	7.50	3.90	2.70	1.50	1.20	0.90	0.60
150	8	1200	100	5.00	2.65	1.87	1.08	0.89	0.69	0.50
200	8	1600	100	3.75	2.03	1.45	0.88	0.73	0.59	0.44
Open to eating/living area										
250	8	2000	100	3.00	1.65	1.20	0.75	0.64	0.53	0.41
300	8	2400	100	2.50	1.40	1.03	0.67	0.58	0.48	0.39
350	8	2800	100	2.14	1.22	0.91	0.61	0.53	0.45	0.38

Figure 4 graphically illustrates data given in Table 2 for the lower range of exhaust fan runtime. Figure 5 and Figure 6 show the same information but for 200 cfm and 300 cfm kitchen exhaust, respectively. Clearly, even at the lowest amount of kitchen exhaust fan runtime (1 hr/day), the kitchen ventilation rate is well above the ventilation rate of the rest of the house. Appendix A and Appendix B provide the complete set of kitchen air change rate tables and charts.

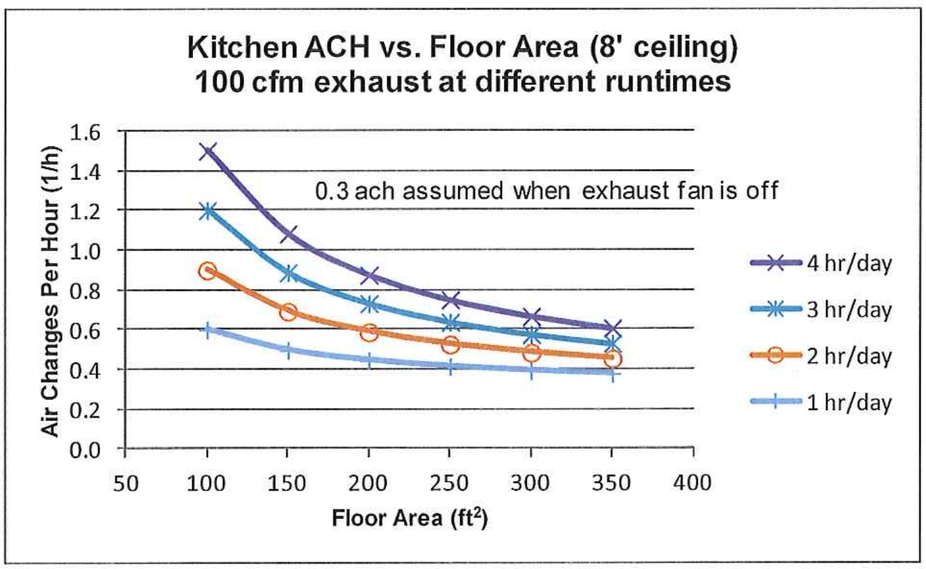

Figure 4. Kitchen air changes per hour (ach) at 100 cfm exhaust (plot of Table 2 data)

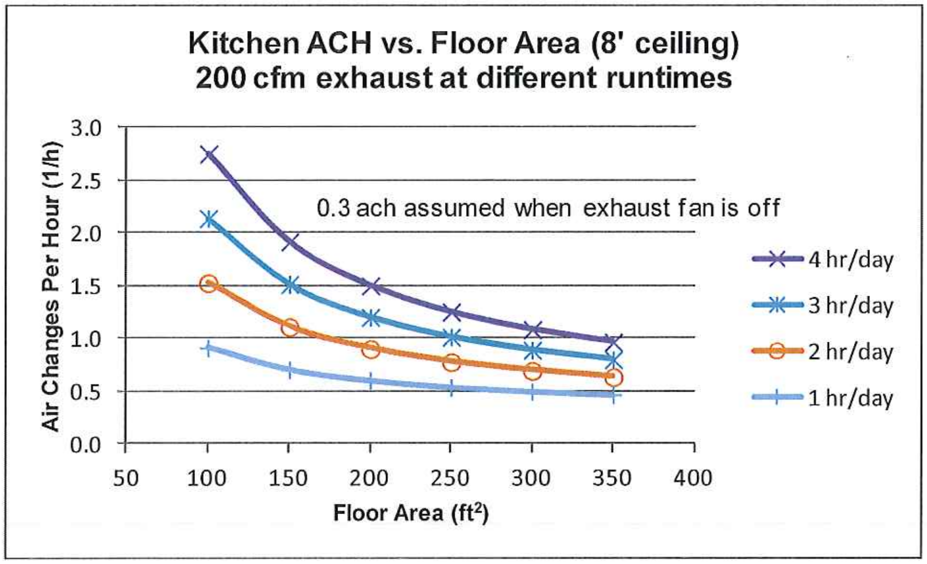

Figure 5. Kitchen air changes per hour (ach) at 200 cfm exhaust

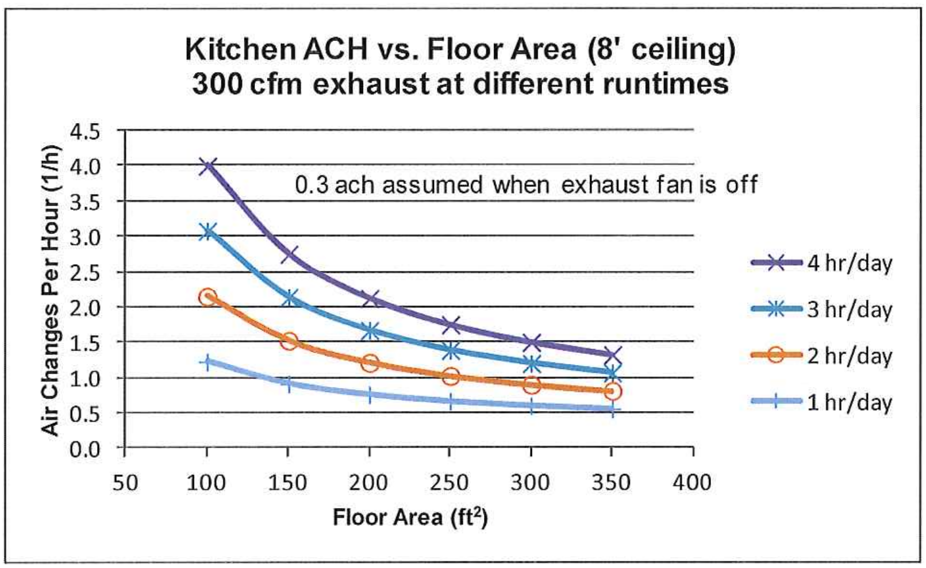

Figure 6. Kitchen air changes per hour (ach) at 300 cfm exhaust

Analysis of Bathroom Air Change Rates

Bathroom dimensions are typically well defined by four floor-to-ceiling walls and a door. However, it is common in modern housing for a bathroom door to be omitted in master bedroom/bathroom suites. Table 3 shows bathroom air change rates based on bathroom size and operation of a 50 cfm bathroom exhaust fan (the code amount) for the listed hours per day. The results in Table 3 assume that a whole-house dilution ventilation system is providing an air exchange rate of 0.3 air changes per hour (ach) when the bathroom exhaust fan is off. The bathroom ventilation rate is more than two times the whole-house ventilation rate when the bathroom exhaust fan is operated for 1 hour/day in a small bathroom or 3 hours/day in a large bathroom.

Table 3. Bathroom air change rate calculations based on bathroom size and operation of a 50 cfm kitchen exhaust fan for the hours per day listed; these results assume whole-house dilution ventilation of 0.3 air changes per hour when the exhaust fan is off

Bathroom Area (ft^2)	Bathroom Height (ft)	Bathroom Volume (ft^3)	Exhaust Airflow (ft^3/min)	Bathroom air changes per hour (1/h) at listed Runtime (hours/day) 24	12	8	4	3	2	1
40	8	320	50	9.38	4.84	3.33	1.81	1.43	1.06	0.68
60	8	480	50	6.25	3.28	2.28	1.29	1.04	0.80	0.55
80	8	640	50	4.69	2.49	1.76	1.03	0.85	0.67	0.48
100	8	800	50	3.75	2.03	1.45	0.88	0.73	0.59	0.44
120	8	960	50	3.13	1.71	1.24	0.77	0.65	0.54	0.42

Figure 7 graphically illustrates data given in Table 3 for the lower range of exhaust fan runtime. Figure 8 and Figure 9 show the same information but for 80 cfm and 110 cfm kitchen exhaust, respectively. Clearly, even at the lowest amount of bathroom exhaust fan runtime (1 hr/day), the bathroom ventilation rate is well above the ventilation rate of the rest of the house. Appendix C and Appendix D provide the complete set of bathroom air change rate tables and charts.

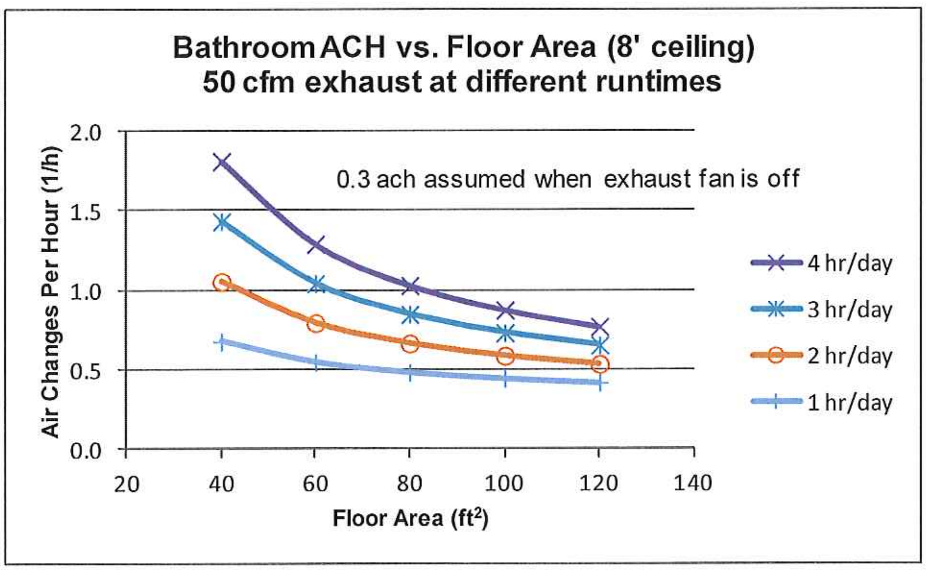

Figure 7. Bathroom air changes per hour (ach) at 50 cfm exhaust (plot of Table 3 data)

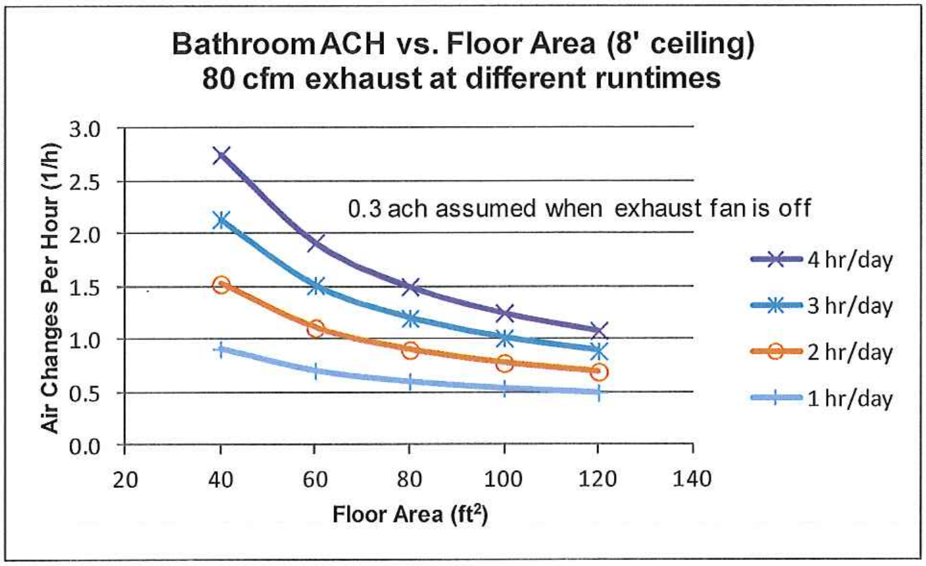

Figure 8. Bathroom air changes per hour (ach) at 80 cfm exhaust

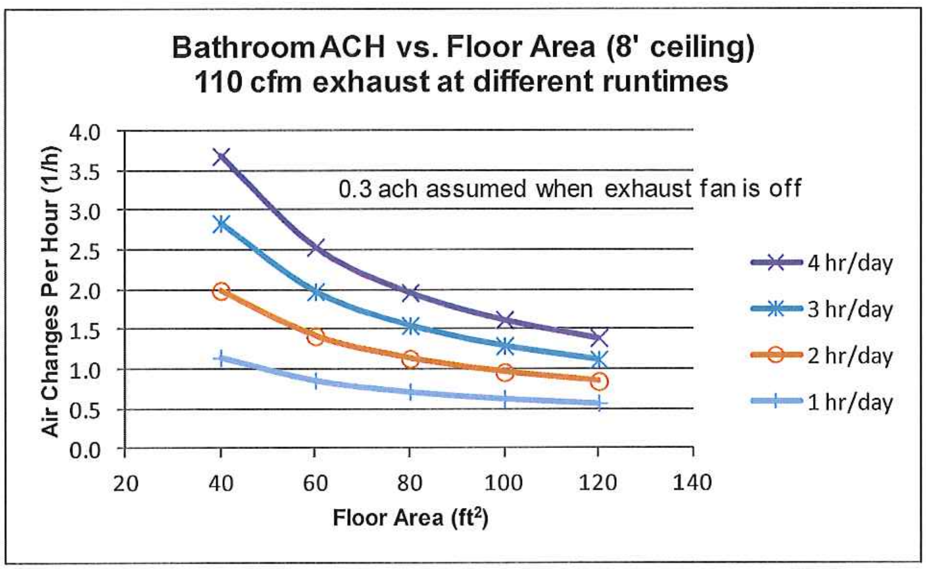

Figure 9. Bathroom air changes per hour (ach) at 110 cfm exhaust

The Importance of Low-Emitting Materials

While kitchens and bathrooms have been shown to be the best ventilated rooms in a house due to local exhaust fan usage, it is still important to use low-emitting materials throughout a house, including in kitchens and bathrooms. By the time furniture, shelving, and carpets are considered, living rooms and bedrooms will typically have just as much if not more material that can emit VOC air contaminants as do kitchens and bathrooms. Volatile organic chemicals, or VOCs, are chemicals that can off-gas from man-made or natural materials and finishes. Manufactures in all sectors have become more aware of this and often work to reduce the potential for VOC off-gassing from the materials they produce. That has especially been true in the building construction industry, including manufacturers of kitchen and bathroom cabinets. Particle board and finishes receive the most attention in this regard. VOCs that off-gas from adhesives used in particle board case parts can be sealed in by capping or sealing exposed surfaces. There are many durable modern finishes that are specially designed to be low emitting. The Kitchen Cabinet Manufacturers Association (KCMA) Environmental Stewardship Program (ESP) requires that certified manufacturers[1] use low formaldehyde-emitting composite wood products.

Conclusions

This analysis has shown that kitchens and bathrooms are indeed the best ventilated rooms in the house when local exhaust ventilation is used at code levels or higher in those spaces. The kitchen ventilation rate is two times the whole-house ventilation rate when the kitchen exhaust fan is operated for 1 hour/day in a small kitchen or 4 hours/day in a large kitchen. The bathroom ventilation rate is more than two times the whole-house ventilation rate when the bathroom exhaust fan is operated for 1 hour/day in a small bathroom or 3 hours/day in a large bathroom. These facts, combined with attention to environmental stewardship directed at reducing contaminant emission levels from cabinet materials and finishes, should clearly alleviate any concerns about kitchen and bathroom cabinets being a detriment to residential indoor air quality.

[1] for more information see www.GreenCabinetSource.org

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ANSI/ASHRAE Standard 62.2-2013. "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings." American Society of Heating Refrigeration and Air-Conditioning Engineers, Atlanta, Georgia.

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Appendix A

Kitchen Air Change Rate Tables

No assumed air change when the kitchen exhaust fan is off

Table A- 1. Kitchen air change rate for 100 cfm exhaust, no whole-house dilution ventilation

Kitchen Area (ft^2)	Kitchen Height (ft)	Kitchen Volume (ft^3)	Exhaust Airflow (ft^3/min)	Kitchen air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
Defined by walls										
100	8	800	100	7.50	3.75	2.50	1.25	0.94	0.63	0.31
150	8	1200	100	5.00	2.50	1.67	0.83	0.63	0.42	0.21
200	8	1600	100	3.75	1.88	1.25	0.63	0.47	0.31	0.16
Open to eating/living area										
250	8	2000	100	3.00	1.50	1.00	0.50	0.38	0.25	0.13
300	8	2400	100	2.50	1.25	0.83	0.42	0.31	0.21	0.10
350	8	2800	100	2.14	1.07	0.71	0.36	0.27	0.18	0.09

Table A- 2. Kitchen air change rate for 200 cfm exhaust, no whole-house dilution ventilation

Kitchen Area (ft^2)	Kitchen Height (ft)	Kitchen Volume (ft^3)	Exhaust Airflow (ft^3/min)	Kitchen air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
Defined by walls										
100	8	800	200	15.00	7.50	5.00	2.50	1.88	1.25	0.63
150	8	1200	200	10.00	5.00	3.33	1.67	1.25	0.83	0.42
200	8	1600	200	7.50	3.75	2.50	1.25	0.94	0.63	0.31
Open to eating/living area										
250	8	2000	200	6.00	3.00	2.00	1.00	0.75	0.50	0.25
300	8	2400	200	5.00	2.50	1.67	0.83	0.63	0.42	0.21
350	8	2800	200	4.29	2.14	1.43	0.71	0.54	0.36	0.18

Table A- 3. Kitchen air change rate for 300 cfm exhaust, no whole-house dilution ventilation

Kitchen Area (ft^2)	Kitchen Height (ft)	Kitchen Volume (ft^3)	Exhaust Airflow (ft^3/min)	Kitchen air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
Defined by walls										
100	8	800	300	22.50	11.25	7.50	3.75	2.81	1.88	0.94
150	8	1200	300	15.00	7.50	5.00	2.50	1.88	1.25	0.63
200	8	1600	300	11.25	5.63	3.75	1.88	1.41	0.94	0.47
Open to eating/living area										
250	8	2000	300	9.00	4.50	3.00	1.50	1.13	0.75	0.38
300	8	2400	300	7.50	3.75	2.50	1.25	0.94	0.63	0.31
350	8	2800	300	6.43	3.21	2.14	1.07	0.80	0.54	0.27

Assumed 0.3 ach air change rate by whole-house dilution ventilation system when the kitchen exhaust fan is off

Table A- 4. Kitchen air change rate for 100 cfm exhaust and whole-house dilution ventilation when the kitchen exhaust fan is off

Kitchen Area (ft^2)	Kitchen Height (ft)	Kitchen Volume (ft^3)	Exhaust Airflow (ft^3/min)	Kitchen air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
Defined by walls										
100	8	800	100	7.50	3.90	2.70	1.50	1.20	0.90	0.60
150	8	1200	100	5.00	2.65	1.87	1.08	0.89	0.69	0.50
200	8	1600	100	3.75	2.03	1.45	0.88	0.73	0.59	0.44
Open to eating/living area										
250	8	2000	100	3.00	1.65	1.20	0.75	0.64	0.53	0.41
300	8	2400	100	2.50	1.40	1.03	0.67	0.58	0.48	0.39
350	8	2800	100	2.14	1.22	0.91	0.61	0.53	0.45	0.38

Table A- 5. Kitchen air change rate for 200 cfm exhaust and whole-house dilution ventilation when the kitchen exhaust fan is off

Kitchen Area (ft^2)	Kitchen Height (ft)	Kitchen Volume (ft^3)	Exhaust Airflow (ft^3/min)	Kitchen air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
Defined by walls										
100	8	800	200	15.00	7.65	5.20	2.75	2.14	1.53	0.91
150	8	1200	200	10.00	5.15	3.53	1.92	1.51	1.11	0.70
200	8	1600	200	7.50	3.90	2.70	1.50	1.20	0.90	0.60
Open to eating/living area										
250	8	2000	200	6.00	3.15	2.20	1.25	1.01	0.78	0.54
300	8	2400	200	5.00	2.65	1.87	1.08	0.89	0.69	0.50
350	8	2800	200	4.29	2.29	1.63	0.96	0.80	0.63	0.47

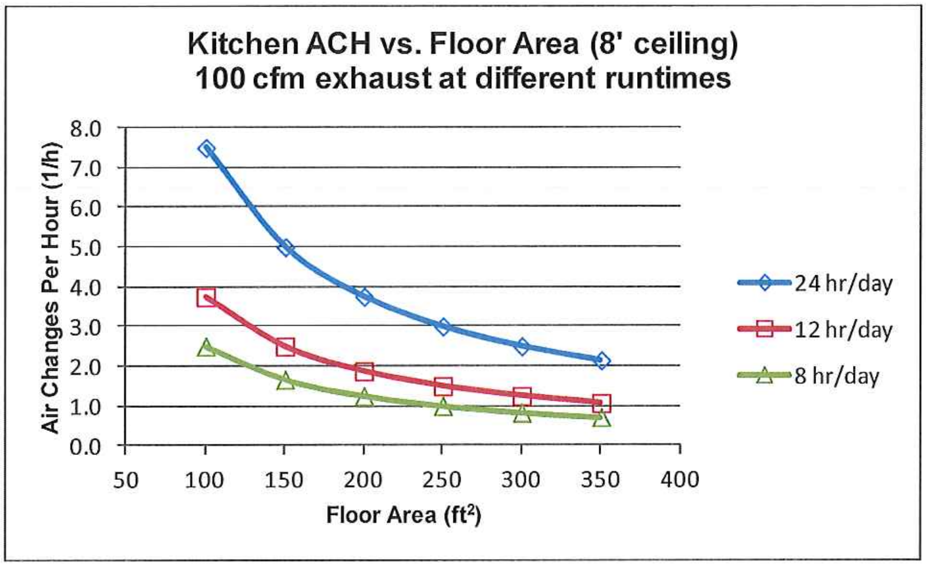
Table A- 6. Kitchen air change rate for 300 cfm exhaust and whole-house dilution ventilation when the kitchen exhaust fan is off

Kitchen Area (ft^2)	Kitchen Height (ft)	Kitchen Volume (ft^3)	Exhaust Airflow (ft^3/min)	Kitchen air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
Defined by walls										
100	8	800	300	22.50	11.40	7.70	4.00	3.08	2.15	1.23
150	8	1200	300	15.00	7.65	5.20	2.75	2.14	1.53	0.91
200	8	1600	300	11.25	5.78	3.95	2.13	1.67	1.21	0.76
Open to eating/living area										
250	8	2000	300	9.00	4.65	3.20	1.75	1.39	1.03	0.66
300	8	2400	300	7.50	3.90	2.70	1.50	1.20	0.90	0.60
350	8	2800	300	6.43	3.36	2.34	1.32	1.07	0.81	0.56

Appendix B

Kitchen Air Change Rate Charts

No assumed air change when the kitchen exhaust fan is off



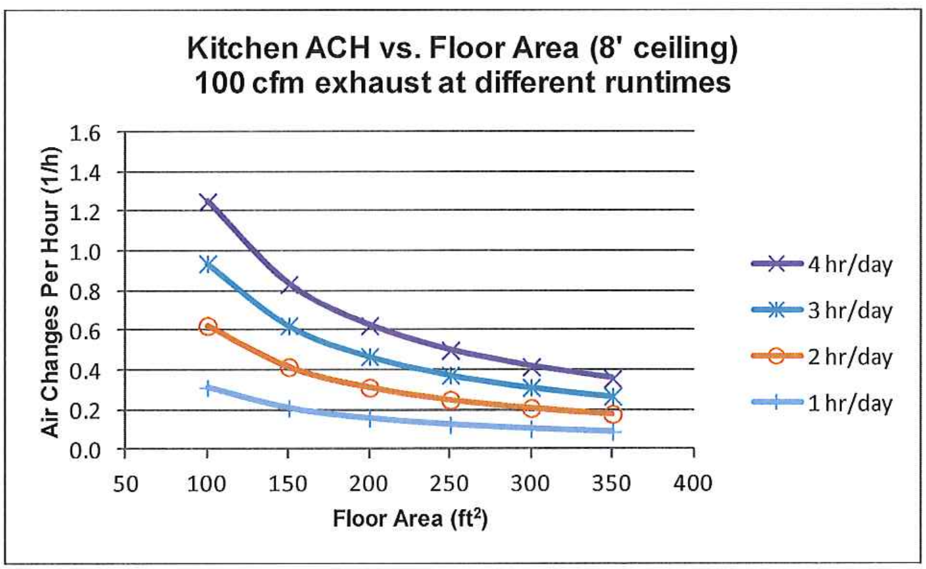
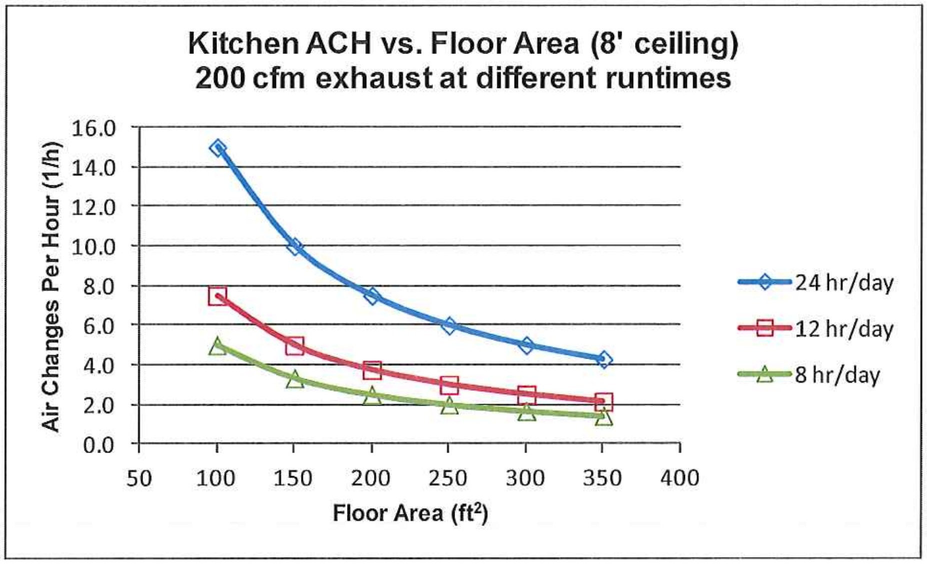


Figure B- 1. Kitchen air change rates with 100 cfm exhaust, no whole-house dilution ventilation



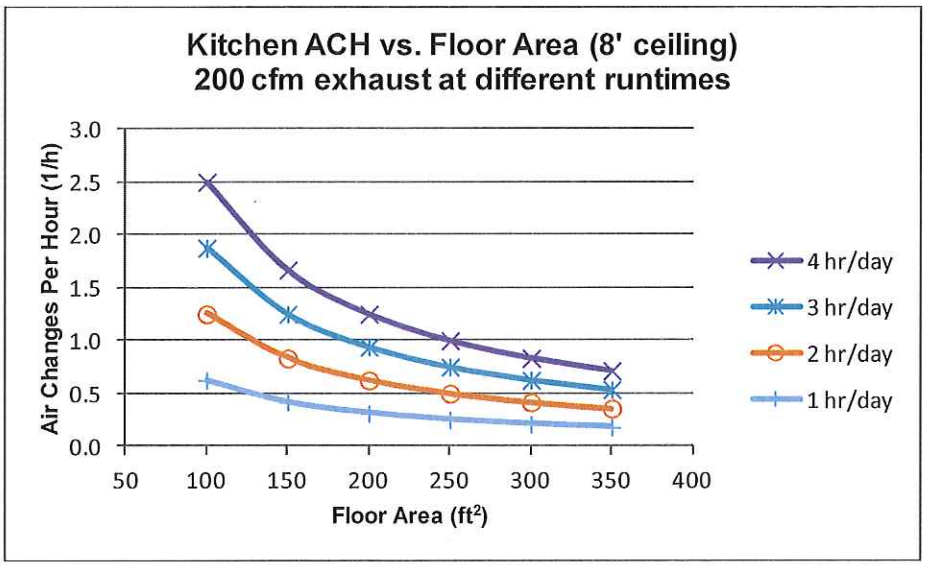
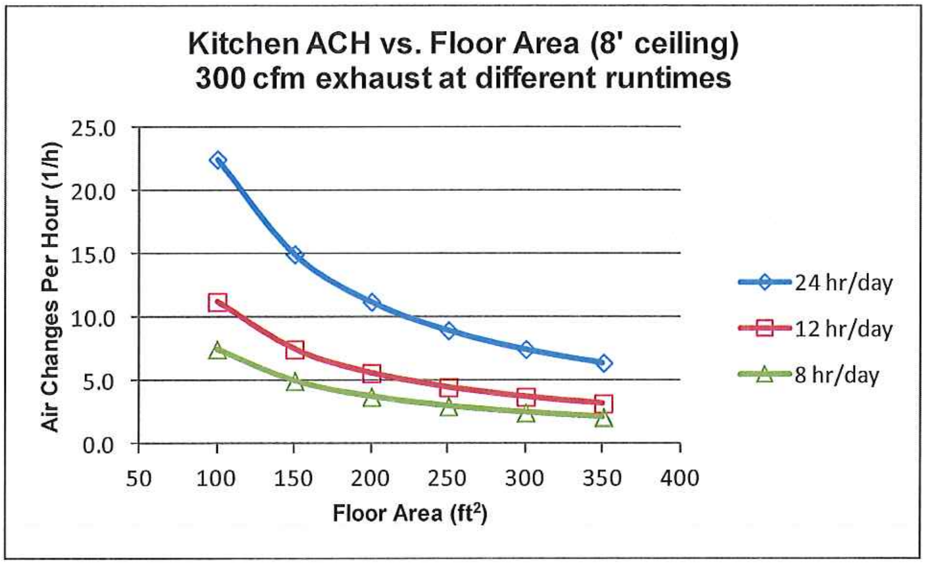


Figure B- 2. Kitchen air change rates with 200 cfm exhaust, no whole-house dilution ventilation



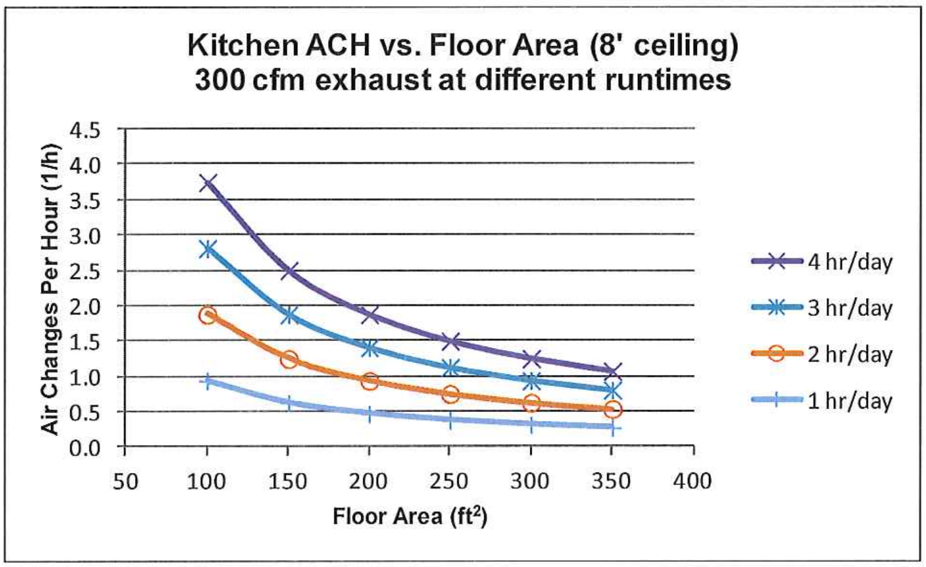
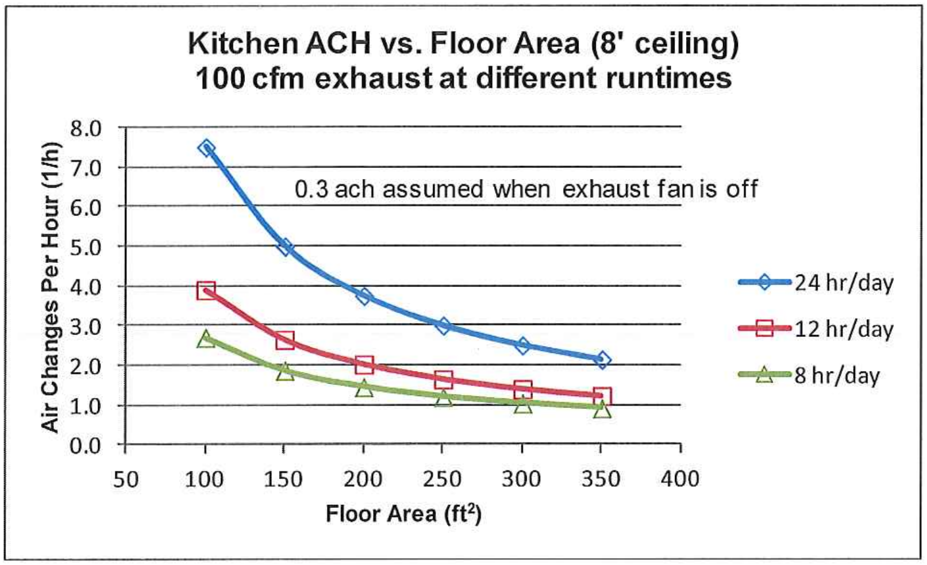


Figure B- 3. Kitchen air change rates with 300 cfm exhaust, no whole-house dilution ventilation

Assumed 0.3 ach air change rate by whole-house dilution ventilation system when the kitchen exhaust fan is off



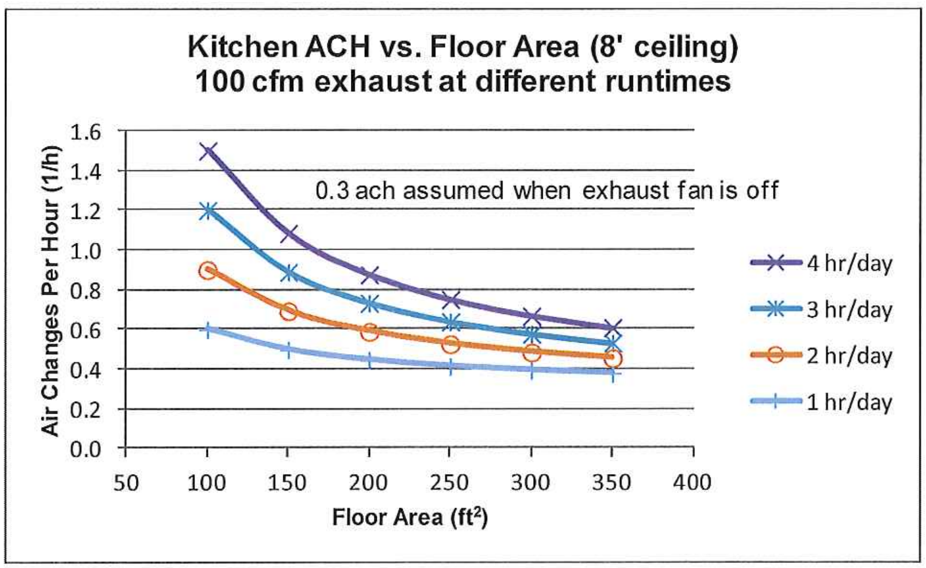
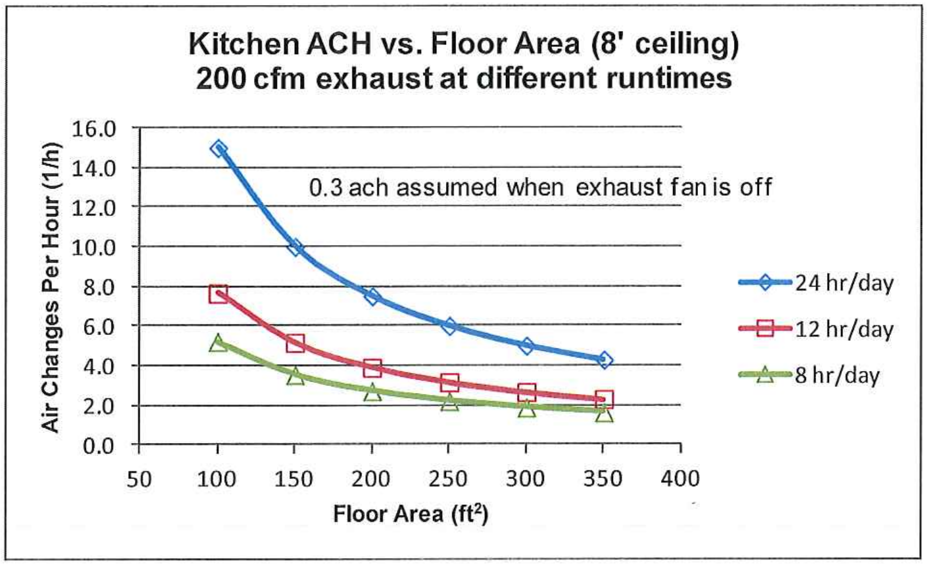


Figure B- 4. Kitchen air change rates with 100 cfm exhaust and whole-house dilution ventilation when the kitchen exhaust fan is off



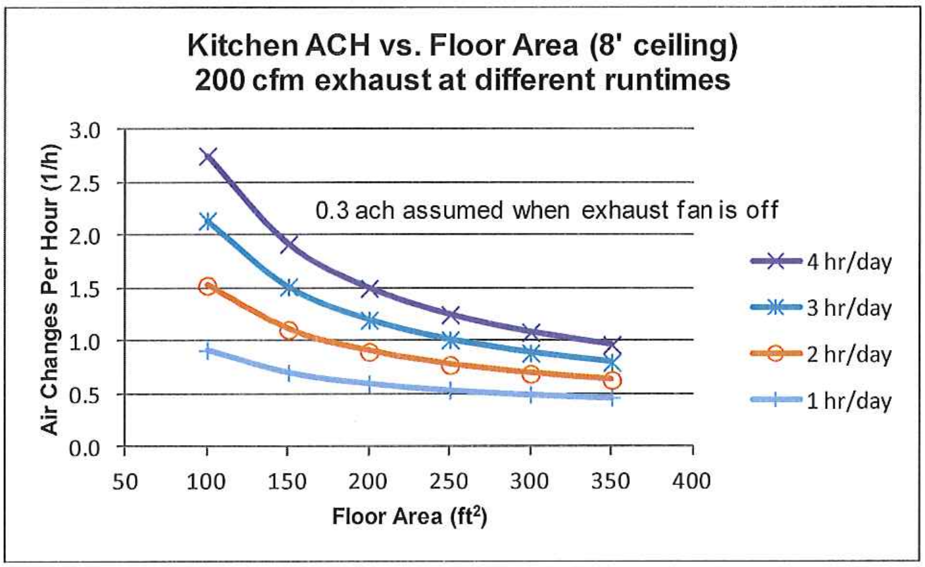
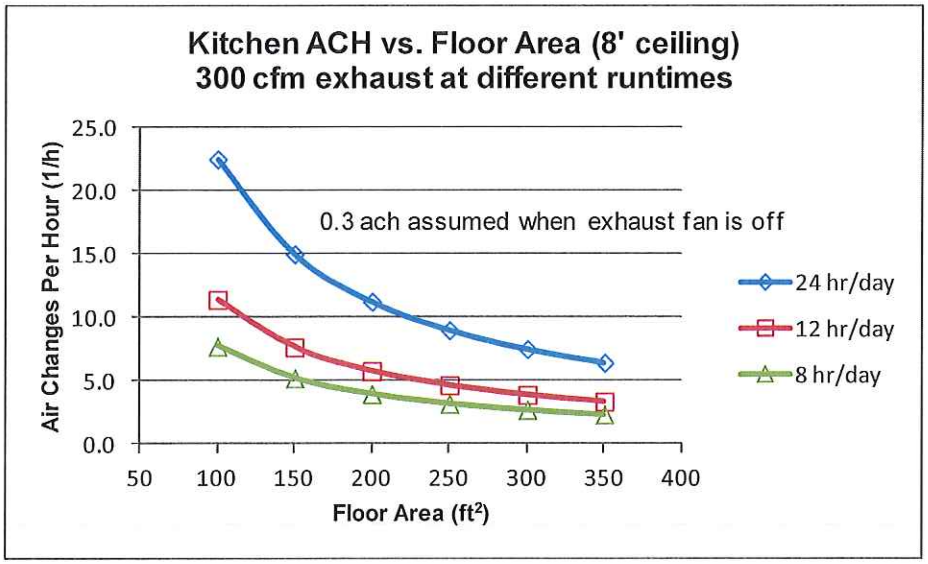


Figure B- 5. Kitchen air change rates with 200 cfm exhaust and whole-house dilution ventilation when the kitchen exhaust fan is off



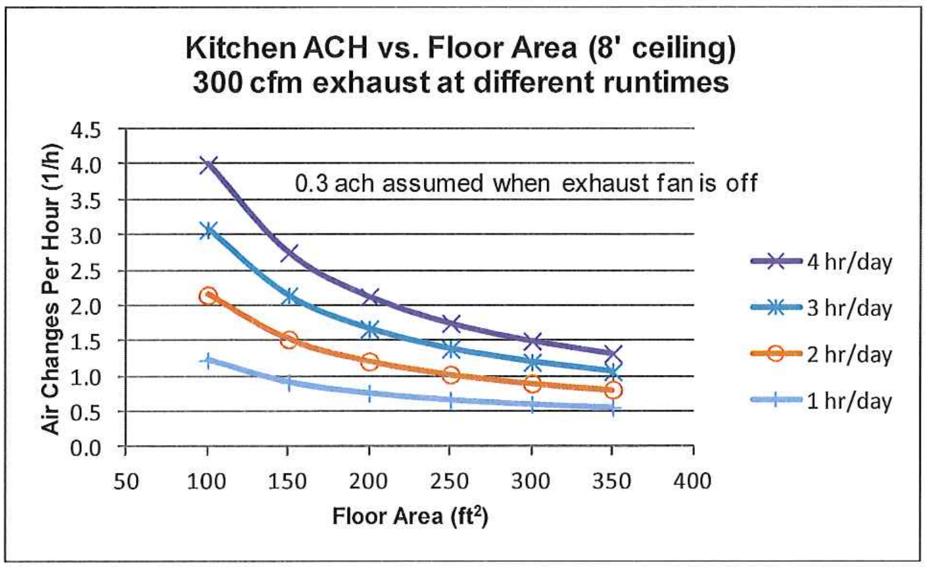


Figure B- 6. Kitchen air change rates with 300 cfm exhaust and whole-house dilution ventilation when the kitchen exhaust fan is off

Appendix C

Bathroom Air Change Rate Tables

No assumed air change when the bathroom fan is off

Table C- 1. Bathroom air change rate for 50 cfm exhaust, no whole-house dilution ventilation

Bathroom Area (ft^2)	Bathroom Height (ft)	Bathroom Volume (ft^3)	Exhaust Airflow (ft^3/min)	Bathroom air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
40	8	320	50	9.38	4.69	3.13	1.56	1.17	0.78	0.39
60	8	480	50	6.25	3.13	2.08	1.04	0.78	0.52	0.26
80	8	640	50	4.69	2.34	1.56	0.78	0.59	0.39	0.20
100	8	800	50	3.75	1.88	1.25	0.63	0.47	0.31	0.16
120	8	960	50	3.13	1.56	1.04	0.52	0.39	0.26	0.13

Table C- 2. Bathroom air change rate for 80 cfm exhaust, no whole-house dilution ventilation

Bathroom Area (ft^2)	Bathroom Height (ft)	Bathroom Volume (ft^3)	Exhaust Airflow (ft^3/min)	Bathroom air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
40	8	320	80	15.00	7.50	5.00	2.50	1.88	1.25	0.63
60	8	480	80	10.00	5.00	3.33	1.67	1.25	0.83	0.42
80	8	640	80	7.50	3.75	2.50	1.25	0.94	0.63	0.31
100	8	800	80	6.00	3.00	2.00	1.00	0.75	0.50	0.25
120	8	960	80	5.00	2.50	1.67	0.83	0.63	0.42	0.21

Table C- 3. Bathroom air change rate for 110 cfm exhaust, no whole-house dilution ventilation

Bathroom Area (ft^2)	Bathroom Height (ft)	Bathroom Volume (ft^3)	Exhaust Airflow (ft^3/min)	Bathroom air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
40	8	320	110	20.63	10.31	6.88	3.44	2.58	1.72	0.86
60	8	480	110	13.75	6.88	4.58	2.29	1.72	1.15	0.57
80	8	640	110	10.31	5.16	3.44	1.72	1.29	0.86	0.43
100	8	800	110	8.25	4.13	2.75	1.38	1.03	0.69	0.34
120	8	960	110	6.88	3.44	2.29	1.15	0.86	0.57	0.29

Assumed 0.3 ach air change rate by whole-house dilution ventilation system when the bathroom exhaust fan is off

Table C- 4. Bathroom air change rate for 50 cfm exhaust and whole-house dilution ventilation when the bathroom exhaust fan is off

Bathroom Area (ft^2)	Bathroom Height (ft)	Bathroom Volume (ft^3)	Exhaust Airflow (ft^3/min)	Bathroom air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
40	8	320	50	9.38	4.84	3.33	1.81	1.43	1.06	0.68
60	8	480	50	6.25	3.28	2.28	1.29	1.04	0.80	0.55
80	8	640	50	4.69	2.49	1.76	1.03	0.85	0.67	0.48
100	8	800	50	3.75	2.03	1.45	0.88	0.73	0.59	0.44
120	8	960	50	3.13	1.71	1.24	0.77	0.65	0.54	0.42

Table C- 5. Bathroom air change rate for 80 cfm exhaust and whole-house dilution ventilation when the bathroom exhaust fan is off

Bathroom Area (ft^2)	Bathroom Height (ft)	Bathroom Volume (ft^3)	Exhaust Airflow (ft^3/min)	Bathroom air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
40	8	320	80	15.00	7.65	5.20	2.75	2.14	1.53	0.91
60	8	480	80	10.00	5.15	3.53	1.92	1.51	1.11	0.70
80	8	640	80	7.50	3.90	2.70	1.50	1.20	0.90	0.60
100	8	800	80	6.00	3.15	2.20	1.25	1.01	0.78	0.54
120	8	960	80	5.00	2.65	1.87	1.08	0.89	0.69	0.50

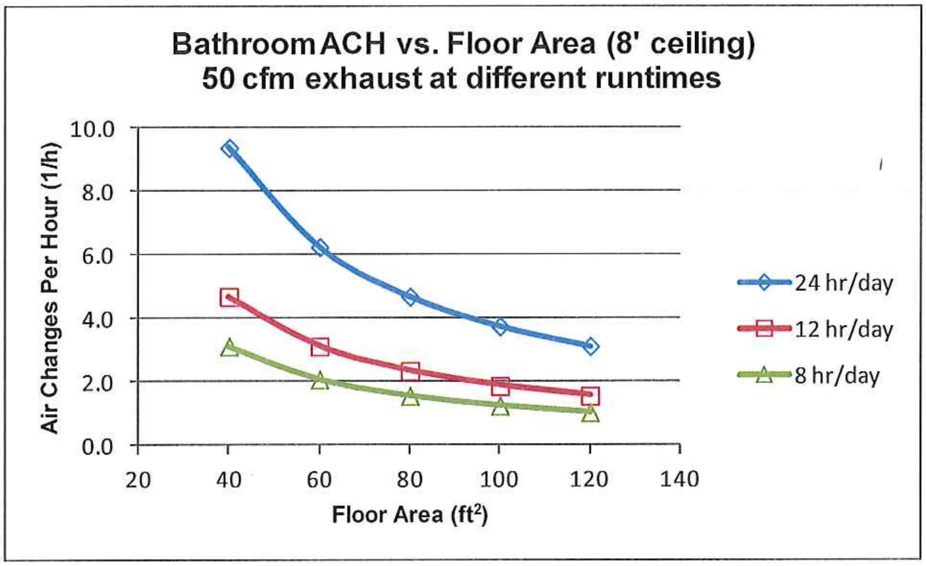
Table C- 6. Bathroom air change rate for 110 cfm exhaust and whole-house dilution ventilation when the bathroom exhaust fan is off

Bathroom Area (ft^2)	Bathroom Height (ft)	Bathroom Volume (ft^3)	Exhaust Airflow (ft^3/min)	Bathroom air changes per hour (1/h) at listed Runtime (hours/day)						
				24	12	8	4	3	2	1
40	8	320	110	20.63	10.46	7.08	3.69	2.84	1.99	1.15
60	8	480	110	13.75	7.03	4.78	2.54	1.98	1.42	0.86
80	8	640	110	10.31	5.31	3.64	1.97	1.55	1.13	0.72
100	8	800	110	8.25	4.28	2.95	1.63	1.29	0.96	0.63
120	8	960	110	6.88	3.59	2.49	1.40	1.12	0.85	0.57

Appendix D

Bathroom Air Change Rate Charts

No assumed air change when the bathroom exhaust fan is off



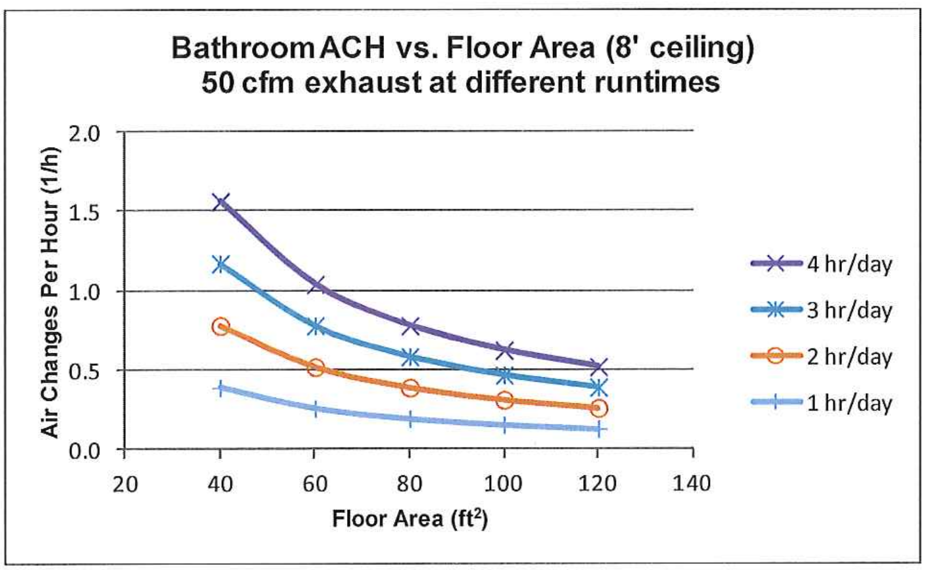
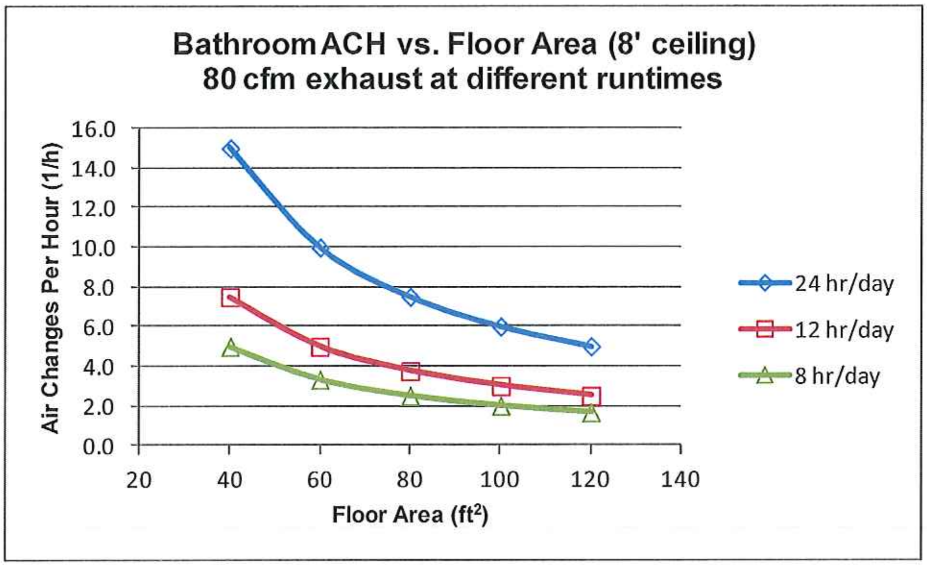


Figure D- 1. Bathroom air change rates with 50 cfm exhaust, no whole-house dilution ventilation



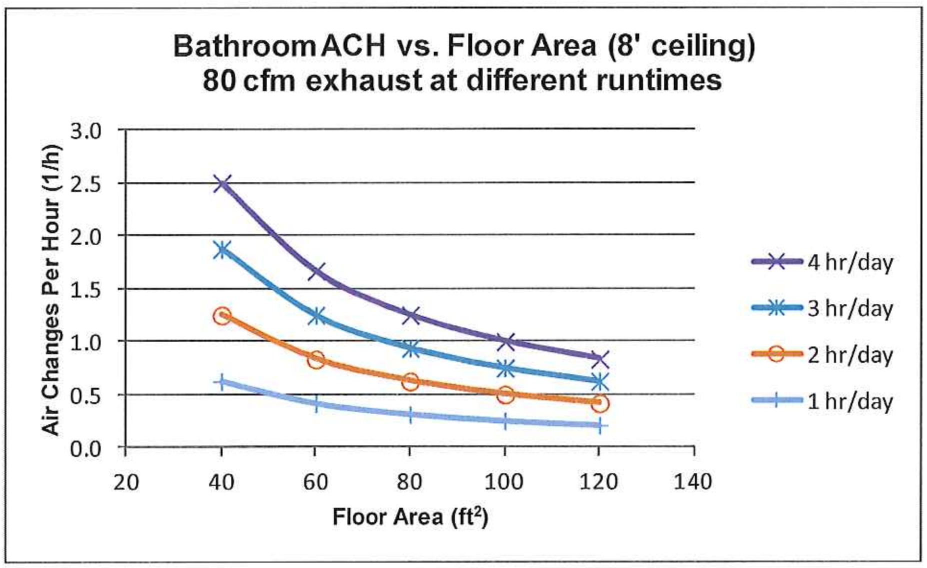
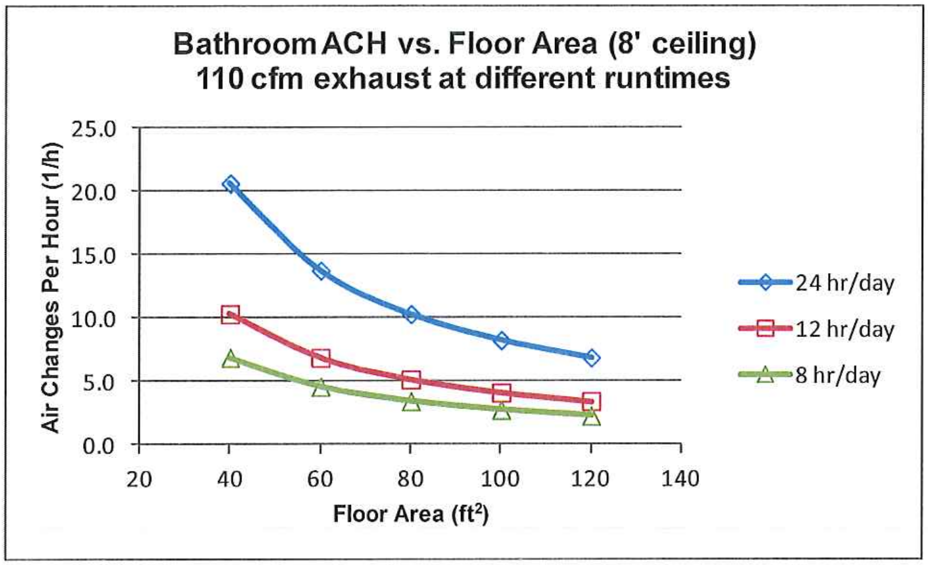


Figure D- 2. Bathroom air change rates with 80 cfm exhaust, no whole-house dilution ventilation



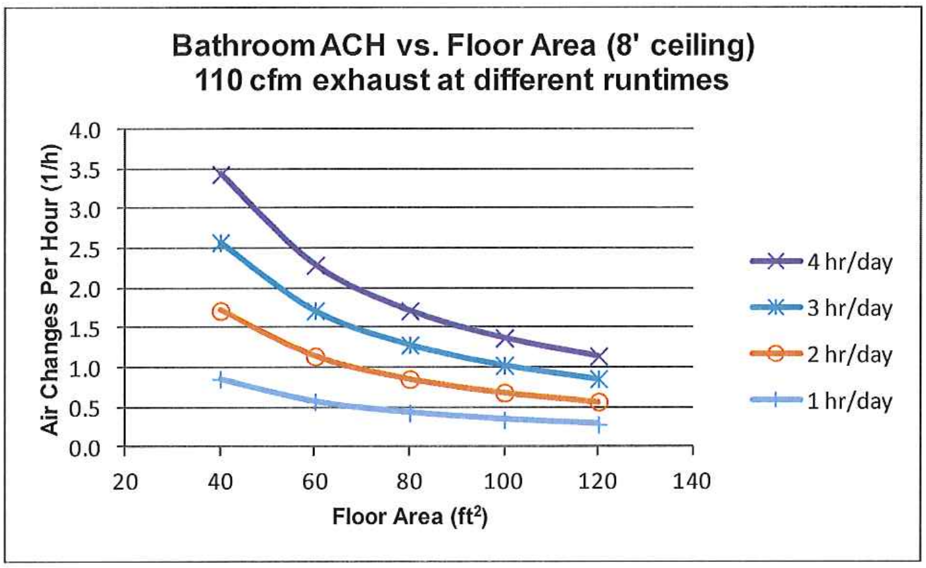
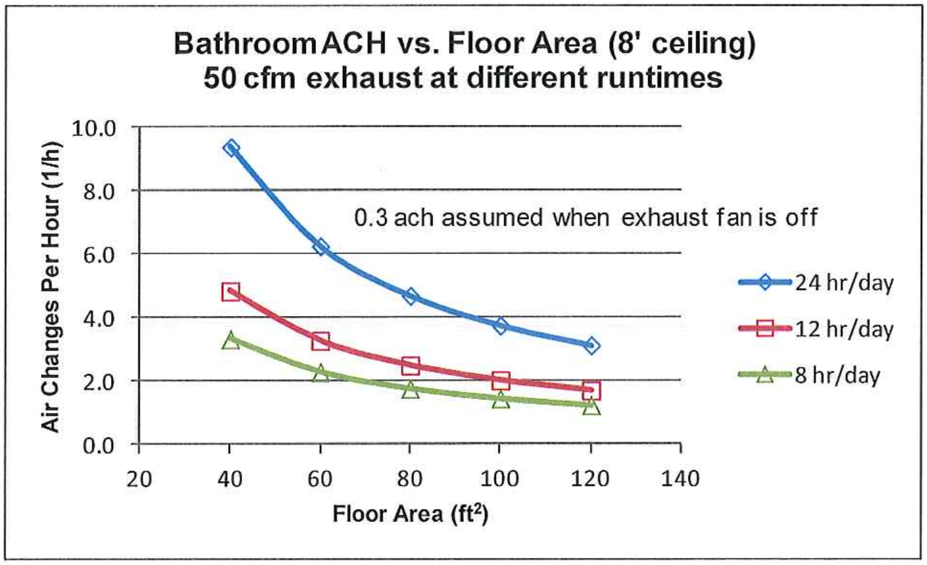


Figure D- 3. Bathroom air change rates with 110 cfm exhaust, no whole-house dilution ventilation

Assumed 0.3 ach air change rate by whole-house dilution ventilation system when the bathroom exhaust fan is off



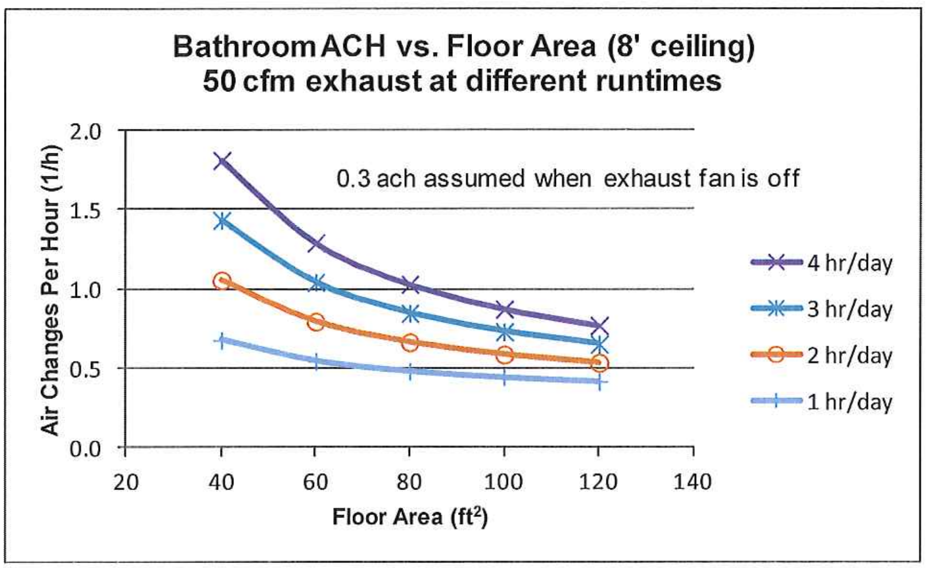
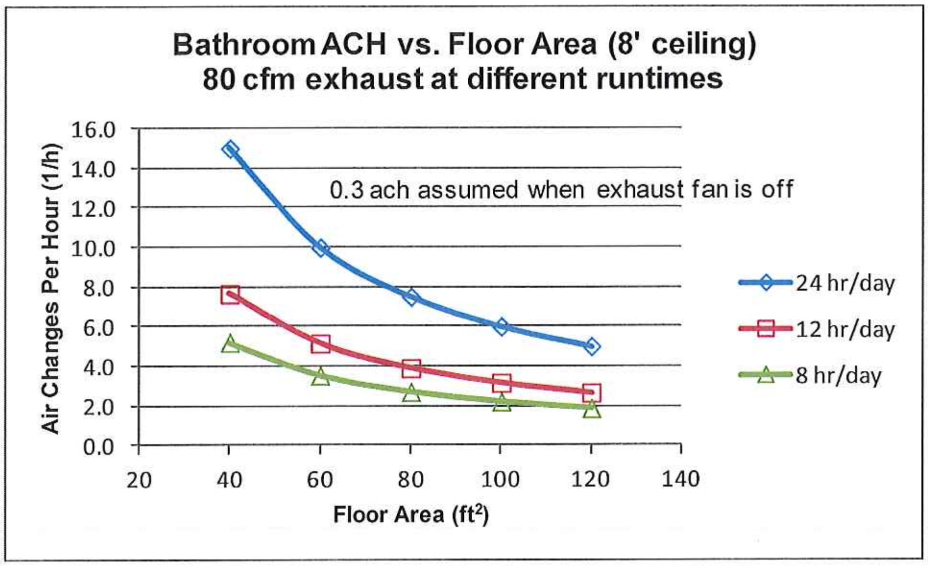


Figure D- 4. Bathroom air change rates with 50 cfm exhaust and whole-house dilution ventilation when the bathroom exhaust fan is off



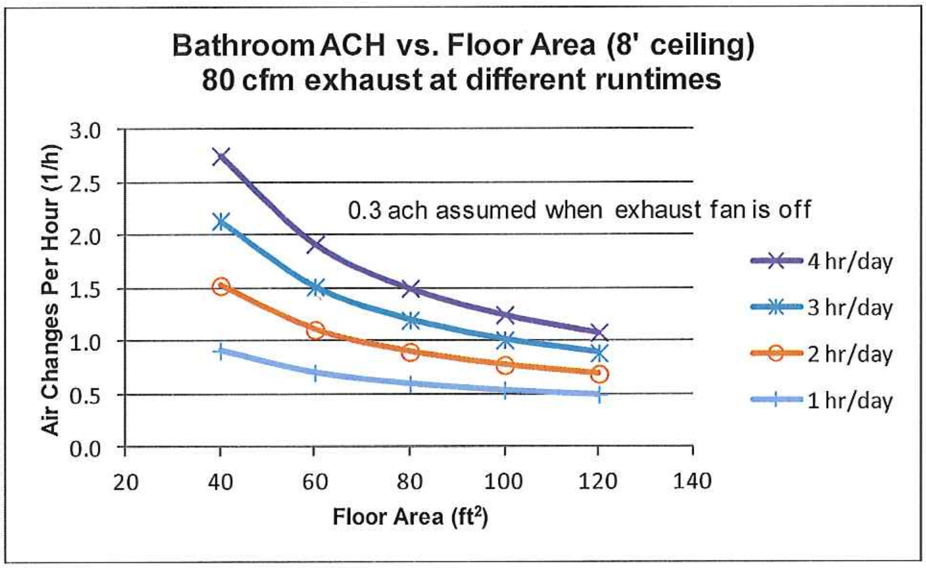
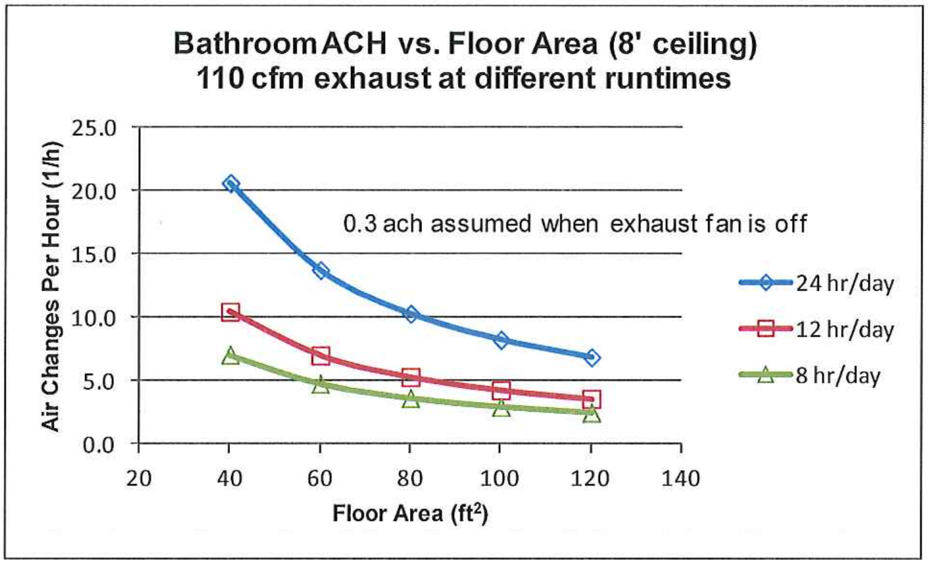


Figure D- 5. Bathroom air change rates with 80 cfm exhaust and whole-house dilution ventilation when the bathroom exhaust fan is off



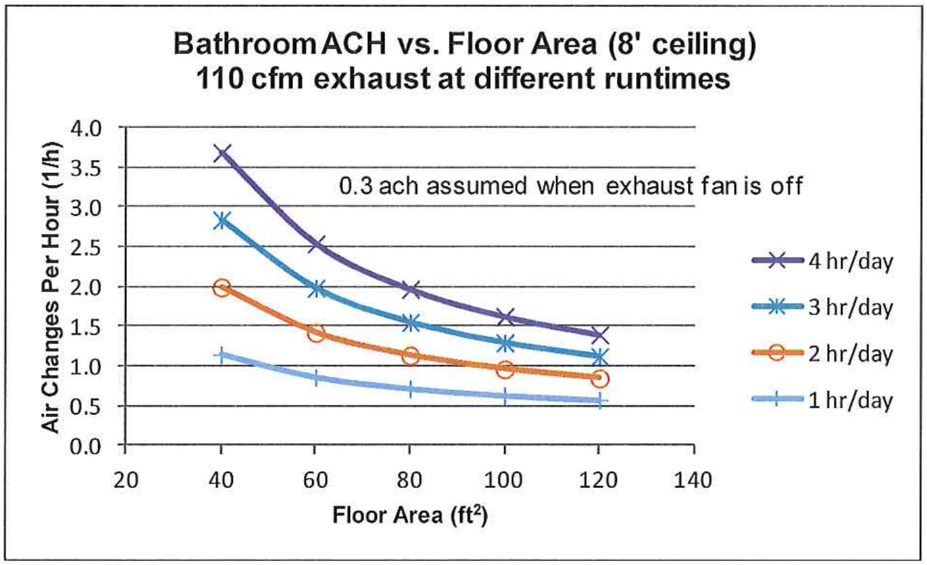


Figure D- 6. Bathroom air change rates with 110 cfm exhaust and whole-house dilution ventilation when the bathroom exhaust fan is off