Reducing In-Home Exposure to Air Pollution

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Table of Contents

Acknowledgments *3*

List of Figures *8*

List of Tables *12*

Abstract *14*

Executive Summary *15*

Background 15

Objectives and Methods 15

Results 17

Conclusions 19

1 INTRODUCTION *20*

2 MATERIALS AND METHODS *27*

2.1 Test House and Mechanical Systems 27

2.1.1 Test house and as-found mechanical systems 27

2.1.2 Ventilation and enhanced pollutant removal (EPR) systems: 29

2.1.2.1 System selection considerations 29

2.1.2.2 Selected systems: conceptual designs 30

2.1.2.3 Installation and integration of systems with heating and cooling equipment 35

2.1.2.4 Specifications of installed ventilation systems 37

2.1.2.5 Specifications of particle removal technologies 38

2.1.2.6 Specifications of volatile organic compound removal technologies 39

2.1.2.7 Installed system performance measurements 39

2.1.3 Other elements of test house set-up 41

2.1.3.1 Internal mixing and window blind positions 41

2.1.3.2 Supplemental cooling for manifold pumps (summer only) 41

2.2 Environmental, air pollutant, and equipment monitoring 42

2.2.1 Environmental monitoring 42

2.2.1.1 Outdoor environmental parameters 42

2.2.1.2 Indoor environmental parameters 42

2.2.2 Time-resolved pollutant monitoring 43

2.2.2.1 Design principle: continuous indoor and outdoor monitoring with periodic switching of air streams for aerosol monitoring 43

2.2.2.2 Air pollutant monitoring equipment 43

2.2.2.3 Calibrations 45

2.2.3 Sampling and analysis for volatile organic compounds (VOCs) 45

2.2.4 Monitoring of mechanical equipment operation 47

2.2.5 Air exchange rate 47

2.3 System operation to determine performance for outdoor particles 48

2.4 Cooking experiments to determine performance for indoor-generated particles 49

2.5 Data processing and analysis 49

2.5.1 Processing to produce time series of indoor and outdoor concentrations 49

2.5.2 Estimation of $PM_{2.5}$ from size-resolved particle number concentrations 54

2.5.3 Analysis of time-resolved environmental and pollutant concentration data 55

2.5.3.1 Screening of data impacted by activities inside the home 55

2.5.3.2 Calculation of 24h, 8h and 1h running averages 55

2.5.3.3 Selection of dividing time for statistics by day 55

2.5.3.4 Identification of highest 1h outdoor and corresponding highest 1h indoor concentrations 56

2.5.3.5 Calculation of indoor/outdoor ratios 56

2.5.4 Analysis of VOC and volatile carbonyl data 56

2.5.5 Analysis of particle data from indoor source events 57

2.5.6 Estimation of particle loss rates due to deposition, penetration and filtration 57

2.6 Quality Assurance 59

2.6.1 System design elements relevant to quality assurance 59

2.6.2 Instrument calibration and operational quality assurance 59

2.6.3 Visual review of data 59

2.6.4 Data analysis for quality assurance 60

2.6.5 Replication of experimental conditions 60
2.7 Estimation of Annual Energy Use 60
3 RESULTS *64*
3.1 Performance for Outdoor Particles 64
3.1.1 Example results for outdoor particles: Reference system during summer 66
3.1.2 Effectiveness of systems at reducing indoor concentrations of outdoor particles 76
3.1.3 Comparison across systems – performance for outdoor particles 85
3.1.4 Measured Air Exchange Rates 91
3.2 Performance for Ozone 92
3.3 Nitrogen Oxides Measurements 94
3.4 Results for Enhanced Removal of VOCs 95
3.4.1 Indoor and outdoor concentrations 95
3.4.2 Indoor/outdoor (IO) ratios 97
3.4.3 Relative reduction in indoor VOC concentrations due to air cleaning 98
3.5 Performance for Indoor-Generated (Cooking) Particles 99
3.5.1 Example results for indoor-generated (cooking) particles: System D 99
3.5.2 Comparison across systems – performance for indoor particles 106
3.6 Size-Resolved Particle Loss and Filter Performance Parameters 108
3.7 Energy Use 115
3.8 Filter Impacts on Airflow and Power Consumption 117
4 DISCUSSION *119*
4.1 Performance for Pollutant Removal and Energy 119
4.2 Comprehensive Assessment of Performance and Suitability for California 122
4.3 Strengths and Limitations of This Study 124
5 SUMMARY AND CONCLUSIONS *125*
6 RECOMMENDATIONS *127*
6.1 Recommendations derived from study findings 127
6.2 Research Recommendations 129

7 REFERENCES 130

8 LIST OF PUBLICATIONS PRODUCED 138

9 GLOSSARY OF TERMS, ABBREVIATIONS AND SYMBOLS 138

10 LIST OF APPENDICES 141

10.1 System Performance for Outdoor Pollutants in Fall/Winter - Appendices 141

10.2 System Performance for Outdoor Pollutants in Summer - Appendices 141

10.3 Performance for Pollutants Generated Indoors by Cooking – Appendices 142

List of Figures

Figure 2.1. Schematic plan view of test house, drawn to scale. 28

Figure 2.2. Schematic of Reference system. 33

Figure 2.3. Schematic of System A. 33

Figure 2.4. Schematic of System B. 34

Figure 2.5. Schematic of System C. 34

Figure 2.6. Schematic of System D. 34

Figure 2.7. Schematic of System E. 34

Figure 2.8. Schematic of System F. 35

Figure 2.9. Schematic of System G. 35

Figure 2.10. Plan view of test house showing air supplies and returns of mechanical systems... 36

Figure 2.11. Thermostat daily schedule based on California Title 24 design standard. 37

Figure 2.12. Weather station and air intakes for supply ventilation and outdoor particle sampling. 42

Figure 2.13. Layout of instrumentation in master bedroom. 45

Figure 2.14. Time series of measurements from two CPC3781 units switching synchronously, on a 15-min interval, between indoor and outdoor sample inlets. 50

Figure 2.15. Time series data shown in Figure 2.14 with post-switching points removed. 51

Figure 2.16. Smoothed time series of indoor measurements from each of two CPCs obtained by applying a python implementation of the LOESS algorithm to data series of each CPC. ... 52

Figure 2.17. Relative difference (top) of smoothed indoor time series (bottom) for each CPC 3781 relative to the mean of the two time instruments. 53

Figure 2.18. Indoor and outdoor time series constructed by aligning data from two instruments alternately measuring indoors and outdoors at 15 min intervals via synchronously switching. 54

Figure 2.19. California climate zone map. 62

Figure 3.1. Operation of bath exhaust fan (low speed for continuous ventilation), forced air unit (FAU), and central air-conditioning (AC) during Reference System operation July 16-22, 2014. 66

Figure 3.2. Environmental parameters during operation of Reference System, July 16-22, 2014. 67

Figure 3.3. Number concentrations of 6 nm to 2.5 μm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014..... 68

Figure 3.4. Number concentrations of 100 nm to 2.5 μm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014..... 69

Figure 3.5. Number concentrations of 6–100 nm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014..... 70

Figure 3.6. Number concentrations of 0.3–0.4 μm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014..... 71

Figure 3.7. Number concentrations of 0.5–0.7 μm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014..... 72

Figure 3.8. Number concentrations of 1.0–2.5 μm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014..... 73

Figure 3.9. Black carbon concentrations measured outdoors and indoors during operation of Reference System, July 16-22, 2014..... 74

Figure 3.10. $PM_{2.5}$ reported by TSI DustTrak II 8530 measurements outdoors and indoors during operation of Reference System, July 16-22, 2014. 75

Figure 3.11. Estimated $PM_{2.5}$ calculated from size-resolved particle number concentrations measured by MetOne and CPC during operation of Reference System, July 16-22, 2014.. 75

Figure 3.12. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for the Reference system during summer and fall/winter operation periods..... 77

Figure 3.13. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System A during summer and fall/winter operation periods. 78

Figure 3.14. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System B during summer and fall/winter operation periods. 79

Figure 3.15. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System C during summer and fall/winter operation periods. 80

Figure 3.16. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System D during summer and fall/winter operation periods. 81

Figure 3.17. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System E during summer and fall/winter operation periods..... 82

Figure 3.18. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System F during summer and fall/winter operation periods..... 83

Figure 3.19. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System G during summer and fall/winter operation periods. 84

Figure 3.20. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for Portable air filtration units during summer and fall/winter operation periods..... 85

Figure 3.21. Distribution of running 24h average indoor/outdoor ratios for black carbon, estimated $PM_{2.5}$ mass, and ultrafine particles (6-100 nm) for each system operating over multi-day periods in fall/winter (FW) and summer (SU) seasons. 86

Figure 3.22. Effectiveness of each system, expressed as the reduction in the time-averaged indoor concentration compared to the time-averaged outdoor concentration of outdoor-origin black carbon (BC), $PM_{2.5}$ mass and ultrafine particles (UFP) over each evaluation period. 89

Figure 3.23. Ratios of highest daily 1h indoor to corresponding highest 1h outdoor concentrations for $PM_{2.5}$ mass and ultrafine particles (6-100 nm) for each system operating over multi-day periods in fall/winter (FW) and summer (SU) seasons. Results are provided as mean and standard deviation across days. 90

Figure 3.24. Time-averaged air exchange rate for each multi-day period of system operation. .. 92

Figure 3.25. Ozone concentrations measured outdoors and indoors during operation of Reference System, July 16-22, 2014. 93

Figure 3.26. Time series of ozone concentration for System B indicating ozone production when the FAU with electronic air cleaner operated (shown in blue shading). 94

Figure 3.27. Total VOC measured in the Reference system outdoors and indoors, as labeled. ... 97

Figure 3.28. Time series of SF_6 tracer concentrations during cooking experiment with System D on July 16, 2014. (Refer to text for a detailed description.) 100

Figure 3.29. Time series of number concentration of 6 nm to 2.5 μm diameter particles during cooking experiment with System D on July 16, 2014. 101

Figure 3.30. Time series of number concentrations of 100 nm to 2.5 μm diameter particles during cooking experiment with System D on July 16, 2014. 102

Figure 3.31. Time series of number concentrations of 6–100 nm diameter particles during cooking experiment with System D on July 16, 2014. 102

Figure 3.32. Time series of number concentrations of 100-300 nm diameter particles during cooking experiment with System D on July 16, 2014. 103

Figure 3.33. Time series of number concentration of 0.3–0.4 μm diameter particles during cooking experiment with System D on July 16, 2014. 104

Figure 3.34. Time series of number concentration of 0.4–0.5 μm diameter particles during cooking experiment with System D on July 16, 2014. 105

Figure 3.35. Time series of estimated $PM_{2.5}$ concentration calculated from size-resolved particle number concentrations during cooking experiment with System D on July 16, 2014. 106

Figure 3.36. Percent reduction in time integrated concentration over 1 h following cooking, relative to reference conditions. 107

Figure 3.37. Estimated potential of systems to reduce time-integrated $PM_{2.5}$ concentrations over 1h following an indoor cooking event, assuming system operates continuously during the hour relative to a baseline Reference test. 108

Figure 3.38. Particle removal rates attributed to system operation, estimated from time series data following scripted cooking events. 110

Figure 3.39. Selection of size-resolved deposition rates from indoor time series following cooking. 111

Figure 3.40. Estimated removal rates and efficiencies of recirculating air components of each system, based on stepwise fitting analysis that started with estimates of deposition after cooking. 112

Figure 3.41. Penetration efficiencies estimated by fitting of time series data from the house configured with the Reference system, during periods when the forced air unit was not operating. 113

Figure 3.42. Indoor deposition rates estimated by fitting of time series data from the house configured with the Reference system, during periods when the forced air unit was not operating. 114

Figure 3.43. Estimated removal efficiency of particles entering home through various airflow pathways and the effective source rates for outdoor particles coming through these pathways. 115

Figure 3.44. Estimated annual energy use of ventilation and enhanced pollutant removal systems evaluated in this study. 116

Figure 3.45. Intersections of forced air unit (FAU) fan curves and inferred systems curves based on product specification sheets and measured airflows. 118

List of Tables

Table ES-1.1. Summary descriptions of system designs selected for testing. 16

Table ES-1.2. Percent reduction in time-averaged indoor concentration compared to the time-averaged outdoor concentration of outdoor-origin $PM_{2.5}$ mass, ultrafine particles (UFP) and black carbon (BC) for each evaluation period. 18

Table 2.1. Weight, approach, and information used to assess systems by each criterion..... 30

Table 2.2. Summary descriptions of system designs selected for testing. 31

Table 2.3. Airflows and power consumption of system components. 40

Table 2.4. Measured air pollutant parameters and monitoring equipment. 44

Table 2.5. Winter 2014 "Shakedown" and pilot experiments to identify and resolve challenges related to weeklong, unattended monitoring..... 48

Table 2.6. Simulation based estimates of annual operating hours for central forced air system in typical new California homes in various California climate zones.[1] 63

Table 3.1. Fall and winter (FW) periods of system performance assessment for outdoor particles. 65

Table 3.2. Summer (SU) periods of system performance assessment for outdoor particles. 65

Table 3.3. Example of summary results provided in appendices for each parameter each measured parameter for each multi-day period of monitoring. This table presents results for the number concentration of particles from 6 nm to 2.5 μm measured during operation of the Reference System, July 16-22, 2014..... 76

Table 3.4. Percent reduction of time-averaged indoor concentration compared to the time-averaged outdoor concentration of outdoor-origin $PM_{2.5}$ mass, ultrafine particles (UFP) and black carbon for each evaluation period; SD is the standard deviation across the mean values for distinct 24h diurnal periods of analysis within each period (refer to discussion of Table 3.3). 87

Table 3.5. Reductions (%) in highest daily 1 h indoor concentrations compared to corresponding highest daily 1h outdoor concentration of outdoor-origin $PM_{2.5}$ mass and ultrafine particles (UFP) over each evaluation period; mean and standard deviation across distinct 24h diurnal periods of analysis within each period (refer to discussion of Table 3.3). 91

Table 3.6. Summary results for ozone.[1] 94

Table 3.7. Days and dates (in 2014) of VOC sample collection for each system. Daylong samples initiated at approximately 7 am on the day noted. 95

Table 3.8. Summary results for VOCs. 96

Table 3.9. Airflow conditions for each of the VOC removing systems. 99

Table 3.10. Summary of calculated indoor decay rates following scripted cooking events.[1] 109

Table 3.11. Deposition and penetration factors used in fitting of time series data to get filtration parameters. 112

Table 3.12. Calculated effect of filters on airflow, power, and fan efficacy. 118

Abstract

California's building code requires mechanical ventilation to manage indoor-generated pollutants in the state's airtight, energy efficient homes. Yet outdoor air also contains pollutants at levels that can be hazardous. This study evaluated eight combinations of ventilation and air cleaning systems for pollutant removal and energy use. Systems were installed in an unoccupied 2006 house located 250 m downwind of I-80 in Sacramento. Systems were evaluated for reduction of outdoor particles (6 nm to 2.5 μm and black carbon) in summer and fall/winter, ozone and VOCs in summer, and indoor particles generated by a scripted cooking procedure. Energy use of the systems was estimated for year-round operation in varied California climates. Results demonstrate substantial benefits of high efficiency filtration at reducing air pollutant exposures, but with varying energy costs. Higher performance MERV16 filtration on supply ventilation reduced outdoor particles by 97-98% with low energy consumption, but provided no benefits for indoor-generated particles. Similarly rated (MERV13 to MERV16) filtration on the central forced air system reduced outdoor $PM_{2.5}$ by 90-97% when operated at least 20 min each hour or continuously at low-speed. Air cleaning on recirculating systems also reduced indoor-emitted pollutants. The energy required to operate central systems for filtration varies. Year-round operation of a system with an efficient blower motor will use about 600 kWh/year of extra site energy. These energy costs can be reduced with a smart ventilation and filtration system that modulates with occupancy. Exhaust ventilation pulling outdoor air through the envelope (the reference system) yielded indoor $PM_{2.5}$ levels that were 70% lower than outdoors. Supply ventilation with a MERV13-rated filter resulted in less protection than the Reference, indicating a need for high performance filtration when using supply ventilation.

Executive Summary

Background

Despite great progress in reducing ambient air pollution, many areas of California still do not meet air quality standards. Ozone and fine particulate matter ($PM_{2.5}$) are the most health significant outdoor pollutants and a recent analysis by Lawrence Berkeley National Laboratory found that $PM_{2.5}$ and certain volatile organic compounds (VOCs) are the most health damaging air pollutants in homes. Air cleaning and filtration can remove these pollutants and reduce exposures.

Objectives and Methods

The objective of this project was to identify and evaluate combinations of mechanical ventilation systems and air cleaning equipment for their effectiveness in reducing in-home exposures to air pollutants of outdoor and indoor origin and also evaluate their impacts on household energy consumption. The pollutants of primary focus were outdoor $PM_{2.5}$, ultrafine particles (UFP), and black carbon (BC). Mitigating exposures to ozone, VOCs and indoor-generated particles was a secondary focus.

The core approach of the study was to install various air cleaning and ventilation systems into an unoccupied test house and evaluate their performance. Seventeen candidate systems were conceived and evaluated on a broad set of criteria, and eight systems including a Reference system were selected for the field test. The systems, described in Table ES-1, featured variations in ventilation design (exhaust, supply or balanced), filtration location (in supply ventilation ducts, or incorporated into forced air heating and cooling system), and filtration quality (based on the ASHRAE Minimum Efficiency Reporting Value or "MERV" rating scale, and ranging from MERV4 to MERV16 and high efficiency particle air or "HEPA" filters). Some systems had a "fan timer" control to ensure air cleaning even when there is no need for heating or cooling. Three systems included technology to reduce VOC concentrations. Limited testing also was conducted for the Reference system with concurrent use of portable air filtration devices. The Reference system featured continuous exhaust ventilation and a low MERV filter on the forced air heating and cooling system. The test house was located in Sacramento, California. This home was built in 2006 and represents typical, modern California home construction.

Two identical sets of air pollutant analyzers were installed in the house and configured to simultaneously and continuously measure indoor and outdoor pollutant levels during all experimental periods. Instruments for particulate matter were configured on manifolds that switched intermittently between indoors and outdoors. Instruments measured particle number concentrations with size resolution in the range of 6 nm to 2.5 μm (including ultrafine particles or "UFP" from 6–100 nm), black carbon (BC), and ozone. $PM_{2.5}$ mass was estimated by a light scattering instrument and from the particle number concentration measurements.

The ventilation and air cleaning systems were operated to assess performance for outdoor particles and ozone over multi-day periods during fall/winter and summer conditions. Data from the two pollutant monitoring apparatuses were combined to produce continuous time series of indoor and outdoor pollutant concentrations. Data were analyzed to calculate indoor and outdoor running 24h and 1h averages. Indoor/outdoor (IO) ratios were calculated for 24h running averages over each monitoring period and for the highest 1h outdoor and corresponding indoor averages each day. These ratios were used to calculate exposure reduction factors (as 1–I/O) that directly convey the level of protection against outdoor air pollution that results in the home, for

each system. To evaluate performance for indoor-generated particles, the systems were also evaluated using a scripted cooking event by comparing calculated 1h exposures for each system to the Reference system following the scripted cooking event. Performance for VOCs was assessed with 24h samples collected indoors and outdoors during two or four days of the summer period. Samples were analyzed to quantify concentrations of formaldehyde and a panel of common VOCs.

Table ES-1.1. Summary descriptions of system designs selected for testing.

System ID	Ventilation System Description	Runtime Control	HVAC return filtration[1]	Supply filtration	VOC removal
Ref.	Exhaust	No	Low efficiency filter on AHU[2]	Building envelope only[3]	None
A	Supply, continuous; distributed by FAU ducts or exiting at return grille[1]	No	Low efficiency filter on AHU[2]	MERV13	None
B	Supply, continuous; distributed by FAU ducts or exiting at return grille[1]	No	ESP[4] + low-efficiency filter on AHU[2]	MERV13	None
C	Supply, continuous; separately ducted and blended	No	Low efficiency filter on AHU[2]	MERV16	Catalyst[5]
D	Supply, on timer[6]; distributed by FAU ducts[1]	Yes	Deep pleated MERV16 at AHU, on timer[6]	MERV8 on supply, MERV16 on AHU	Chemi-sorbent[7]
E	Exhaust	Yes	MERV13 at return grille (1" deep), on timer[6]	Building envelope only[3]	None
F	Exhaust	Conti-nuous[8]	MERV13 at return of Mini-Split	Building envelope only[3]	None
G	HRV[9], on timer[6]; Via central FA system	Yes	HEPA on bypass, on timer[6] + low-eff. filter on AHU[2]	MERV8 on HRV + HEPA bypass	Activated Carbon
Ref + Port-ables	Exhaust	No	Two standalone units with HEPA	Building envelope only[3]	None

[1]Filtration on a substantial recirculating air flow (e.g. on order of 1 air change per hour or greater). For a standard central forced air unit (FAU) with ductwork, the filter can be at the return grille or at the air handling unit (AHU). [2]The low efficiency filter is intended only as minimal protection for the furnace and air conditioning unit; it typically has no substantial effectiveness for health relevant airborne particles. The initial plan was to use a MERV6 filter in this location; but the actual filter used was MERV4. AHU = air handling unit / fan. [3]Building envelopes can remove particles as air infiltrates through the shell to replace air being removed by the exhaust ventilation system; particle removal characteristics of building envelopes vary. This mechanism is much less important for systems with supply ventilation. [4]ESP = electrostatic precipitator. [5]Manganese oxide catalyst that oxidizes formaldehyde and other VOCs at room temperature (Sidheswaran et al, 2011). [6] Operates the AHU for at least 20 min of each hour, irrespective of thermal conditioning needs. [7]Intended to remove formaldehyde and other VOCs. [8]The mini-split fan ran continuously on low speed to provide low pressure drop filtration and operated at higher speeds as needed for thermal conditioning. [9]Heat recovery ventilator.

Energy impacts were calculated from measurements and rated power consumption of system components and estimates of system run time for the purposes of air cleaning. For systems that added filtration and/or VOC air cleaning into the central forced air unit, the energy analysis started with an estimate of the incremental system run time, i.e., the extra hours that a system was run for the express purpose of air cleaning, when there was no need for heating or cooling. Incremental run times were estimated for several California climate zones.

Results

Summary results, presented as the reduction in time-averaged indoor concentrations relative to time-averaged outdoor concentrations, are provided in Table ES-1.2. All systems reduced in-home concentrations of outdoor particles, and several were especially effective at reducing all particle sizes and types. Systems that recirculated indoor air also reduced concentrations of indoor generated particles. Higher performance was demonstrated by systems that operated continuously or had minimum run-time controls, and used MERV13 to MERV16 filters.

The Reference system provided substantial protection against outdoor pollutants in both fall/winter and summer: time-averaged concentrations in the house were lower than outdoor levels by 66–73% for $PM_{2.5}$, 84–87% for UFP, 48–58% for BC, and at least 97% for ozone. Performance of filtration on supply ventilation was sensitive to the level of filtration used. With high performance filtration (MERV16) on a supply system (C) that blended 40% outdoor air with 60% indoor air for thermal tempering, much greater reductions were seen; the indoor concentrations were lower than outdoor levels by 97–98% for $PM_{2.5}$, 97–99% for UFP, at least 84–92% for BC, and at least 97% for ozone. System (A), with MERV13 filtration on the ventilation supply, performed a bit worse than the Reference. System (B), with the same MERV13 supply filtration that included an electrostatic precipitator (ESP) on the thermostatically controlled central forced air unit, produced better results than the Reference during summer; reductions of indoor relative to outdoor particles were 81% for $PM_{2.5}$, 90% for UFP, and 73% for BC when the ESP operated for several hours each day along with the FAU air conditioner. During fall/winter operation of this system, the furnace, and hence the ESP, did not operate much, and performance was similar to the system with only the MERV13 supply ventilation. A system (D) that added MERV16 filtration to the central forced air system and added a controller to run the forced air system air handler for at least 20 min of each hour (20/60 control) provided time-averaged concentrations indoors that were lower than outdoors by 97% for $PM_{2.5}$, 97–98% for UFP, and at least 93–96% for BC and 97% for ozone. System (E), with MERV13 filtration on the same controller, provided protection levels that were substantially better than the Reference, though less than those provided by MERV16 filtration. For this system, indoor levels were lower than outdoors by 88–91% for $PM_{2.5}$, 93% for UFP, and at least 80–84% for BC. A system (F) that featured a mini-split thermal conditioning system operating with MERV13 filtration on continuous low speed airflow provided indoor concentrations that were lower than outdoors by 95–96% for $PM_{2.5}$, 96% for UFP, and at least 86–92% for BC. (Ozone results were not obtained for the last two systems discussed.) A system with a HEPA filter + activated carbon bypass loop that was operated at lower air exchange rates than recommended by the manufacturer (since it was sized for continuous operation but operated with the 20/60 controller) provided greater reductions in outdoor particles than did the Reference (78-79% for $PM_{2.5}$, 83% for UFP, and 65-68% for BC). In limited testing, a set of two portable air filtration units provided protection factors on par with the system featuring MERV13 filtration on the forced air unit with 20/60 controller.

Table ES-1.2. Percent reduction in time-averaged indoor concentration compared to the time-averaged outdoor concentration of outdoor-origin $PM_{2.5}$ mass, ultrafine particles (UFP) and black carbon (BC) for each evaluation period.

System	$PM_{2.5}$				UFP				BC			
	SU		FW		SU		FW		SU		FW	
	Mean	SD[2]	Mean	SD[2]	Mean	SD[2]	Mean	SD[2]	Mean	SD[2]	Mean	SD[2]
Ref	73	4	66	3	87	1	84	3	58	3	48	10
A	67	3	63	5	82	3	76	8	40	9	38	6
B	81	5	70	5	90	3	77	4	73	7	50	8
C	97	0	98	0	97	0	99	0	92	3	84	10
D	97	0	97	1	98	0	97	0	93	2	96	1
E	91	1	88	1	93	1	93	1	84	2	80	7
F	96	0	95	1	96	0	96	0	86	4	92	1
G	79	1	78	3	83	1	83	3	65	2	68	5
Port	nd[1]	nd[1]	90	2	nd[1]	nd[1]	91	2	nd[1]	nd[1]	85	2

[1] No data. [2] SD is the standard deviation across the mean values for distinct 24h diurnal periods of analysis within each period. For more details, refer to discussion of Table 3.3).

The VOC assessment was limited by low concentrations of outdoor total VOCs (~15 μg/m^3 TVOC). Indoor VOC concentrations were substantially higher, around 300 μg/m^3 TVOC, with formaldehyde being the predominant species accounting for ~1/3 of the total. All three systems with VOC removal technology achieved modest improvements over the Reference system.

Experiments in which cooking was used as a source of indoor-generated particles showed that some sort of recirculating indoor air system with a MERV13 or better filter can significantly reduce the concentration of these particles. The recirculating system needs to operate either continuously or with a run-time controller to realize this benefit. The system that worked best continuously operated the central system with a MERV13 filter that reduced indoor $PM_{2.5}$ from cooking by 70%. Additional calculations showed that reductions of 75% could be achieved if a MERV16 filter was used.

An analysis using published results from energy and ventilation modeling of California homes found that the incremental run time when air cleaning was installed on the central forced air system did not vary much across climate zones, principally because heating and cooling systems are sized for the climate. Among the systems that had >90% reduction in outdoor $PM_{2.5}$, the lowest energy burden (of 260 kWh/year) is estimated for the blended supply ventilation system with MERV16 filter. Systems that use the central forced air system for filtration have the highest estimated annual energy use of 1440 kWh/year or greater, assuming a conventional (permanent split capacitor) motor and regular, intermittent operation on a 20/60 controller. A system that uses a central forced air blower operating continuously on low speed when there is no need for heating or cooling is estimated to use roughly 600 kWh/hr. Increased airflow resistance, often cited as a limiting factor for use of high MERV filters in existing central systems, was not found

to be an issue in this study; a deep pleat MERV16 filter reduced airflow by just 2.7%, and a 1-inch MERV13 filter reduced airflow by 4.9%.

Conclusions

Performance measurements and energy use analysis indicate that high efficiency filtration on a supply ventilation system provides the best protection against outdoor particles at lowest incremental energy cost. The limitation that supply filtration does nothing to reduce exposures to indoor-generated particles can be overcome by using on-demand exhaust ventilation (e.g., for cooking, cleaning and hobbies) and/or portable air cleaners as needed. Two energy-efficient portable air filtration units provided substantial reductions in concentrations of particles from both outdoor and indoor sources at relatively low energy cost. Such equipment may be employed as desired by residents but the equipment is not suitable for specification in high performance home standards. Using a conventional forced air system to provide enhanced filtration incurred a substantial energy cost when added to a forced air system with a conventional motor. Although not evaluated in this study, the energy use of this approach can be reduced by combining an energy efficient blower fan with well a well-designed low air flow resistance duct system and operating the blower continuously on low speed where blower efficacy (in cfm/W) is greatest. Another alternative could be to use a mini-split system, with an energy efficient motor and employing control strategies to maximize air movement efficiency to provide filtration only when needed. These design features can make high performance filtration on central forced air (CFA) systems viable from an energy perspective.

1 INTRODUCTION

The indoor environment has evolved to provide increasingly more advanced shelter from the outside world. Homes keep us safe from physical dangers and the natural hazards of excessive heat, cold and storms. Improving protection from the outside has been achieved in part by increasing building air tightness with the direct consequence of increasing the potential for unpleasant or unhealthy conditions resulting from inadequate ventilation. Through much of the history of cities there has been a tension between keeping polluted outdoor air out of residences and removing odors and other indoor pollutants that can accumulate when there is insufficient ventilation. The great expansion of cities in the modern era brought dramatic increases in outdoor air pollution, associated first with wood, then coal, then liquid fuel combustion. Over the early part of this period indoor environmental conditions improved overall as we improved venting and shifted practices related to indoor combustion sources, as our increasing national wealth enabled us to reduce occupant density in residences, and as we constructed buildings that were more protective from the outdoors. The pendulum swung back toward indoor air quality as a leading concern as outdoor air pollution has started to improve as a result of extensive control efforts, as homes were tightened for energy efficiency, and pollutants from indoor sources – including chemicals and combustion – accounted for a greater fraction of total pollutant exposure.

Despite the progress and successes in emission control efforts over the past several decades, outdoor air quality still does not meet state and federal standards in many areas of California. Air quality is additionally degraded downwind of large roadways and ports. As many California municipalities seek to accommodate infill development to advance local economies in concert with statewide sustainability and energy efficiency goals, concerns about ambient air pollutant impacts must be addressed. One avenue to accomplish this objective is to improve the protection provided for people in their homes. Starting in 2008, California's Title 24 Residential Building Standards (CEC 2008 and 2008b) have included mechanical ventilation requirements as protection from pollutants emitted indoors. The ventilation requirements currently include no provision for filtration. This project focuses on the potential benefits of enhanced pollutant removal technology integrated with residential ventilation systems.

The ambient air pollutants of greatest concern in California are fine particulate matter ($PM_{2.5}$) and ozone. Downwind of freeways and ports, the pollutants of concern additionally include ultrafine particles, diesel particulate matter, certain VOCs, and nitrogen dioxide.

Studies conducted in California show that $PM_{2.5}$ concentrations are about the same near busy roadways as distant from them (Kim et al., 2004; Zhu et al., 2006). However, black carbon (BC), often used as an indicator of diesel exhaust, and ultrafine particles (UFP), which are emitted in very high numbers from vehicles, are often 2 to 10 times higher near roadways and freeways (Zhu et al., 2002a, 2002b, and 2006; Westerdahl et al., 2005; Ntziachristos et al., 2007; Moore et al., 2007; Kozawa et al., 2009). Nitrogen oxides (NO_x) also are elevated near roadways, approximately 2 to 3 times the levels measured at a distance from the roadway (Kim et al., 2004; Singer et al., 2004; Moore et al., 2007; Kozawa et al., 2009; Durant et al., 2010). Proximity to busy roadways has been associated in several studies with a number of adverse health impacts, including increased asthma and other respiratory disease, increased heart disease, reduced birth weight in babies whose mothers live near busy roadways, and various immune system effects (HEI, 2010). Children appear to be particularly vulnerable to the adverse effects of traffic-related

air pollutants. Epidemiological studies have found significant associations of children living near high traffic areas with decreased lung function (Brunekreef et al., 1997), increased medical visits and hospital admissions for childhood asthma (English et al., 1999; Lin et al., 2002), increased wheezing (Venn et al., 2001), and increased childhood asthma and bronchitis (Kim et al., 2004), including development of new asthma cases (McConnell et al., 2006). There is great interest in reducing indoor concentrations of ultrafine particles and other pollutants emitted by roadway vehicles to improve health of nearby residents.

Although state and federal regulations focus on air pollutant concentrations in ambient, or outdoor air, most human inhalation of air pollutants occurs inside buildings. On average, Americans spend about 90% of our time inside buildings and 70% within our homes. In buildings people are exposed to pollutants that are emitted indoors and pollutants that enter with outdoor ventilation air. The relative importance of indoor and outdoor sources as contributors to overall air pollutant health impacts varies across the population, across buildings, and over various time frames. The U.S. Clean Air Act and related Amendments set criteria for ambient air pollutant concentrations with the idea that the ambient air should be safe for the general population. When outdoor air is safe, ventilation can be used as one key element of indoor air quality management. When outdoor air is not safe, viz. when pollutant concentrations exceed air quality standards, ventilation standards must consider the potential harm of increasing the rate at which outdoor pollutants are brought inside.

For much of the history of residential buildings, the exchange of air between indoors and outdoors has been managed by opening or closing of windows and doors. In addition, a substantial amount of airflow has occurred and still occurs via uncontrolled, pressure-driven airflow through cracks and other unintentional openings in the building envelope. Infiltration airflow increases with the area of leakage openings and with the magnitude of the pressure difference. Natural pressure differences are created by winds and by indoor-outdoor temperature differences. For most homes in the US envelope leakage pathways have been relied upon to provide a minimum level of ventilation to dilute indoor pollutants and to provide combustion air for fireplaces and gas appliances.

As homes have become tighter to increase comfort and reduce heating and cooling costs, concerns about indoor air quality led the American Society of Heating, Refrigerating and Air-conditioning Engineers (now officially called "ASHRAE") to develop Standard 62.2 to specify minimum ventilation system requirements for low-rise residential buildings. The most recent version of this standard (ASHRAE, 2013) specifies a minimum amount of outdoor air exchange based on floor area (as a surrogate for material based chemical emissions) and number of bedrooms (as a surrogate for occupancy). For any home that is tight to the level that infiltration cannot be relied upon to provide a specified level of air exchange, a mechanical system is required. The standard additionally requires exhaust fans with minimum airflow requirements in kitchens and bathrooms. Mechanical ventilation can be provided by any combination of exhaust or supply fans that meet the required airflow rates. Intermittent ventilation is allowed within specified constraints. The ASHRAE 62.2 standard is becoming increasingly important as it is substantially incorporated into mandatory building codes including California's Title 24 Building Standards, voluntary programs such as EPA's Energy Star Indoor Air Plus Program, and various guidance standards in the home performance industry.

Though as yet unsubstantiated with a clear data record, it appears clear from reports of industry professionals that the most common type of mechanical ventilation system being installed in new California homes is a continuous exhaust fan. A common variant is a bathroom fan that operates continuously at a lower speed to meet the requirement for overall air exchange rate then operates at a higher speed when needed for local bath exhaust. The higher speed operation can be initiated manually or by a sensor that detects motion (i.e. occupancy) or excess humidity.

The most common type of heating and cooling system is a ducted, forced air system that uses a large air handler blower to recirculate air from a centrally located return duct, through a heat exchanger that either adds or removes heat from the air stream, then distributes the thermally conditioned air throughout the home via a series of supply ducts.

Filtration has been recognized for some time as an important component of recirculating heating, ventilating and air conditioning (HVAC) systems. Filters were initially employed to remove dust, animal dander and other large particles that can deposit on heat exchanger surfaces and fan blades and degrade performance. Over time it was recognized that filtration and other forms of air cleaning (e.g. removal of odors) offer the potential to improve indoor air quality. Many large commercial building HVAC systems now include filters to remove at least some fraction of the inhalable particles in the recirculation air supply and some include technologies to remove other pollutants.

While the use of engineered systems to enhance pollutant removal in residences currently is not common, the potential to do so represents an opportunity for air pollutant health impact mitigation. This project helps document this potential.

The ability of filters to clean air is given by the Minimum Efficiency Reporting Value (MERV) rating - with a higher numerical MERV rating indicating better filtration of particles. MERV ratings are determined using the test procedures in ASHRAE Standard 52.2 (ASHRAE 1999). This standard evaluates the filter's ability to remove particles in 12 particle size bins. The bins have mean particle sizes ranging from 0.35 to 8.5 micrometers (μm). The measurements are made for each size of particles then combined into three groups: 0.3-1, 1-3, and 3-10 micrometers. The performance in each group is combined to determine the MERV rating. The 2010 version of the ASHRAE 62.2 standard requires use of a "MERV6" filter on recirculating forced air heating or cooling systems. MERV6 is rated at 35-50% removal of particles from the largest group (3-10 micrometer). Ratings and standards for removal of the smallest particle size bins start with MERV13 filters. There are other standards for rating filters, such as AHRI 680 (2009) and 3M's proprietary "Filtrete" rating that follow roughly similar approaches. The California Building Energy Efficiency Standard also requires MERV6 filtration as it is based on and refers directly to ASHRAE 62.2.

Interest in residential air cleaning (including filtration) is rising as more people become aware of the health hazards of air pollutant exposures. In general, the occupants of residential buildings are becoming more aware of the potential benefit of filtering both incoming outdoor air and recirculating indoor air. The American Lung Association and other institutions that focus on health guidance for the general public recommend the use of high efficiency air filters corresponding to MERV10 or higher (ALA 2006). Therefore, it is likely that we will see even more use of higher MERV filters in the future in California residences. As well as increasing filter performance, it is being recommended (also by the ALA) and becoming more common to

use the central forced air system blowers to move air through filters continuously, rather than only when heating or cooling. In Canada and some other nations, there is a relatively broad acceptance of continuous operation of central forced air systems in order to provide air filtration and to reduce air stratification to improve comfort. However, this is still not common in the US.

Air pollutant removal occurs through other mechanisms in residences. Reactive and semi-volatile gases can deposit on surfaces at rates that produce overall first order deposition or loss rates that can far exceed air exchange rates, which are typically in the range of 0.2 h^{-1} to 1 h^{-1}. For example, Lee et al. (1999) reported ozone first decay coefficients of 2.8±1.3 h^{-1} in 43 Southern California homes. For nitrogen dioxide, first order decay rates of 0.11 to 1.4 h^{-1} have been reported for furnished residences (Nazaroff et al. 1993; Spengler et al. 1994; Spicer et al. 1994; Yang et al. 2004a). Deposition loss rates for particles vary with particle size.

The same physical mechanisms that account for deposition of air pollutants in residences result in removal as air infiltrates through the building envelope and in many cases as air moves through the ducts of recirculating HVAC systems. The following papers provide some insight about the potential significance of these processes to indoor exposures to ultrafine particles from outdoors or indoors. Through indoor and outdoor measurements of UFP in an airport nearby to a freeway, Zhu et al. (2005) found substantial filtering during penetration and also substantial indoor deposition. With windows closed, indoor/outdoor ratios were about 0.6 for 100 nm particles and about 0.35 for 20 nm particles. Based on analysis of indoor and outdoor size resolved particle measurements from 7 Boston area homes, Bennett and Koutrakis (2006) calculated "dynamic infiltration factors" (DIFs) that combine losses during penetration and indoor deposition. The DIFs were roughly 0.3-0.5 for 20-30 nm particles increasing to 0.7-0.9 for 80-100 nm particles. Chen and Zhao (2011) reviewed studies reporting indoor / outdoor ratios of particles. They present a compilation of studies showing that the penetration factors for UFP are on order of 0.6 for 100 nm particles decreasing to about 0.2 for 10 nm particles. Rim et al. (2010) conducted experiments in a test house. For the windows closed condition, they reported penetration factors of 0.2 for 10 nm particles increasing to 0.6 for 30-100 nm particles. Wallace et al. (2004) reported overall size-dependent loss rates of particles in a home following indoor emission events. They compared loss rates under four conditions: (1) no air handler, (s) air handler without filtration, (3) air handler with mechanical filtration, (4) air handler with ESP. Measurements on either side of the filter indicate that it was largely ineffective for 0.3 to 2.5 um particles. There was substantial loss of UFP under all 4 conditions. Loss rates (1/h) for 100 nm particles were 0.7, 0.9, 0.9 and 2.7 for the four cases. Loss rates (1/h) of 30 nm particles were 1.7, 2.1, 3.0 and 3.6. Stephens and Siegel (2012) measured envelope penetration factors for non-size-resolved sub-micron particles in 19 non-mechanically ventilated homes. They found a range of penetration factors from 0.17 to 0.72 with a mean of 0.45. Williams et al. (2003) reported penetration factors from 37 homes with a range from 0.11 for new homes to 0.7-1 for older homes.

The most common way of meeting the ASHRAE ventilation standard is to have a continually operating exhaust fan. Typically this is a bathroom fan that allows both the local bathroom exhaust and whole house minimum mechanical rate to be met at the same time. For these exhaust systems the additional air entering the building comes in through holes and cracks in the building envelope. These airflow paths in the building envelope can provide some filtering of outdoor air. For example, a study by Walker et al. (2009) concluded that: "*In general, the envelope is a better ozone filter than typical HVAC filters, so systems that depressurize the house*

lead to lower indoor ozone levels. The peak levels follow the same trends." This study also illustrated how open windows lead to high, unfiltered ventilation rates that significantly reduce the sheltering effect of being indoors for ozone. There is also the potential for significant particle filtration for air entering through the building envelope.

In colder northern climates and in very tight homes heat or energy recovery ventilators (HRV/ERV) are popular. HRVs and ERVs can either be stand alone – with their own independent duct system – or coupled to the central forced air heating and cooling system. In the latter case the fans in the HRV/ERV are interlocked with the central forced air system blower fan so that they operate at the same time. The supply air for HRVs/ERVs is filtered – but usually only with a low particle removal efficiency (<MERV6) filter designed to prevent heat exchanger and fan/motor fouling and entry of insects or small vermin.

Another system seen in California is the combined exhaust fan with an opening in the return duct that draws in outdoor air when the central forced air HVAC system operates. These latter systems often have a timer to ensure that the central fan (and thus the air supplied from outside) operate over some fraction (typically 20 minutes) each hour. This ensures some supply ventilation when the house is not being heated or cooled. As with HRVs/ERVs the filtration of the supply air is minimal.

Although not yet common, economizers are being used more frequently in California, and due to changes in Title 24 are likely to be used more in the future. An economizer operates for thermal control rather than air quality. An economizer uses the whole house space conditioning system with the normal return air path sealed and air brought directly from outside and distributed by the forced air system when it is cooler outside than inside. This offsets potential air conditioner use as an energy saving strategy. The airflows that occur during operation are an order of magnitude greater then those required for ventilation. This air may be filtered if there is a filter at the furnace inlet through which the outdoor air flows. System with filters only at the inlet to the return duct (at the grill) will not filter air during economizer operation.

While better filters will tend to result in improved indoor air quality, there is cost associated with their improved performance. The key issue is that improved filtration can be associated with greater airflow resistance (for some specific data see Kowalski and Bahnfleth 2002). However, the effects of other design factors including pleating, depth and area are important enough that MERV rating (or equivalent filter efficiency rating) alone is not sufficient to estimate filter pressure drop. For example, 4- inch pleated filters can reduce filter pressure drops by factors of four to seven compared with one inch filters of the same MERV rating (http://homes.cerias.purdue.edu/~pmeunier/filters/filters.html). For commercial HVAC systems there has been work on converting these changes in system pressure drop into extra fan power requirements (e.g., Fisk et al. 2002). However, these approaches for commercial systems assumed constant blower efficiencies and airflow. In residential systems blower performance is strongly dependent on system pressures. In recent work for the Department of Energy (Walker (2005), the Commission (Walker 2006b and Lutz et al. 2006), and Pacific Gas and Electric (Walker 2006a), LBNL has shown that residential furnace airflow and power consumption can be significantly changed by changing system static pressures. These flow changes result in lower air conditioner efficiencies (a simple method of estimating these changes is given in ASHRAE Standard 152 and is also accounted for in Title 24 in the ACM Appendix RE and Section 4 that have a 7.5% SEER adjustment for low air flow). Furthermore, this work has

shown that the two current motor technologies available in residential HVAC systems have very different reactions to increased system pressures. The Permanent Split Capacitor (PSC) motors that are about 90% of the market show reduced airflow and power draw with increasing system pressures. Conversely, variable speed motors maintain airflow but have increases in power with increased system pressures. Therefore the impact of filtration is different for these two motor types. Another issue is variable capacity systems that operate for most of the time in a low-fire/low-speed mode. This further complicates the impact of filtration because in low speed operation the system airflows are much lower (typically half) of the full speed flows. This leads to much lower system pressure differences and the impact of filters will be altered. In particular, when brushless permanent magnet motors are used for these applications they have significant performance gains because their performance increases as static pressure goes down. Previous studies have indicated that the changes in fan power use when changing to more efficiency filters may be minimal (Fugler et al. 2000). A recent study for the Commission by LBNL (Walker et al. 2013) reached similar conclusions with the exception of the highest level of filtration and insufficient filter depth (2 in. deep MERV16 Filters). So it is possible that high efficiency filters could be used with relatively little energy use when seeking improve filtration on a central forced air system.

The power and energy requirements for furnace and air conditioner blowers have been investigated in several field studies (see Field Testing Bibliography Appendix) that have shown that existing fans in residential air handlers typically consume about 500W, supply about 2 cubic feet per min of airflow per W of power consumption (L/s/W) and have efficiencies on the order of 10% to 15%. Some studies have looked at the cost of using furnace blowers to continuously filter indoor air and distribute ventilation air. These studies have shown energy savings of factors of five or more for brushless permanent magnet (BPM) motors. In addition to airflows, these field studies concurred on typical system static pressures of 0.5 in. of water (125 Pa) for heating only and 0.8 in. of water (200 Pa) for systems with cooling coils. Filters contribute 0.15 in. of water (37.5 Pa) to this total.

In addition to the energy use implications of filtration there can be serious consequences of filter changing that are poorly understood by homeowners. Most existing homes HVAC systems were designed and installed for use with simple glass fiber filters that are typically rated at MERV 2 or less. The change to higher MERV filtration and its associated greater filter pressure drop and system air flow reduction can result in premature blower failure, furnace heat exchangers reaching high temperatures that set off limit switches and the potential for coil icing and premature compressor failure in cooling systems. This can lead to safety issues as well as not meeting building loads. For cooling systems, the performance reductions change rapidly below about 200 L/s per ton of cooling capacity (Rodriguez (1995) and Parker et al. (1997).

Filter airflow resistance increases as filters become dirty or fouled. This is why it is important to periodically change the filters. Currently there are rough guidelines for changing filters that are usually time based, e.g., change filters every four months. Some thermostats track system runtime and provide a visual reminder on the thermostat display for filter changing. A research project by LBNL for the California Energy Commission (Walker et al., 2013a and 2103b) performed long-term measurements of filter pressure drop changes in real houses to get a better understanding of fouling in real-life situations. This study found that most homes had very little change in flow rates, fan power or HVAC efficiency over several months of operation for

MERV10-13 filters. The exceptions were a home in a more rural area with two large dogs that had filters show significant fouling effects including dog hair accumulation and systems that used 2 in. deep MERV16 filters (that introduced blower power increases of about 20%). Other work in Texas (Stephens et al., 2010) performed detailed energy monitoring on two homes in Texas over a four-month period with MERV 11-12 filters and also concluded that filters did not have much of an impact on energy consumption in residential air-conditioning test systems and that other factors should govern filter selection. These studies indicate that, while fouling or the introduction of improved filters may be significant in some cases, it is generally not a strong driver of system performance.

The study described in this report aimed to provide field measurements of actual filter performance, in terms of particle removal rates and corresponding indoor concentrations, combined with system energy use. In the constant evolution of standards we need the technical background to show when additional outdoor air provision may not improve indoor air quality and filtration can be a better approach, and show how filtration may be used in concert with mechanical ventilation to facilitate energy efficient improvements in homes while simultaneously improving residential indoor air quality and public health.

2 MATERIALS AND METHODS

2.1 TEST HOUSE AND MECHANICAL SYSTEMS

2.1.1 Test house and as-found mechanical systems

All experiments were conducted in a detached, single-family house located in Sacramento, California, that was built in 2006. The house was leased from September 2013 to February 2015 for the sole purpose of conducting this study. A plan-view schematic of the house is provided in Figure 2.1 below. The house is has a floor area of 106.7 m^2 (1,148 ft^2) and 3 bedrooms, with an attached 2 car-garage. It has typical construction features for California homes of its vintage: single-story, concrete slab foundation, stucco exterior, and tile roofing. All ceiling heights were 2.75 m (9 ft) except for the kitchen / living space which had a sloped ceiling starting at 2.75 m (9 ft) at the wall along the back of the house and rising to a height of 4 m (13 ft) at the front most boundary of the room. A "blower door" test (ASTM E1827-11) conducted in the house as-found confirmed the house was reasonably air tight, with air leakage of 438 L/s (928 cfm) at a 50 Pa indoor-outdoor pressure difference. For a calculated interior volume of 316 m^3 (11,154 ft^3) this corresponds to 5.0 air changes per hour at the 50 Pa pressure difference (ACH50).

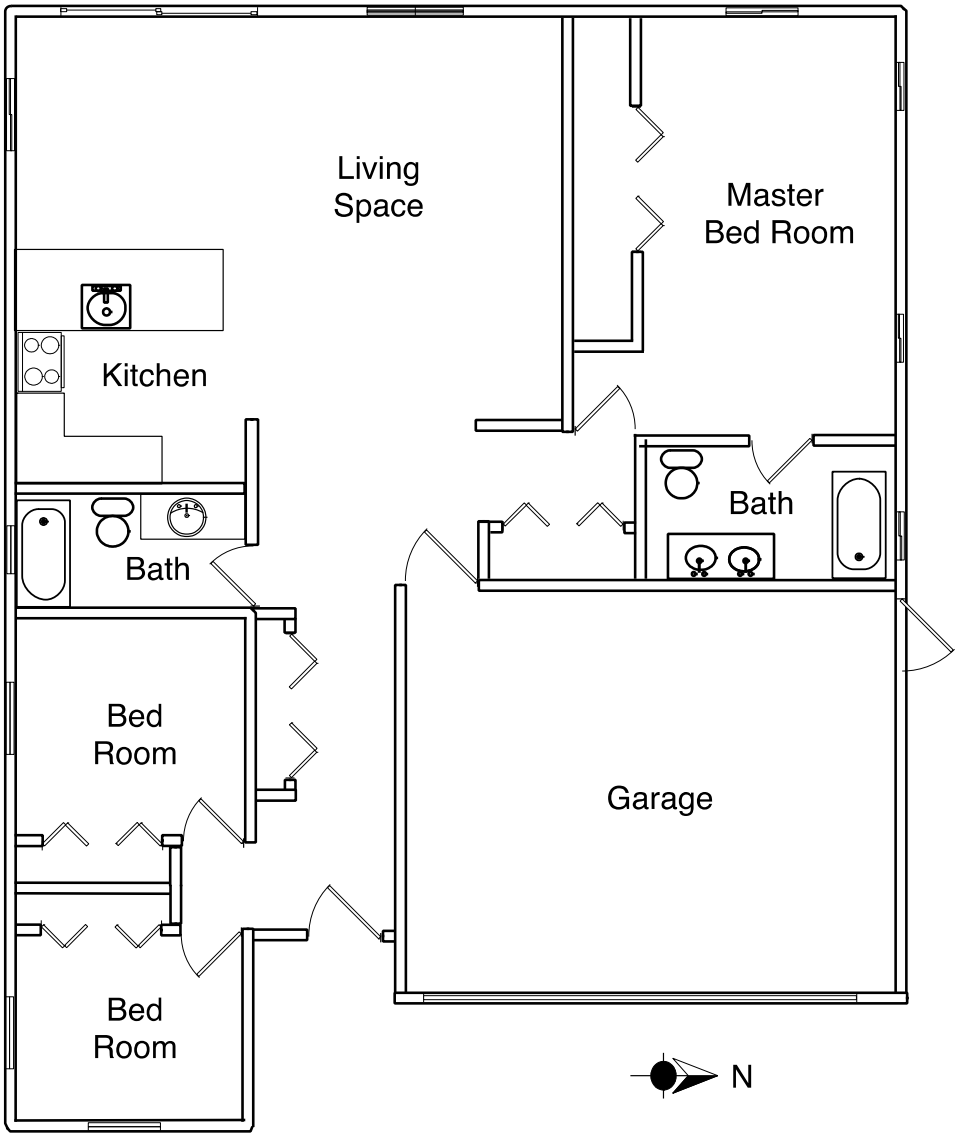

Figure 2.1. Schematic plan view of test house, drawn to scale.

As found, the house had a thermal conditioning system that is very typical of California homes of this vintage. Heating and cooling were provided by a forced air unit (FAU) with gas furnace and split air conditioner. The package included a single-stage 75,000 Btu/h, 80% AFUE furnace; a 2.5 ton, an air conditioning unit with seasonal energy efficiency rating (SEER) of 13; and a blower with a nominal 600 W permanent split capacitor (PSC) motor. The return duct was located in the ceiling of the central hallway, at 2.75 m (9 ft) height, in the place marked on Figure 2.10, and insulated flex duct distributed conditioned air to registers located in each room. Measurements of airflows at all heating/cooling supply registers were used to determine the total system airflow of 566 L/s (1200 cfm).

Importantly to this study, the home is located 250 m north – the predominantly downwind direction – of Interstate 80. It is situated in a small group of houses with little through traffic and

no arterials close enough to result in widely varying pollutant concentrations on different sides of the house. This feature was important to ensure that the pollutant concentrations measured at a single point outside of the home were generally representative of the air entering through infiltration around the exterior.

2.1.2 Ventilation and enhanced pollutant removal (EPR) systems:

2.1.2.1 System selection considerations

Systems comprising combinations of mechanical ventilation and enhanced pollutant removal components were selected through a collaborative process involving the research team and ARB's contract management team, with review and input provided by a technical advisory committee. Broadly, the objective of this process was to select system designs and components that could be suitable for large-scale implementation in California homes and that meet, to various degrees, a varied collection of performance objectives. The process involved specification of basic system design options and identification and evaluation of component technologies with varying performance characteristics.

The first stage of the process involved specification of seventeen candidate systems followed by a semi-quantitative evaluation of each system on the eleven criteria noted in Table 2.1 below. The systems included various combinations of ventilation approaches (exhaust, supply, balanced), particle filtration locations (as part of supply ventilation, as part of forced air heating and cooling system, standalone), particle filtration quality (MERV8 through HEPA), VOC removal technologies (physical sorbents, chemisorbents, photocatylitic oxidation, etc.), and operational approaches (continuous, minimum of 20 min of every 60, only when heating or cooling required, etc.). The categorical scoring approach was designed primarily to elucidate strengths and weaknesses of the systems rather than to provide a firm priority order for testing.

Table 2.1. Weight, approach, and information used to assess systems by each criterion.

Evaluation Criterion	Weight	Considerations
Outdoor-generated particle removal efficiency	10	Filter efficiency rating and configuration. Exhaust ventilation scored same as MERV8 on supply because of building shell filtration
Outdoor VOC/ozone removal effectiveness	8	Available product information (limited)
Energy Performance	8	Based on residential energy model simulations, power ratings from the Home Ventilating Institute (HVI) product database and manufacturer specs, and engineering estimates
Indoor-generated particle removal efficiency	7	Filter efficiency rating and configuration
Noise	5	Home Ventilating Institute (HVI) product database and contractor input
Suitability for California climate and construction practices	5	Contractor input and researcher assessment
Maintenance requirements	4	Manufacturer's recommended maintenance schedules and contractor input
Component availability	3	Contractor input and product searches on internet
Durability (including. performance with imperfect maintenance)	3	Assessment based on system complexity, how long technology available; contractor input
Initial cost of equipment and installation	3	Contractor estimated costs
Annual operating costs in addition to energy	2	Maintenance kit costs as provided by on-line vendors

2.1.2.2 Selected systems: conceptual designs

Eight systems were selected for installation and evaluation in the test house. They included a reference system with mechanical ventilation that complies with California's 2013 version of the Title 24 Building Code and no enhanced pollutant removal, and seven other systems that have Title 24 compliant ventilation with one or more components for enhanced pollutant removal. Limited testing was also conducted on a system that added two portable air filtration devices to the Reference configuration.

The final set of systems includes technology and/or design variations for each major component: (a) exhaust, supply and balanced ventilation systems; (b) particle removal using MERV13, MERV16, and HEPA levels of filtration and one system with an electrostatic precipitator (ESP); (c) VOC removal using Purafil, activated carbon, and novel catalyst technologies; (d) supply and balanced ventilation provided via the central forced air ductwork, using either the central blower on a timer control or using just the ventilation supply fan to slowly push air through the ductwork; and supply ventilation provided via separate ductwork. The set of systems includes some that are designed for exceptional pollutant removal including VOC removal and some that can be accomplished at relatively low incremental cost when installed with common HVAC configurations in California.

The selected system designs are described in Table 2.2 and schematics of the systems are provided in Figure 2.2 through Figure 2.9. The paragraphs that follow identify the systems that satisfy each technology or design objective.

Table 2.2. Summary descriptions of system designs selected for testing.

System ID	Ventilation System Description	Runtime Control	HVAC return filtration[1]	Supply filtration	VOC removal
Ref.	Exhaust	No	Low efficiency filter on AHU[2]	Building envelope only[3]	None
A	Supply, continuous; distributed by FAU ducts or exiting at return grille[1]	No	Low efficiency filter on AHU[2]	MERV13	None
B	Supply, continuous; distributed by FAU ducts or exiting at return grille[1]	No	ESP[4] + low-efficiency filter on AHU[2]	MERV13	None
C	Supply, continuous; separately ducted and blended	No	Low efficiency filter on AHU[2]	MERV16	Catalyst[5]
D	Supply, on timer[6]; distributed by FAU ducts[1]	Yes	Deep pleated MERV16 at AHU, on timer[6]	MERV8 on supply, MERV16 on AHU	Chemi-sorbent[7]
E	Exhaust	Yes	MERV13 at return grille (1" deep), on timer[6]	Building envelope only[3]	None
F	Exhaust	Conti-nuous[8]	MERV13 at return of Mini-Split	Building envelope only[3]	None
G	HRV, on timer[6]; Via central FA system	Yes	HEPA on bypass, on timer[6] + low-eff. filter on AHU[2]	MERV8 on HRV[9] + HEPA bypass	Activated Carbon
Ref + Port-ables	Exhaust	No	Two standalone units with HEPA.	Building envelope only[3]	None

[1]Filtration on a substantial recirculating air flow (e.g. on order of 1 air change per hour or greater). For a standard central forced air heating and cooling system with ductwork, the filter can be at the return air grille or at the air handling unit (AHU). [2]The low efficiency filter is intended only as minimal protection for the furnace and air conditioning unit; it typically has no substantial effectiveness for health relevant airborne particles. The initial plan was to use a MERV6 filter in this location; but the actual filter used was MERV4. AHU = air handling unit / fan. [3]Building envelopes can remove particles as air infiltrates through the shell to replace air being removed by the exhaust ventilation system; particle removal characteristics of building envelopes vary. This mechanism is much less important for systems with supply ventilation. [4]ESP = electrostatic precipitator. [5]Manganese oxide catalyst that oxidizes formaldehyde and other VOCs at room temperature (Sidheswaran et al, 2011). [6]Operates the central forced air system for at least 20 min of each hour, irrespective of thermal conditioning needs. [7]Intended to remove formaldehyde and other VOCs. [8]The mini-split fan ran continuously on low speed to provide low pressure drop filtration and operated at higher speeds as needed for thermal conditioning. [9]Heat recovery ventilator.

(a) Ventilation. There were 4 systems with supply ventilation specified, including three (A-C) with continuous supply fans and one that operated intermittently with a run-time controller (D). All provided enhanced filtration on the supply air, with MERV13 on the supply duct of A and B; MERV16 on C, and the timer-coordinated supply ventilation and AHU with MERV16 filter for D. The airtight envelope was thought to provide something akin to supply filtration but the effectiveness was unknown. System G used an HRV linked to the central system air handler,

with enhanced filtration provided by the HEPA bypass that was designed to operate whenever the HRV was operating.

(b) Particle removal. For the Reference system having no enhanced filtration, we specified a low-efficiency filter of the type that has been used historically to reduce dust accumulation on cooling coils. This corresponds to MERV4. This filter was used in the return of several other systems that featured enhanced filtration at another location. System A had enhanced particle filtration only for ventilation supply air. System B had additional filtration with an ESP in the FA system, but that was designed to operate only when heating or cooling was needed. System C was primarily a supply filtration design but also provided filtration to the indoor air that was blended into the supply for tempering (the blending air was roughly twice the mechanical ventilation air flow rate). System G had a MERV8 filter on the supply, with higher performance HEPA bypass filtration at the central system return. The bypass unit directs a portion of the air moving through the FAU ductwork through the HEPA filter assembly; the remainder of the air moving through the AHU passes through the low efficiency filter only. The other three systems featured high performance filters on a central forced air system return: MERV16 for D, MERV13 for E and F. Systems D-G were designed to provide regular filtration for particles already in the house owing to programmed operation of the system for at least 20 min of each hour with the runtime controller (D-E) and continuous, lower speed/flow operation of System F. Any system with enhanced filtration on a recirculation loop (B, D-G) could be operated on demand when indoor particle sources are known to be present.

(c) VOC removal. We selected three technologies for VOC removal. For System C, we specified inclusion of a recently developed (by LBNL) manganese oxide catalyst that oxidizes formaldehyde and other VOCs at room temperature (Sidheswaran at al., 2011). For System D, the intent was to use a chemisorbent that removes formaldehyde (and potentially also nitrogen dioxide) in addition to other VOCs. For System G, we specified activated carbon, which is the most common of the technologies available for VOC removal in residential HVAC systems and is known to remove some VOCs, such as the BTEX compounds, but is not very effective for removal of formaldehyde.

(d) Design of supply ventilation. There were two systems (D and G) in which outdoor air was supplied via the central forced air ducting system with intermittent operation of the AHU. There were three supply systems (A-C) featuring continuous supply ventilation that did not rely on the central blower. These designs were selected in place of the more common intermittent supply using the AHU to avoid the energy costs of running the typically much larger, and higher power consumption AHU blower. To avoid pushing supply air back through the central system filter that is used to protect equipment, the system protection filter was moved from the return grille to a slot just before the AHU for systems A and B.

(e) Systems that are low-cost. Systems A, B, E, and F are all relatively simple and should be relatively low initial cost (with the exception of the ESP on system B).

(f) System for low-load homes. System F explores a technology combination – ducted mini-split heat pump with a custom, low pressure drop MERV13 filter compartment – that is applicable to low-load homes including homes that have undergone energy efficiency retrofits to achieve very low loads.

(g) Low-energy pollutant removal. Systems A and F should incur relatively low energy costs as they use low resistance filtration with efficient fans. System C may also be low energy provided a low resistance MERV16 filter is available.

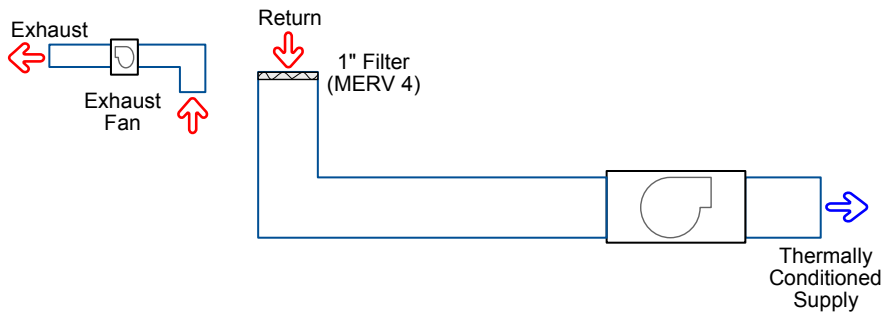

Figure 2.2. Schematic of Reference system.

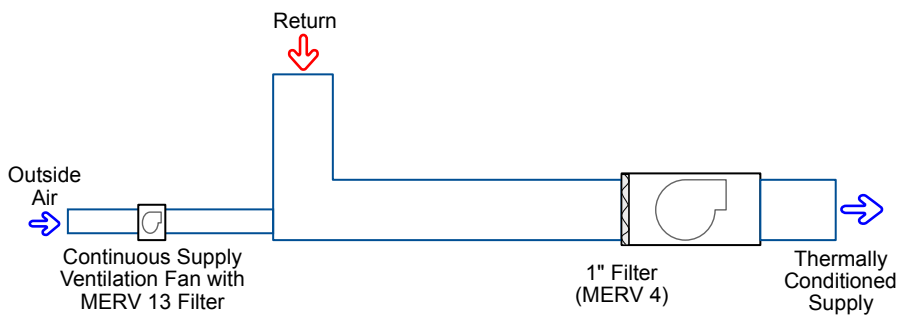

Figure 2.3. Schematic of System A.

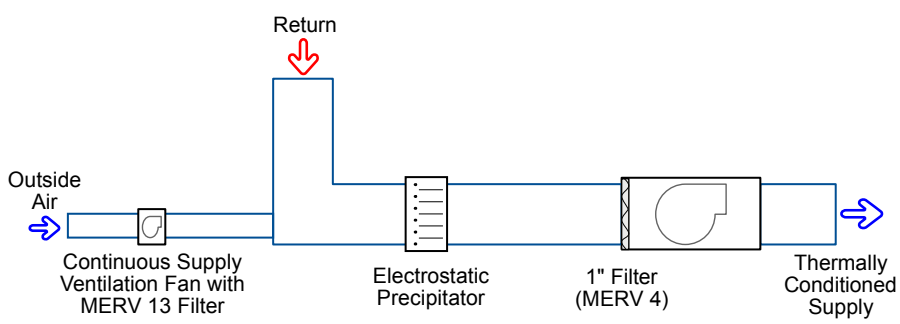

Figure 2.4. Schematic of System B.

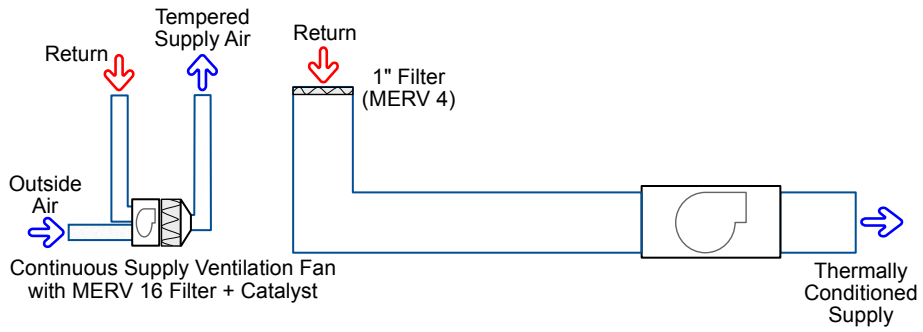

Figure 2.5. Schematic of System C.

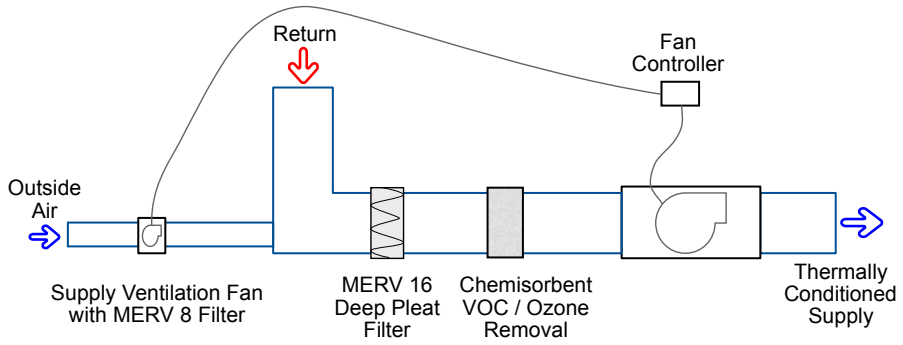

Figure 2.6. Schematic of System D.

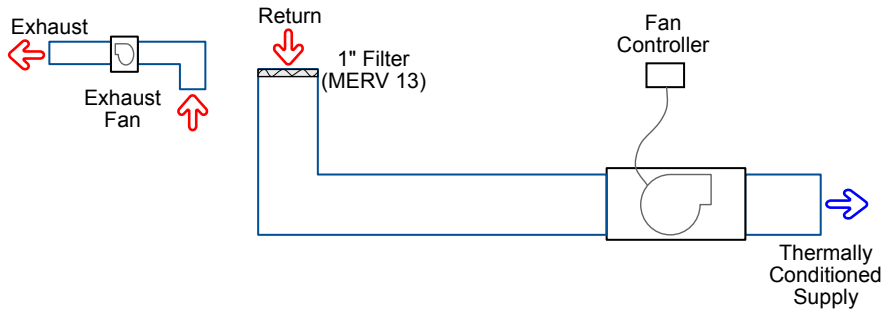

Figure 2.7. Schematic of System E.

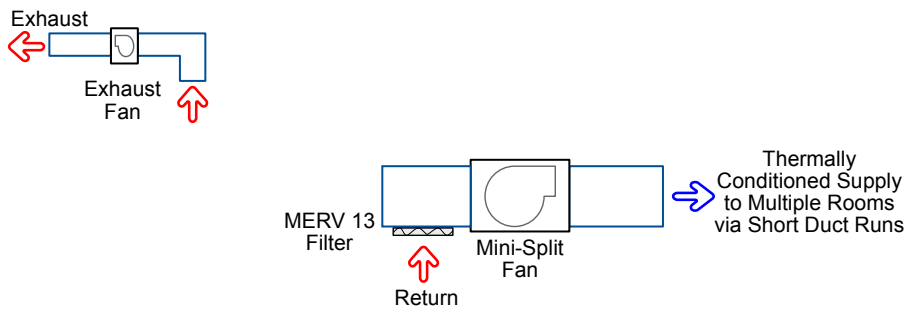

Figure 2.8. Schematic of System F.

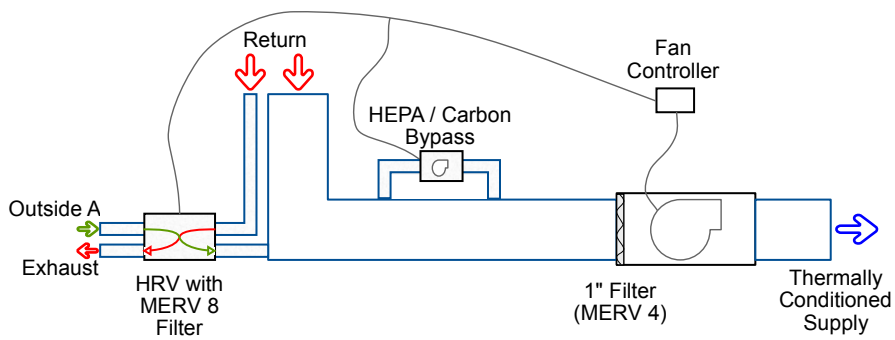

Figure 2.9. Schematic of System G.

2.1.2.3 Installation and integration of systems with heating and cooling equipment

The basic study design called for all systems to be installed and operated in the same test house to enable evaluation under similar environmental conditions (same seasons) and facing similar outdoor pollutant mixtures. To accomplish this, the eight systems had to be engineered and installed in parallel to enable relatively rapid switching between systems.

Balance Point Home Performance (BPHP), a company which specializes in retrofitting California homes to achieve high performance (comfort, indoor air quality, durability, etc.) with low-energy consumption was contracted to design and install systems meeting the basic architectures described in the prior sub-section. The design intent was to install all systems at the same time with ducting, high-quality dampers, and appropriately located supply and return registers to enable each system to be operated without being affected by the presence of the components installed for other systems. The contractor conducted duct leakage tests to confirm low leakage rates after completing construction and our research team conducted additional performance measurements during the study.

The locations of supply and return registers for the various systems are shown in Figure 2.10.

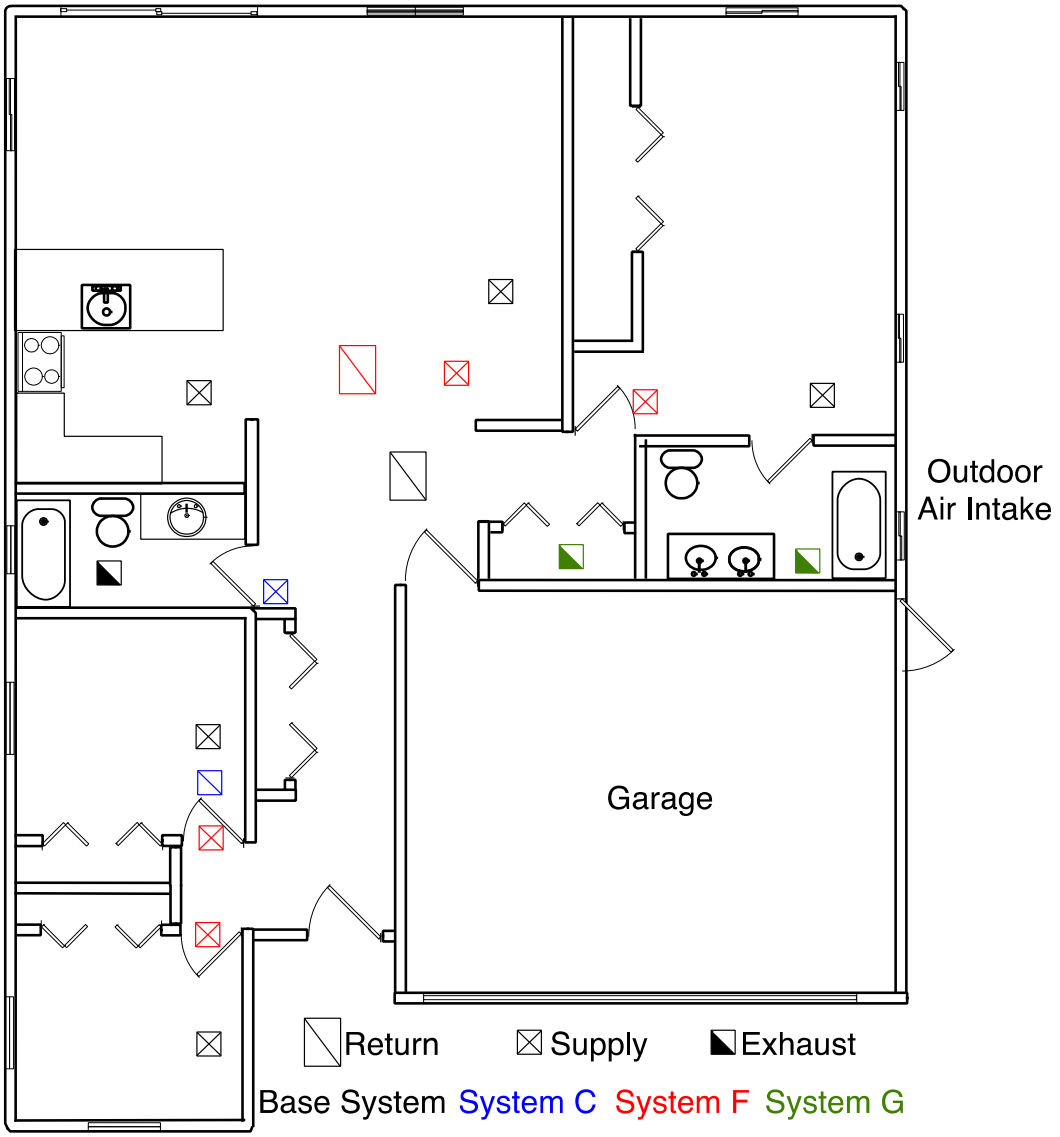

Figure 2.10. Plan view of test house showing air supplies and returns of mechanical systems. System elements identified by color: black for system as found, blue for System C, red for System F, and green for system G. Drawn to scale.

The as-found mechanical heating and cooling equipment and FAU were retained and extensive revisions were made to the ducting to accommodate the various elements of Systems A-E and G. An Ecobee thermostat (model Smart SI Thermostat) was installed to provide programmed thermal control with remote accessibility. The thermostat schedules were set to emulate the operating pattern assumed in Table 2.19 of the Title 24-2013 Residential Alternative Calculation Method (CEC, 2013). Title 24 has two pathways for compliance, prescriptive or performance. The performance pathway is model based, and the prescribed model inputs are covered in the Alternative Calculation Methods (ACM) manual. The schedules are shown in Figure 2.11 below.

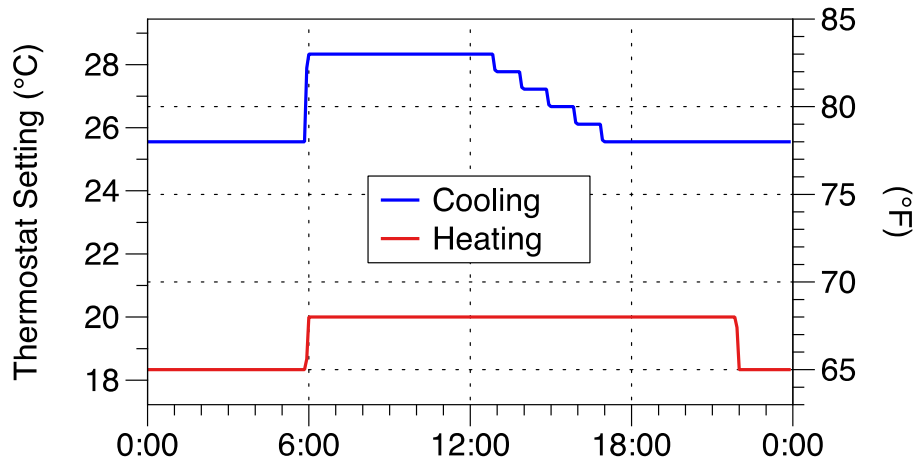

Figure 2.11. Thermostat daily schedule based on California Title 24 design standard.

For System F, heating and cooling were provided by a mini-split heat pump (Daikin SkyAir 18 kbtu Minisplit with ducts & control) with the fan-coil unit mounted on scaffolding that was installed in the large common room for the duration of all experimental periods. A manifold at the outlet of the fan-coil unit fed smooth, sheet metal (for low pressure drop) duct runs to each of the three bedrooms. The mini-split was rated at 20 kbtuh for heating and (HSPF 10.6), 18 kbtuh for cooling (SEER 17.5). The instrument's native control system was programmed to operate on the Title 24 schedule described above.

2.1.2.4 Specifications of installed ventilation systems

The exhaust fan used in Systems Ref, E and F (Panasonic model FV-08VKS3) was a "double-duty" fan installed in the bathroom. The double-duty refers to the fan providing continuous exhaust ventilation at the rate required to meet Title 24 / ASHRAE 62.2-2010, 17.5 L/s (37cfm) while having a higher speed of 41.5 L/s (88cfm) that can be manually initiated when needed for bathroom humidity or odor control.

All of the systems that provided ventilation through a dedicated supply fan (including A, B, C, D, and G) pulled outdoor air from the same location (the gable end vent on the north end of the house), which was nearby to the sampling point used to characterize particle levels in outdoor air.

The same supply fan was used for Systems A, B, and D (Fantech model FR125). For System D the fan speed was set to provide a flow rate of 51.4 L/s (109 cfm) to meet the Title 24 / ASHRAE 62.2-2010 airflow requirement when operated for 20 min of each hour. A balancing damper just downstream of the fan was used to reduce the airflow rate for continuous operation for Systems A and B. The damper position that provided the desired continuous airflow (the same flow as that used for the exhaust fan) was determined and marked prior to the start of multi-day experiments and the damper was set to this position when System A or B was tested. The actual flows achieved with the damper were not precisely 1/3 of the intermittent rate.

The blended supply ventilation for System C was provided by a commercially available product (American Aldes Model BV120). This product blended 16.5 L/s (35 cfm) indoor air

drawn from the one of the small bedrooms and 28.3 L/s (60 cfm) of outdoor air drawn from the same location as the other supply fans, and supplied this mixture to the hallway in front of the main bathroom. The blending unit was mounted on the ceiling in the hallway closet.

The heat recovery ventilator (Fantech model FLEX 100H) used in System G was installed in the garage. It pulled outdoor air from the common intake used for all supply systems and provided that ventilation air to the return side of the FAU after heat exchange. The exhaust side of the HRV pulled indoor air from the laundry and master bathrooms, and exhausted that airstream to under an eave on the side of the house. Active flow-capture measurements using an Energy Conservatory Duct Blaster confirmed the supply and exhaust airflows were balanced at 52.9 L/s (112 cfm).

2.1.2.5 Specifications of particle removal technologies

The Reference system featured a nominal 1-inch (2.5 cm) thick, 50 x 76 cm (20 x 30 in.) filter (Purolator F312) installed at the return grille. The design intent was to use a low-efficiency (i.e., low MERV) filter that protects the heating and cooling equipment from dust but does not provide any benefit of enhanced particle removal. The decision to use the F312, which is rated as MERV4, instead of a MERV6 filter as specified by ASHRAE62.2, was based on input from HVAC and home performance contractors who conveyed to us that the lower quality filter is much more widely available and more commonly used. The same filter was installed at the return grille for System C and an appropriately sized 51 x 63 cm (20 x 25 in.) version of this product was installed at the AHU for System A, B and G.

Systems A and B both included a nominal 2-inch (5cm) thick, 41 x 34 cm (16 x 14 in.) MERV13 filter installed at the junction of the supply ventilation duct and the return air duct. Since this was not a commonly available size, the local filter vendor (Air Filter Supply in Sacramento, CA) fabricated these filters from media that met the MERV13 specification (Airguard DP-g13een). System B additionally incorporated an ESP, marketed as an Electronic Air Cleaner (Honeywell model F300A2025/U), installed between the supply air junction and the central heating and cooling equipment. The ESP only operated when the central FAU was operating for thermal control.

System C utilized the same MERV4 filter at the FAU return grill as the Reference system, but also included a MERV16 filter on the blended air system. The MERV16 filter was a specially modified IQAir model HyperHEPA cartridge. The filter was downstream of the blending, and the fan was always on.

System D included a nominal 1-inch (5cm) thick, 41 x 36 cm (16 by 14 in.) MERV8 filter installed at the junction of the supply ventilation duct and the return air duct. As with the supply filter for Systems A and B, this filter was fabricated as a special order by Air Filter Supply in Sacramento CA using media that met the MERV8 specification (AirGuard DP-Max). System D also included a nominal 5-inch (13 cm) thick, 51 x 63 cm (20 x 25 in.) MERV16 filter (Lennox model X8313). Both the ventilation fan and the FAU were controlled by an AirCycler controller (model g2) serving as a runtime controller to ensure that the FAU with this filter in-line operated for at least 20 min of each hour, irrespective of cooling or heating demand.

System E provided the simplest filtration upgrade, relative to the Reference, with a nominal 1-inch (2.5 cm) thick, 50 x 76 cm (20 x 30 in.) MERV13 filter (FiltersFast model FFM1361) installed at the return air grille and the AirCycler controller (model g2) serving as a runtime

controller to ensure that the FAU with this filter in-line operated for at least 20 min of each hour, irrespective of cooling or heating demand.

System F incorporated a nominal 1-inch (2.5 cm) thick, 81x 63 cm (32 x 25 in.) MERV13 filter (FiltersFast model FFM1361) into a custom-built sheet-metal box that was attached to the return side of the mini-split evaporator and fan unit. The purpose of the custom box was to enable use of a high quality filter with low enough pressure drop to meet the mini-split's pressure tolerance limits. The outlet of the mini-split was directed through smooth, low-pressure drop ductwork to deliver filtered and conditioned (when needed) air to the living space and three bedrooms.

System G had the previously described MERV4 filter installed at the AHU. It also included a HEPA bypass unit (Lennox model HEPA-20 with optional 94X98 carbon canister). The bypass unit drew 85 L/s (180 cfm) from the return plenum downstream of where the HRV airstream entered, and discharged the filtered air just upstream of the FAU. The AirCycler controller (model g2) served as a runtime controller to ensure that the FAU with the bypass filter and HRV operated for at least 20 min of each hour, irrespective of cooling or heating demand.

The portable air filters were RabbitAir model SPA-780A (A2-minus) with a HEPA main filter and the "pet / allergy" pre-filter. One was set up in the living room and the other was in the front hallway by the entry door. For one of the two test periods the units were operated in an AUTO mode where the speed of the fan increases if the unit senses high particle concentrations. The other week had the units running at a fixed medium speed. Both weeks had the air ionizer turned off but main filter and pre-filters in place.

2.1.2.6 Specifications of volatile organic compound removal technologies

Equipment to reduce volatile organic compound concentrations was incorporated into three of the systems. System C incorporated a MERV16 particle filter manufactured with microfibers coated with a manganese oxide catalyst. The catalyst was developed by LBNL and oxidizes formaldehyde and other VOCs at room temperature (Sidheswaran at al., 2011). The filter was prepared as a prototype by a company that specializes in high performance filtration. System D incorporated a PuraGrid Filter with IAQ Media Blend (PG20252-IAQ 20x25x2) manufactured by Purafil, Inc. System G incorporated a Healthy Climate HEPA-20 by-pass filtration system with a 1.4 kg (3 lb) Carbon canister.

2.1.2.7 Installed system performance measurements

Airflow and power consumption were measured for each air-moving component (AHU, ventilation fans, etc.) and power consumption was measured for the ESP of System B. For the AHU, airflows were measured as the sum of the exiting airflows at all supply registers, after the distribution system was balanced according to the industry standard Manual J heating and cooling load calculations. Airflows were measured using the Energy Conservatory DuctBlaster™ and the active flow capture methods outlined in the product manual. For components with plugs, we made spot power measurements using a portable, plug-through power meter (WattsUp PRO). We also calculated power draws from the monitoring of operational schedules and energy consumption of all system components using the WattNode current transducers (model WNB-3Y-208P) and a PointSix wireless data logging system.

Performance measurements of installed system components are summarized in Table 2.3.

Table 2.3. Airflows and power consumption of system components.

Component, Setting	Airflow [L/s]	Measured Power [W]	Catalog Power [W]	Notes
Exhaust fan for Systems E, F, Ref. (continuous)	17.5	4.2	3.7	Catalog power for 18.9 L/s @ 25 Pa
Supply fan, continuous setting for Systems A-B	17.5	17.7	18	Flow set with balancing damper. May have varied each time System A or B was set up.
Supply fan, intermittent setting for System D	51.4	18.0	18	
Blending supply fan for System C	44.8	33.8	43	Flow from outdoors = 17.4 L/s Flow from indoors = 27.4 L/s
HRV for System G, during intermittent operation	52.9	111.3	102	Catalog power for 46.7 L/s
HRV for System G, standby mode	No flow	10.1	N/A[1]	
AHU, high speed w/MERV4	566	660	N/A[1]	Cooling mode, sum of flows measured at supply registers
AHU, high speed w/MERV13	NM[1]	627	N/A[1]	System E; flow not measured in this configuration
AHU, high speed w/ESP	NM[1]	659	N/A[1]	System B; flow not measured in this configuration
AHU, high speed w/MERV16 + VOC	NM[1]	605	N/A[1]	System D; flow not measured in this configuration
AHU, medium high speed w/MERV4	500	N/A	N/A[1]	Heating mode, sum of flows measured at supply registers
AHU, standby mode	No flow	7.6	N/A	
System F mini-split, continuous setting for filtration	282	106.5	N/A[1]	Power measured by WattNode.
Electronic air cleaner (ESP) for System B	NR[1]	23.8	36	Catalog power is the maximum power
HEPA bypass for System G	85	121.1	125	Flow from manufacturer spec sheet.
Portable air filtration devices (n=2), Auto setting (~99% Low)	55	8.2	N/A[1]	Flow from manufacturer spec sheet (Low speed). Power measured over operating period
Portable air filtration devices (n=2), Medium setting	106	19.7	N/A[1]	Flow from manufacturer spec sheet (Medium speed). Power measured over operating period

[1] NM = Not measured in this configuration; N/A = not available; NR = not relevant to equipment.

Prior to the start of the fall monitoring campaign, we again measured the envelope air tightness and also measured air leakage in the FAU ductwork configured for the Reference system. The envelope air leakage was 5.0 ± 0.2 air changes per hour at 50 Pascal indoor-outdoor pressure difference. Duct leakage was determined by a "Delta-Q" test (Walker et al., 2001) to be

4.2 ± 0.5 % of system flow on the return side and 3.8 ± 0.5 % on the supply side of the FAU. Here the uncertainty reflects the precision of the measured value. Measurements of air exchange rates in the house with and without the FAU operating during the cooking experiments suggest lower duct leakage than implied by these measurements. This is possible because the relative accuracy of the Delta-Q test decreases as duct leakage airflows become small relative to envelope leakage airflows.

2.1.3 Other elements of test house set-up

2.1.3.1 Internal mixing and window blind positions

Indoor pollutants were sampled at a single indoor location. To ensure that this location is representative of the air throughout the house, internal air mixing is required. Interior mixing is also required for the tracer gas ventilation measurements. Several of the test systems were operated in a manner that promotes air mixing by pulling air in at one location, moving the air through a filter, and supplying the treated air to other locations through ductwork. Systems D, E, and G all had a timer controller to initiate central system operation for at least 20 min of each hour. System F featured a ducted mini-split that continuously pulled air from the great room and distributed it to the two front bedrooms. System C drew conditioned indoor air from one of the small bedrooms to temper the outdoor supply air, and provided this mixed air stream to the hallway right in front of the main bathroom. By contrast, the Reference and Systems A-B had no programmed mixing of indoor air. Owing to the relatively mild winter weather in Sacramento and energy-efficient construction dictated by California building code, we could not rely on cooling and heating demand to force operation of the FAU to achieve mixing. We therefore installed supplemental mixing fans. During the pilot experiments of Winter 2014, air mixing was promoted by three portable desk fans (AirKing Model 9102) with each rated at 439 L/s (930 cfm). The desk fans were installed by the front door, on the kitchen counter, and in the hallway near the return grill. In May we installed an additional mixing fan (FanTech FR-100) with ducting to move air at roughly 52 L/s (110 cfm) from the master bedroom to the great room in the back of the house. This was also designed to move heat generated by the instruments, which were located in the master bedroom, to other parts of the house.

All windows in the house were equipped with horizontal metal blinds and the back patio doors were equipped with vertical blinds. During all monitoring periods, the horizontal blinds were angled to block incoming sunlight and all blinds were adjusted to a mostly closed position. The intent was to limit solar insolation through the window and door glass and to limit visibility of the house interior from outside.

2.1.3.2 Supplemental cooling for manifold pumps (summer only)

The two large diaphragm pumps that pulled air through the instrument manifolds were located in the garage to reduce heat gain to the house interior. This appeared to be sufficient during the winter operation period; but we observed when restarting the systems in May that heating of the garage by the pumps would have a substantial impact on cooling demand and AHU operation for cooling.

To solve this problem, we constructed a chamber to house the pumps and provided supplemental mechanical cooling to this chamber. The chamber, situated in the garage, close to the common wall with the house, was constructed of wood and measured 1.2 m high by 2.4 m

wide by 0.8 m deep. Cooling was provided by a 2.7 kW (9300 Btu/h) portable air conditioner (Friedrich model P09B) located in the garage with the hose for venting the condenser heat connected to the outdoors through the side door of the garage,

2.2 ENVIRONMENTAL, AIR POLLUTANT, AND EQUIPMENT MONITORING

2.2.1 Environmental monitoring

2.2.1.1 Outdoor environmental parameters

Local wind speed and direction were measured with an anemometer (Met One 010C wind speed sensor and a Met One 020C wind direction sensor) mounted above the roofline, adjacent to the air intakes for supply ventilation and outdoor particles. The relative positions of these components are shown in Figure 2.12. Temperature and relative humidity were logged every five min using ONSET HOBO loggers (model U23-001). Outdoor T and RH were measured on the north end of the house approximately 1 m above the ground directly below the sample inlet.

Figure 2.12. Weather station and air intakes for supply ventilation and outdoor particle sampling. This view of the house shows the north end of the house. The meteorology instrument tower is visible above the roofline. Just above the apex of the room, on the same tower, is the outdoor aerosol sample inlet. The outdoor air inlet for all of the supply ventilation systems is through the visible gable end vent. Outdoor NO_X, and O_3 measurements were made just outside the master bathroom window (visible below the met tower). The outdoor VOC samples were taken from a shielded box mounted on the other side of the fence.

Data on precipitation and fog were obtained from measurements at the nearby McClellan air force base, located approximately 5 km from the test house (the closest runway edge is roughly 3.5 km from the house). The data were downloaded from www.weatherunderground.com and the METAR locator is KMCC.

2.2.1.2 Indoor environmental parameters

Temperature and relative humidity inside the home were logged every five min using ONSET HOBO loggers (model U12-012). Measurements were made at 1 m height in the front bedroom

and master bedroom, in the supply register in the master bedroom, in the return plenum, and in the garage. In addition to this we were able to retrieve T and RH data from the ECOBEE thermostat, this data was logged on a 15 min interval.

2.2.2 Time-resolved pollutant monitoring

2.2.2.1 Design principle: continuous indoor and outdoor monitoring with periodic switching of air streams for aerosol monitoring

The measurement system was designed to achieve continuous, unattended monitoring of indoor and outdoor concentrations of various size fractions of $PM_{2.5}$, black carbon, and selected pollutant gases. Pairs of identical real-time monitoring instruments simultaneously measured indoor and outdoor air with functionally identical sample line architectures. The outdoor air inlet was installed to pull air from approximately 0.5 m above the apex of the roof just above the supply air inlet, as shown in Figure 2.12. The indoor air inlet was located in the central hallway at a height of approximately 1.5 m. Sample air was drawn at 0.28 L/s (0.59 cfm) through each sample line using a vacuum pump.

Size fractions of $PM_{2.5}$ aerosol were measured from air streams pulled through sampling lines and manifold systems designed for isokinetic sampling. The aerosol inlet assembly (BGI, Inc.) on each sampling line comprised a PM_{10} inlet with rain shield coupled with a sharp cut 2.5 μm cyclone. Sample lines connected to indoor and outdoor inlets had identical lengths of conductive tubing and similar bends to arrive at a set of switching valves that connected the two air streams to manifolds from which aerosol instruments sampled. The main sampling lines – from inlet assemblies to switching system leading into instrument manifolds – were 7 m long. The lines used for winter 2014 monitoring had internal diameters (ID) of 11.1 mm (0.436 in.). Prior to the start of summer monitoring, we changed sample inlet tubing for both indoor and outdoor inlets, using larger diameter samples lines. The sample lines used for all of the summer and fall 2014 monitoring had ID of 14.1 mm (0.555 in.). The move to larger diameter sampling lines was expected to provide a marginal benefit in slightly lower particle deposition losses. This should have a negligible impact on the analysis of system performance since the indoor and outdoor sampling lines were identical both before and after the switch.

The valve system was designed to simultaneously switch the indoor and outdoor sample inlets between the two manifolds and sets of aerosol instruments. The two purposes for this switching configuration were (1) to minimize errors in comparisons of indoor and outdoor particle levels that would result from drifts in instrument response, and (2) to reduce data loss by ensuring that at least a semi-continuous signal would be obtained for each location in the event of instrument failure during unattended operation. Switching was initially set to occur every 10 min. This configuration was used for pilot monitoring in Jan-Feb 2014 and for the cold weather operation of the Reference system and System C that started during Feb 2014. The switching interval was changed to 15 min on March 6, 2014 and this interval was used for all subsequent measurement periods. This change was made to reduce the fraction of samples that had to be removed because they straddled a switch and thus reflected a combination of both indoor and outdoor air.

2.2.2.2 Air pollutant monitoring equipment

Table 2.4 presents a list of the air pollutant parameters that were measured and the instrumentation used to measure each parameter. All instruments other than the aethalometer

were set to calculate and record 1-min average values throughout all monitoring periods. The Aethalometers were initially set to record 1-min average values then reset on March 6, 2014 to record 3-min running averages. The longer sample time provided a lower minimum quantitation limit and improved resolution for systems with high efficiency filters.

Table 2.4. Measured air pollutant parameters and monitoring equipment.

Parameter	Device	Quantitation limit (QL)	Calibration and nominal accuracy.
Number conc. of particles ≥6 nm	TSI Condensation Particle Counter (CPC) Model 3781	Max. QL 500,000 particles cm^{-3}	Manufacturer calibrated before deployment.
Number conc. of particles ≥100 nm	TSI CPC Model 3787 with TSI particle size selector	Max. QL 500,000 particles cm^{-3}	Manufacturer calibrated before deployment.
Number conc. of particles in 6 bins from >0.3μm to >2.5μm[1]	MetOne Optical Particle Counter Model BT-637S	Max. QL 10^7 particles cm^{-3}	Manufacturer calibrated before deployment. Accuracy: ±10% to calibration aerosol.
$PM_{2.5}$ mass estimated by light scattering	TSI DustTrak II 8530	Min. QL 4 μg m^{-3} for 1h avg[2]	Manufacturer calibrated before deployment.
Mass concentration of black carbon aerosol (BC)	Magee Scientific Aethalometer AE22	Min. QL 30 ng m^{-3} for 3 min sample[3]	Manufacturer calibrated before deployment.
Ozone (O_3)	2BTech Model 202 UV-absorbance analyzer	Min. QL 4.5 ppb	Manufacturer calibrated before deployment. Nominal accuracy: larger of 1.5 ppb or 2% of reading;
Nitrogen oxides (NO_X, NO, NO_2)	API 200A / 200E chemiluminescence analyzers	0-2000 ppb range	~Weekly zero and span-check with NO at 480 ppb. Linearity 1%. Span drift <1%/week.

[1]Bins defined by lower size cut, e.g. >0.3, >0.4, >0.5, >0.7, >1.0, >2.5μm. [2]Reported by Wallace et al. (2011), Journal of Exposure Science and Environmental Epidemiology 21: 49-64. [3]Estimated based on visual review of data. Estimated min. QL of 90 ng m^{-3} for 1-min sample duration.

Air pollutant monitoring instruments and switching valves were located in the master bedroom. Along each of the two sampling streams, aerosol instruments drew from a central line / manifold connected to a vacuum pump, which was located in the garage. The layout of the aerosol instruments is shown in Figure 2.13.

Figure 2.13. Layout of instrumentation in master bedroom.
This photo shows the two manifolds with the identical sets of particle instruments. The Aethalometers, which are the last instruments on the manifold, are the large blue boxes at the bottom left of the photo. Moving toward the inlet of the manifold (and up and to the right in the photo), there are CPC 3781s with water bottles on top, CPC 3787s without covers, MetOne OPCs, and DustTraks (small, dark blue cases). The switching valves are visible at the inlet of the manifold, toward the right edge of the photo. In the background, towards the top of the photo and in the corner of the room, are the API NO_X analyzers (large white boxes on table), the 2BTech ozone analyzers (sitting atop one of the NO_X analyzers), and the B&K instrument (far corner).

The NO_X and ozone analyzers were not connected to the sample lines on the switching systems. Instead, each of these instruments sampled from a dedicated location: indoors or outdoors. Outdoor sampling for NO_X and ozone was from a location approximately 2.5 m below the supply ventilation inlet and roughly 0.5 m from the exterior wall of the house. Indoor sampling was from the same location as the indoor aerosol inlet. Air samples were pulled from these locations through Teflon tubing with interior diameter of 3.2 mm and a length of 5 m to the NO_X and ozone instruments located in the master bedroom. NO_X and ozone data are available only for outdoor pollutant performance monitoring and indoor (cooking) performance in summer 2014.

2.2.2.3 Calibrations

All of the aerosol instruments and the ozone analyzers were sent for manufacturer calibration prior to deployment at the test house. The NO_X analyzers were zero and span-calibrated (at 480 ppb) on June 6 2014, prior to the start of the summer season and indoor (cooking) source performance evaluations.

2.2.3 Sampling and analysis for volatile organic compounds (VOCs)

Speciated volatile organic compound concentrations were quantified for several 24h integrated periods during summer operation of the three systems that featured VOC removal technologies (C, D, and G) and the reference system. These experiments took place during July and August 2014.

Two different types of samples were collected simultaneously, to identify and quantify a broad range of VOCs and volatile carbonyls, respectively. The broad range of VOCs was sampled onto glass tubes containing a dual graphitized carbon black sorbent bed (Carbopack™, Supelco, PA) that had been preconditioned and kept in a freezer prior to sampling. Indoor air samples were collected using two identical tubes operating in parallel by connecting on the downstream end a peristaltic pump drawing a constant airflow. The upstream end of the tubes were pointing to the middle of the room from which the air was being sampled (living room), and placed at a height of approximately 1 meter. In the case of outdoor samples, due to the high level of ozone present, two different sets of duplicate samples were collected. One set was sampling directly from outdoor air adjacent to the house. Tubes from the other set were preceded by scrubbers to remove ozone upstream of the sampling media. The scrubbers consisted of glass fiber filters impregnated with sodium thiosulfate ($Na_2S_2O_3$), and were prepared according to Pollmann et al. (2005). Outdoor sampling tubes were housed inside a perforated metal cabinet with heavy-duty aluminum foil laid overtop to allow free air movement through while preventing direct exposure to the sun. The cabinet was attached to a fence, at approximately one meter from the floor level of the house and one meter away from exterior walls. Peristaltic pumps used for outdoor samples were kept inside the house (in the bathroom) and were connected with outdoor sample locations through several meters of tubing. Both indoor and outdoor samples were collected at airflows between 5 and 6 cm^3 min^{-1}, to achieve sample volumes of about 7 to 9 L after roughly 24 hours of continuous operation. Sample flow rates were measured using a bubble flow meter. The sampling system was initially tested in the laboratory to confirm effective ozone removal by the scrubbers.

Volatile carbonyls were collected on silica gel cartridges coated with 2,4-dinitrophenylhydrazine (DNPH) that had been kept in a freezer prior to sampling. DNPH-impregnated silica gel cartridges (XpoSure, #WAT047205, Waters Corp., U.S.) were preceded by an ozone scrubber (Sep-Pak WAT054420, Waters Corp., USA) in both indoor and outdoor samples. Two replicate samples were collected simultaneously indoors, and another set of duplicates was taken outdoors during the same period. The flow through the samplers, between 80 and 100 mL min^{-1}, was measured using a calibrated flow meter (BIOS). The volume of air sampled was between 110 and 140 L.

For each tested system, 24-h samples were collected either during 2 or 4 days of system operation. The peristaltic pumps were connected to timers that enabled either a delayed start (to allow for the house to return to a steady-state following perturbations due to the presence of the researchers), or stopping the sampling automatically at a given time. All samples were scheduled to start and end around 7 am, to capture the majority of outdoor emissions taking place during the day, including both commuting periods. Samples were collected on the same days of the week (Thu, Fri, Mon, Tue; or Mon, Tue) for a more consistent comparison among systems. For each sample, new sorbent tubes and DNPH cartridges were installed and the flows measured and recorded. At the end of each period, flows were measured again, recorded, and the sorbent tubes and cartridges were retrieved. Sorbent tubes were placed in their containers, provided with Teflon-lined caps. DNPH cartridges were capped with Luer fittings and placed in individual pouches One sealed sorbent tube and one capped DNPH cartridge were deployed as a blank sample, and otherwise treated using the same protocol as the rest of the samples. At the end of the sampling period for each system, samples were transported in a cooler to LBNL for their analysis.

The sorbent tubes were analyzed by thermal desorption / gas chromatography / mass spectrometry (TD/GC/MS) following the EPA Method TO-1 (EPA, 1984). A volume of 5 mL of air containing 120 ng of an internal standard of 1-bromo-4-fluorobenzene was injected in each tube under a flow of helium prior to analysis. Samples were thermally desorbed and concentrated on a cryogenic Thermal Desorption System (TDS, Gerstel Corp.) fitted to the GC/MS inlet. Sample desorption temperature was held above 200°C for 5 min, with the trap cooled at −20°C and heated to 235°C for injection. Multipoint calibrations were referenced to the internal standard, in the range 5 – 150 ng. A total of approximately 30 individual target VOCs were quantified in our samples, most of which coincided with those typically found in indoor and outdoor air and are commonly analyzed at LBNL. The analyte concentrations in reactants blanks and field blanks were determined for each system.

DNPH cartridges were extracted with a 2-mL acetonitrile aliquot, and analyzed by high performance liquid chromatograph (HPLC) with ultraviolet (UV) detection (Agilent 1200) following the EPA TO-11 method (EPA, 1999). Three volatile carbonyls –formaldehyde, acetaldehyde and acetone– were quantified using calibration curves prepared with authentic standards of the corresponding DNPH hydrazone derivatives. The analyte concentrations in reactants blanks and field blanks were determined for each system.

The detection limit for each VOC was typically 1 ng or lower, corresponding to a concentration in air of <0.1 μg m^{-3}. The detection limit for each volatile carbonyl determined by the DNPH/HPLC method was typically 10 ng or lower, corresponding to a concentration in air of <0.1 μg m^{-3}.

2.2.4 Monitoring of mechanical equipment operation

Energy use and operating patterns of mechanical systems were monitored using WattNode current transducers (model WNB-3Y-208P) connected to a PointSix wireless data logging system. The following systems were monitored: central air handling unit (AHU); exhaust fan used by Systems Ref, E, F; Supply fan used by Systems A, B, D; the mini-split unit of System F; the HRV of System G; and the HEPA bypass of System G. The ECOBEE thermostat system logged set points and system operation at 15 min resolution.

2.2.5 Air exchange rate

The air exchange rate was measured by continuous release and time-resolved measurement of sulfur hexafluoride (SF_6) tracer gas. The tracer was continuously released at two locations: on the kitchen peninsula counter and at 1 m height in the nook just outside of the two smaller bedrooms. At each location the tracer was released using a peristaltic pump connected to a Tedlar bag containing pure SF_6 and a 30 cm axial fan was positioned to blow the tracer outward for mixing. Concentrations of SF_6 were measured in the central hallway, near the FAU return, at a height of 2 m using a Bruel & Kjaer (now Innova) 1312 photoacoustic infrared analyzer. A measurement of SF_6 was recorded at approximately a 1-min interval. The instrument was zero-checked on approximately a weekly basis during the monitoring campaigns and a span calibration was conducted at the start of each seasonal campaign.

The time-resolved air exchange rate was calculated according to the constant injection method specified in ASTM Standard E741-11.

2.3 SYSTEM OPERATION TO DETERMINE PERFORMANCE FOR OUTDOOR PARTICLES

We started with a series of "shakedown" and pilot experiments conducted from mid-January through the first few weeks of February 2014, as summarized in Table 2.5. These mostly used the Reference system. One objective was to confirm performance of the switching, parallel manifold systems and all instrumentation for unattended monitoring periods lasting approximately one week. Another objective was to develop and test algorithms for a remote, daily review of data to affirm proper operation and to generate data that was used to develop processing and analysis algorithms for assessing enhanced particle removal. During two of these early monitoring periods we obtained data sets that were complete enough to use for the analysis of system performance under winter conditions. All systems and instruments were powered down on March 19 and instruments were serviced as needed.

Table 2.5. Winter 2014 "Shakedown" and pilot experiments to identify and resolve challenges related to weeklong, unattended monitoring.

Dates	System	Data Notes
1/15–1/22	Reference	Monitoring systems operating in parallel, no switching. Outdoor 3781 and Aeths offline for repairs. DustTraks off manifolds.
1/23–1/29	Reference	Outdoor 3781 offline for repairs. Switching started. AER 2x design b/c bath fan set too high. DustTraks off manifolds.
1/29–2/6	Reference	Outdoor 3781 offline for repairs. AER still 2x design. DustTraks off manifolds.
2/6–2/12	C: Blended Supply, MERV16	Outdoor 3781 offline for repairs. DustTraks off manifolds. Indoor DustTrak and BC below QL much of week.
2/12–2/19	Reference	No data from 3781s starting 2/13; pump failure. Indoor BC below QL for much of week. Response shift of 3781s on 2/16.
2/20–2/27	Reference[1]	DustTraks on manifolds; curious data 2/20-2/22. Increase Aeth flow to 4 L/min. Other instruments and systems operating as designed.
2/27–3/6	C: Blended Supply, MERV16[1]	No AER data from 2/28; B&K problem. Other instruments and systems operating as designed.
3/6–3/12	A: Cont. Supply w/MERV13.	One 3781 not operating; take offline to repair. Computer down 3/7-3/8.
3/13–3/19	E: MERV13 on return	Lost power to one manifold on 3/16. Various other problems.
3/19	Shutdown	Power down all equipment for service.

[1]Data collected in this period used for system performance analysis.

Monitoring systems were restarted in early May 2014 to conduct pilot experiments with indoor-generated particles and to prepare for assessments during the late spring and summer.

The test house was restarted in May 2014 and operated from June through August 2014 to determine system performance for outdoor particles during summer, hot weather conditions. All systems were powered down on August 6 and instruments were serviced. The monitoring system was restarted in early October and the ventilation and enhanced pollutant removal systems were operated serially from October through December 2014 to complete performance evaluations for outdoor particles during cool and cold weather.

2.4 COOKING EXPERIMENTS TO DETERMINE PERFORMANCE FOR INDOOR-GENERATED PARTICLES

System performance for indoor-generated particles was assessed by executing a scripted cooking activity designed to generate a relatively consistent aerosol with particles spanning from the ultrafine mode (<100 nm) to >1 μm. The scripted cooking procedure involved stir-frying of string beans with oil, in a wok, over high heat for about 5 min. The procedure was initially developed to evaluate the performance of kitchen exhaust hoods at removing particles generated during cooking (Lunden et al., 2014). The potential use of candles as an indoor particle source was investigated in early May 2014 but rejected since the emitted particle size distribution was not as broad and the total mass emission rate was lower than for the cooking-generated aerosol.

The cooking procedure was synchronized with the hourly intermittent operating cycle for Systems A, B, D, E, and G. The cooking procedure was started to coincide with the start of the hourly cycle. Since cooking took about 5 min, the result was a roughly 40 min period in which particles mixed throughout the house and were removed by ventilation and deposition, but not enhanced filtration. For each of these systems, roughly 40 min after the start of cooking, and roughly 35 min after the end of cooking, the central air handler with enhanced particle removal initiated a 20 min period of operation. Systems A and B were operated through one of these hour-long cycles and Systems D, E, and G were operated through two cycles.

For Systems C, F, and the Reference, system performance was tracked for roughly 80-90 min following the start of cooking.

Following completion of the cooking experiments noted above, we operated a supplemental 566 L/s (1200 cfm) fan (Dayton model 7M7T1) with HEPA filter unit (AirHandler model 2EJY3) along with the two portable air cleaners set to high speed, for 30 minutes to an hour. The large, supplemental HEPA filter unit was located in the large room at the back of the house. The intent was to remove any particles that remained from the cooking procedure prior to setting the house for the next period of outdoor particle monitoring.

2.5 DATA PROCESSING AND ANALYSIS

2.5.1 Processing to produce time series of indoor and outdoor concentrations

The first step of pollutant data analysis was to filter/remove data points from the measurements that were recorded just after the two manifolds synchronously switched between indoor and outdoor inlets. During the first two months of sampling in Jan-Feb, 2014, the manifolds switched on 10 min intervals. On March 6, the switching interval was changed to 15 min. Measurements just after switching reflect a combination of air from indoors and outdoors, and are thus not valid as indicators of concentrations in either location. For the instruments that were on the manifolds and that recorded measurements at 1 min intervals, i.e. CPCs, Optical particle counters (OPCs), and DustTraks, it was typically the case that only the first data point after the switch was invalid as a measurement of either indoor or outdoor air. However, in a non-negligible number of cases, the first data point was so close in time to the switch that a second measurement was impacted. For consistent and efficient data handling, two data points were filtered from the time series from these instruments following each synchronous manifold switch. Starting on March 6, only one point was filtered from aethalometer time series data because that instrument was configured to switch every 3 minutes. Prior to March 6, the

aethalometers sampled every 1 min; so two aethalometer measurements were removed following manifold switching for data collected prior to March 6.

An example of after-switching data filtering is shown in the two figures below. Figure 2.14 displays particle number concentration time series that include all of the measurements output by the two CPCs; data from one instrument are shown in blue, the other in red. The instruments sampled from manifolds that switched every 15 min between indoor and outdoor inlets. At many of the manifold switches, there are two blue and two red data points that reflect a combined indoor and outdoor air sample. The time series with these points removed are shown in Figure 2.15.

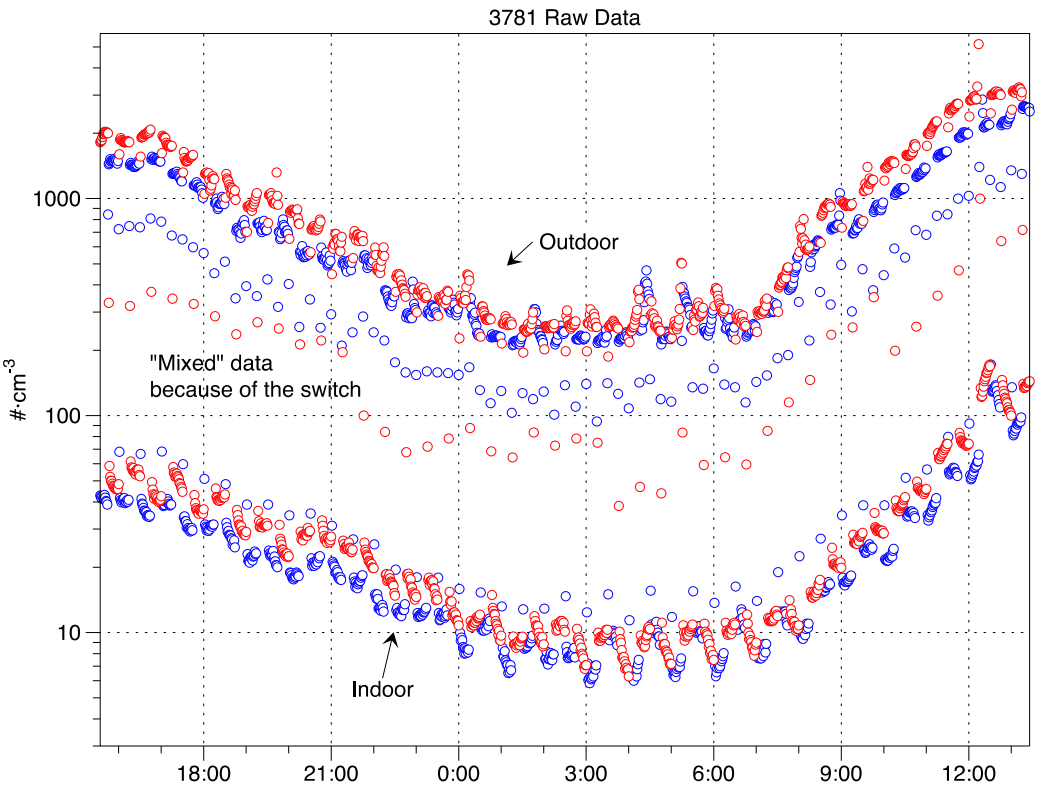

Figure 2.14. Time series of measurements from two CPC3781 units switching synchronously, on a 15-min interval, between indoor and outdoor sample inlets.
Data from one instrument displayed as red circles; the other instrument displayed as blue. The red and blue circles in top half of figure are outdoor measurements. The red and blue circles in bottom half of plot are indoor . Units of y-axis are particles cm^{-3} for size range of 100 nm to 2.5 µm diameter particles. Points between the outdoor and indoor series occur just after the switch and reflect measurements in air samples drawn partly from each location.

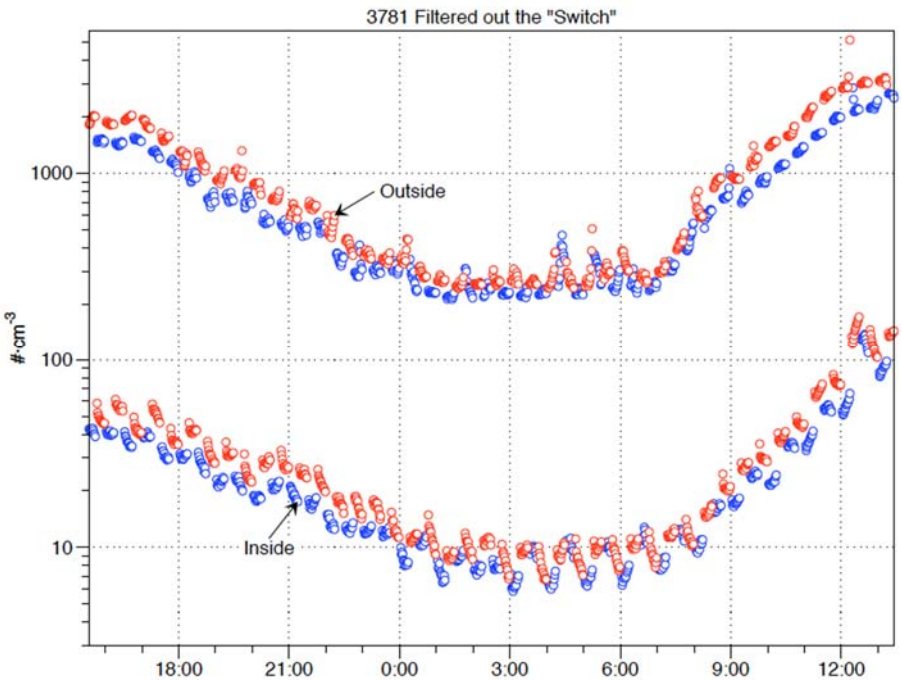

Figure 2.15. Time series data shown in Figure 2.14 with post-switching points removed.
Units of y-axis are particles cm^{-3} for size range of 100 nm to 2.5 µm.

The next step in the analysis was to align the indoor and outdoor data from the two instruments to create nearly continuous data series for indoor and outdoor sampling locations. To accomplish this alignment, we compared the indoor time series of the two instruments as a form of cross-calibration; then used the relative responses to adjust both indoor and outdoor data. The cross-calibration and adjustment is needed because instrument responses drift apart over time and field calibration of particle instrumentation is not practical. Alignment was accomplished as follows. We first applied a locally weighted scatterplot-smoothing algorithm to the available indoor data for each instrument. The available data excluded the post-switching data points and any missing data. We used an open source python implementation[1] of the LOESS[2] algorithm that is based on methods first proposed by Cleveland (1979) and further developed in Cleveland (1981) and Cleveland and Devlin (1988). A good description of the method is available via Wikipedia[3]. Briefly, the algorithm uses near-neighbor data points, weighted by proximity, to develop a low order polynomial fit to the data around each point. When applied across a time series, the algorithm produces a smoothed series with 1-min time resolution. At each time interval, the two LOESS-smoothed indoor time series were compared to the mean of the two series to determine a scaling factor to align the time series from each instrument to the mean of the two instruments. This provides a one-min resolution time-series of a scaling factor that was applied to the data from both instruments to create merged indoor and outdoor time series. The

[1]http://statsmodels.sourceforge.net/devel/generated/statsmodels.nonparametric.smoothers_lowess.lowess.html.
[2]LOESS, in capital letters, is a particular form of the smoothing algorithm. It is not an acronym.
[3]As of Oct 2015, a good description of method is presented on Wikipedia:
http://en.wikipedia.org/wiki/Local_regression

following three figures demonstrate this procedure. Linear interpolation was used to impute concentrations for the two-min period following each switching event.

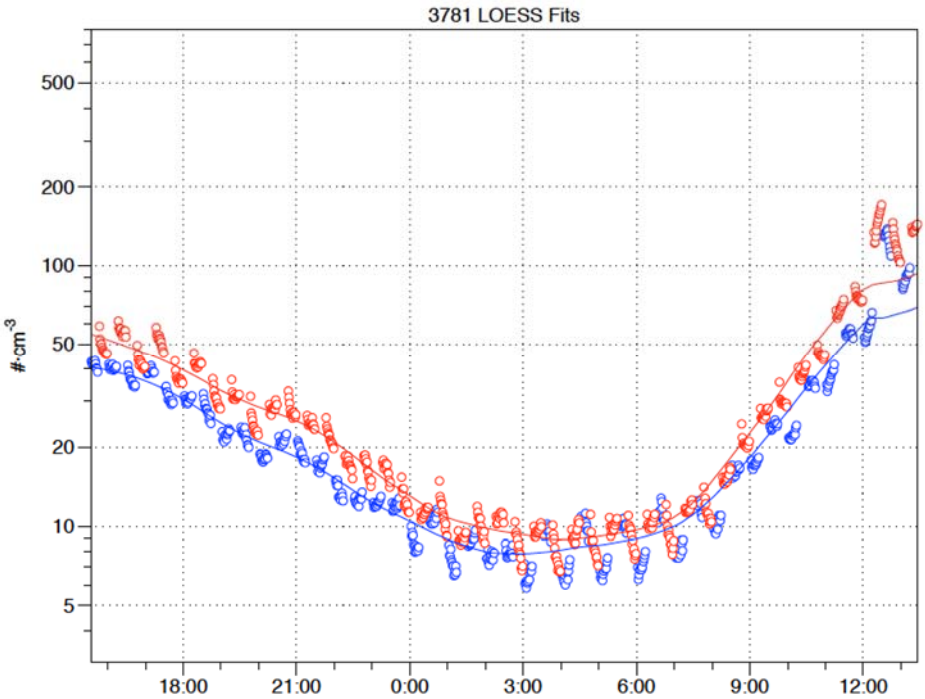

Figure 2.16. Smoothed time series of indoor measurements from each of two CPCs obtained by applying a python implementation of the LOESS algorithm to data series of each CPC.
Red circles are from one instrument; blue circles are from the second instrument. Units of y-axis are particles cm^{-3} for size range of 100 nm to 2.5 µm.

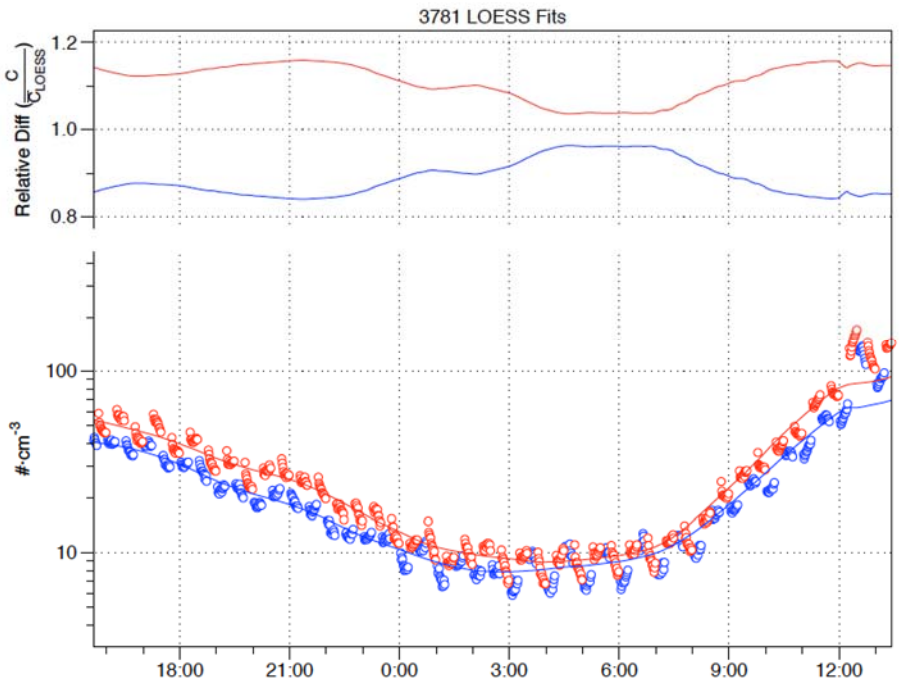

Figure 2.17. Relative difference (top) of smoothed indoor time series (bottom) for each CPC 3781 relative to the mean of the two time instruments.
The time-resolved relative difference functions are used to align the indoor and outdoor time series for the two instruments. Units of y-axis on bottom panel are particles cm^{-3} for size range of 100 nm to 2.5 µm.

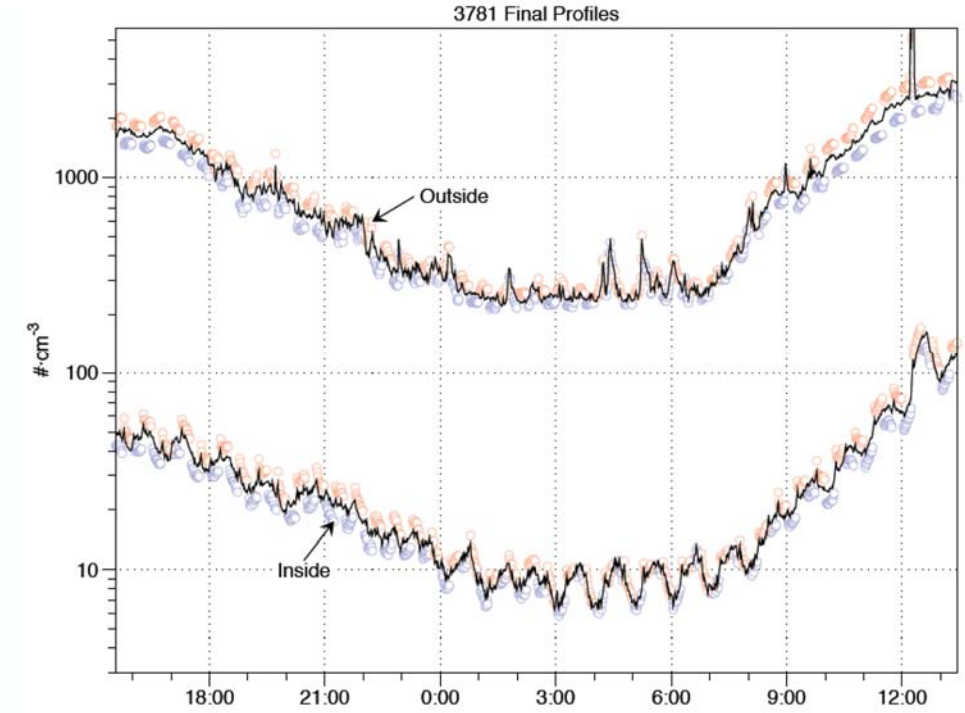

Figure 2.18. Indoor and outdoor time series constructed by aligning data from two instruments alternately measuring indoors and outdoors at 15 min intervals via synchronously switching.
Raw data show as partially opaque red and blue open circles. Units of y-axis are particles cm^{-3} for size range of 100 nm to 2.5 µm. The saw tooth pattern indoors (e.g. during the hours of 3:00 to 8:00) results from intermittent operation of a filtration system.

2.5.2 Estimation of $PM_{2.5}$ from size-resolved particle number concentrations

The particle number concentration data were used to estimate outdoor and indoor $PM_{2.5}$ mass concentrations for the purpose of estimating filtration system effectiveness for $PM_{2.5}$. We applied the basic approach described by Sioutas et al. (1999) using data from a scanning mobility particle sizer (SMPS) and an aerosol particle sizer (APS). The method was applied and validated in field studies in Pittsburgh (Khlystov et al., 2004) and Los Angeles (Shen et al., 2002). The method was applied using a MetOne and CPC by Chan and Noris (2011) and using only a MetOne optical particle counter (OPC) by Tittarelli et al. (2008). Our application of this approach uses the following simplifying assumptions: (1) all particles are assumed spherical; (2) the mass mean diameter within each size bin is assumed to be the midpoint diameter of the bin, and (3) all particles are assumed to have the same seasonally dependent density. Based on the first assumption, the volume of an individual particle is taken as $V_p=4/3\pi(d/2)^3$ where d is particle diameter. The second assumption translates to using the intermediate diameter within a bin to calculate the volume of all particles within the bin. The total volume of the n_i particles within bin i, is thus $V_{bin}=n_i*V_{p,i}$. The volume estimates are converted to mass estimates using the seasonally dependent densities of 2.16 g cm^{-3} for winter and 1.43 g cm^{-3} for summer, as reported in Table 2 of Hasheminassab et al. (2014). Our size bins, in units of µm, were 0.06–0.1, 0.1–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.7, 0.7–1.0, and 1.0–2.5. Number concentrations for the first bin were calculated as the difference between CPC 3787 (0.06–2.5 µm) and CPC 3781 (0.1–2.5 µm) measurements. The second bin was obtained as the difference between CPC 3781 data and the summed total of

particle counts from the MetOne channels between 0.1 and 2.5 μm. The other bins are those of the MetOne OPC.

The $PM_{2.5}$ mass concentrations estimated by this method may differ from the $PM_{2.5}$ that would be measured using gravimetric or other federal reference methods. The mass for any individual bin will be biased if the midpoint is not the mass mean diameter, or if the effective density varies substantially from the assumed value of 1.6 g cm^{-3}. The relationship between estimated and FRM-measured $PM_{2.5}$ could vary by season, day of week and even diurnally as the composition and the size distribution of local $PM_{2.5}$ within each bin varies. However, our method should be reasonable if size distribution and effective density within the bins that account for the majority of the calculated mass are similar between outdoors and indoors over the periods for which the indoor/outdoor ratios are calculated (e.g., over 1h, 8h and 24h averaging times).

2.5.3 Analysis of time-resolved environmental and pollutant concentration data

2.5.3.1 Screening of data impacted by activities inside the home

For multi-day monitoring periods, a screen was applied to the start of the time series data to avoid any biases from field technician impacts on indoor particle levels. Appendix plots thus display data minutely starting roughly 3-4 h after the field technician exited the test house. A varying delay was applied to the start of the running 24h averages, with the delay determined from a visual review of data. For each week of monitoring, we applied the same initial delay to all pollutant parameters. This screening was not applied to the highest daily 1h outdoor and indoor values because the short-term running averages were not as impacted by earlier activity in the homes.

Additional masking of 24h running average time series data was done on monitoring days when the house was accessed by a field technician. These included set-up of VOC samples on the days noted in Table 3.7 and a system check by the HVAC contractor on 19-Jun. Additional details are provided in the Appendix results for each system.

2.5.3.2 Calculation of 24h, 8h and 1h running averages

After screening the data as described in the preceding sub-section, we calculated running statistics (mean, median, standard deviation) from the 1-min data for each of the measured parameters (and 3 min data for BC). Running statistics were calculated for time windows of 1, 8, and 24 hours. When calculating summary statistics for a monitoring period, we did not use running 8h and 24h mean values until a sufficient amount of time had elapsed that these means were representative. This initial delay varied from a few hours to nearly 24h.

2.5.3.3 Selection of dividing time for statistics by day

Distinct 24h diurnal periods ("days") within a monitoring period were set by selecting a daily dividing time, with the intent that this would be at a time of low outdoor concentrations. The diurnal patterns varied seasonally, across weeks within a season and sometimes even across days within a monitoring period. A daily dividing time was selected for each multi-day monitoring period by visual review of the time series for all measured parameters. Summary statistics were then calculated for all data available during each specified day during the monitoring period. The dividing time for each period is specified at the front of the appendix that presents data from the period.

2.5.3.4 Identification of highest 1h outdoor and corresponding highest 1h indoor concentrations

We analyzed the effectiveness of each system at reducing exposures to short-term outdoor events by identifying the highest 1h mean outdoor concentration and the corresponding highest 1h indoor concentration during each diurnal period. Since indoor values will continue to rise after a peak passes outside, the corresponding peak may be offset by several hours. We wrote an algorithm that found the outdoor peak, and the highest indoor values up to 4 hours after the outdoor peak. This was done for each one of the parameters.

2.5.3.5 Calculation of indoor/outdoor ratios

The principle metric for determining the effectiveness of any system is looking at the ratio of the indoor to outdoor (IO) concentration values. Using the averaged values over a sufficiently wide period of time IO is interpreted as the exposure reduction by being indoors. We calculated IOs by using the running averages of the appropriate parameter.

2.5.4 Analysis of VOC and volatile carbonyl data

Indoor and outdoor concentrations of VOCs (including the three volatile carbonyls) in each 24-h sample were calculated as the average of all determinations for each system. In two cases (Systems G and D), the number of values included in the average was eight, corresponding to four sets of duplicate determinations. In the other two cases (Systems C and Reference), the number of values included in the average was four, corresponding to two sets of duplicate determinations. The experimental error reported in each case corresponds to the standard deviation of those determinations. In all cases, concentrations were calculated (and are reported) in units of microgram per cubic meter (μg m^{-3}).

In order to better quantify the effect of each system on indoor pollutant levels, two additional parameters were calculated:

The Indoor/Outdoor (IO) ratio for each particular sample, defined as the ratio of the time-averaged indoor concentration to the time averaged outdoor concentration for each pollutant determined for each system, as follows:

$$IO = \frac{\overline{C_{in,\,System\,C/D/G}}}{\overline{C_{out,\,System\,C/D/G}}} \tag{1}$$

The relative difference in differential concentrations (subtracting contributions from outdoor air) between each system and the reference system, *%ΔC,* is defined as

$$\%\Delta C = \frac{\varphi(\text{System C/D/G}) - \varphi(\text{Reference System})}{\varphi(\text{Reference System})} \times 100 \tag{2}$$

where

$$\phi(\text{System C/D/G}) = C(\text{indoors, System C/D/G}) - C(\text{outdoors, System C/D/G}) \tag{3}$$

and

$$\phi(\text{Reference}) = C(\text{indoors, Reference}) - C(\text{outdoors, Reference}) \tag{4}$$

2.5.5 Analysis of particle data from indoor source events

Time series of pollutant concentrations measured following cooking events were first analyzed to determine first order decay rates under relevant variations of system operation. Each 10-min interval of data from a single instrument was fitted to a first order (logarithmic) decay model (linear fit natural log of data). When the 10-min data collection period was interrupted by a change of state in the experiment (e.g. air handler turned on), shorter sections of data were fit.

The summary performance metric for the indoor source data was the relative change in the time-integrated concentration over the first hour following the peak indoor concentration after cooking. The time integrated concentration is the exposure that would occur for a household occupant; it was calculated as the integral of concentration × time. We then calculated the first order decay rate that produces the actual, observed ratio of concentration at 1 h over the peak concentration, for each measured parameter.

Additionally, we calculated the theoretical performance potential for each system with intermittent recirculation filtration. This potential is based on operating the system continuously during and after cooking. To get this number, we calculated the integral of the time series that results when the increased decay rate during system operation is applied to the entire hour.

For both summary metrics we compared the calculated exposures to the exposures for the Reference system without air handler operation.

2.5.6 Estimation of particle loss rates due to deposition, penetration and filtration

We analyzed time series data to determine size-resolved rate parameters for particle losses to indoor deposition, removal during outdoor air infiltration through the building shell, and in the forced air systems with varying filtration components. Relevant analyses were conducted for particles generated from the scripted cooking event and also for outdoor particles.

Time series of indoor concentrations following cooking were analyzed to estimate indoor deposition rates and removal rates in recirculating forced air systems. For the cooking data, we calculated the least squares linear fit to the natural logarithm of the indoor concentration time series for each particle size bin. This provides an estimate of the first order decay rate. Fits were calculated for each 15-min series of data from a single instrument because the small differences in instrument response were magnified during the period of rapid changes to the indoor particle concentrations during the post-cooking period. Decay due to deposition was calculated as the difference between the estimated decay rate and the decay of the conserved SF_6 tracer gas (which quantifies removal by air exchange) during the same period. To estimate performance of intermittently operating systems (D, E, and G) at removing particles, we calculated the difference between the first order decay determined during system operation and the decay rates (from deposition + air exchange) determined from fits to the data just before and just after the first period of system operation. For Systems D and G, we additionally accounted for the increased air exchange rate during system operation since these systems featured intermitted supply (D) or balanced (G) ventilation. For System F, which operated continuously, we started with the fitted decay rates for operation 45-60 min after the start of cooking, and subtracted both the air exchange rate determined for the System F cooking experiment and the estimates of particle deposition obtained during the same time interval from the Reference and Systems A and B.

The analysis for outdoor particles used the governing pollutant material balance of particles entering and leaving the inside of the house, provided below as Equation 5. The equation treats the house volume as perfectly well mixed and thus presents the material balance in terms of concentrations rather than mass (determined as concentration × volume). In the simplest conceptualization, the change in mass (concentration) inside the house (dC_{in}) is equal to what is internally generated plus what comes into the house from outside minus what leaves the house during a discrete time interval. Pollutants leave the house air through ventilation (at rate λ, h^{-1}), deposition to indoor surfaces (at rate κ, h^{-1}), and removal by mechanical systems including the FAU and ductwork and enhanced filtration components. Removal in mechanical systems is the product of air exchange rate through the component (λ_{mech}, h^{-1}), the removal efficiency (η_{filter}), and whether the system is operating (δ_{mech}). What comes in from outside is also subjected to losses as the particles penetrate through the building envelope; this is indicated as a penetration efficiency (P). We did not explicitly include phase changes such as evaporation of ammonium nitrate, or evaporation or condensation of organics and/or water vapor. While these processes may have a form that is not first order, directional impacts should be reflected in the fitted penetration efficiency (e.g., evaporation will be reflected in a lower penetration efficiency). The equation is applied across any pollutant species *i*. Our analysis considered each particle size bin as an independent species.

$$\frac{\mathrm{d}C_{i,in}}{\mathrm{d}t} = P_i \lambda C_{i,out} - (\lambda + \kappa_i + \delta_{mech}\lambda_{mech}\eta_{i,filter})C_{i,in} \tag{5}$$

For the Reference system, an approximation to the time-dependent material change from time *t-1* to time *t* can be written as:

$$C_{in,i}(t) = C_{in,i}(t-1) + P_i * \lambda * C_{out,i}(t) - C_{in,i}(t-1)\left(\kappa_i + \lambda_i + \eta_{filt,i}\lambda_{mech}\delta_{mech}\right) \tag{6}$$

The other systems have similar representations with additional terms for other components, e.g., supply air filters.

Time series data were fit to Equation 6 using the LMFIT Non-Linear Least Squares Minimization and Curve Fitting package for Python (Newville et al., 2014). In this package, each parameter can be fully free to settle on any value, pinned down to a specific value, or bound by a possible range of values.

We conducted two analyses to estimate parameters for outdoor particles. In the first analysis, we started with deposition rates determined from cooking experiments. Setting these parameters as fixed values, and using the measured air exchange rate, we fit Equation 6 to indoor and outdoor time series data during periods of no system operation to get penetration efficiency by particle size. With these fixed parameters for deposition and penetration, we fit Equation 6 to periods when the filtration components were operating to estimate the relevant system parameters. This analysis is described in more detail in the Results section.

In the second analysis, we fit Equation 6 to intervals of outdoor and indoor time series data to simultaneously determine deposition and penetration. For this analysis, we used data from the Reference system at times when the FAU was not operating, i.e. for $\delta_{mech} = 0$. The air exchange rate was set at the value measured during that time interval and the values for penetration and deposition were allowed to vary freely. Recognizing that the composition of $PM_{2.5}$ and even particles within a given size bin can vary seasonally – with potential effects on the apparent

penetration efficiency – we conducted analyses using both summer and winter data. For summer, we fit the equation to data from six discrete intervals, typically from midnight to noon, during the two periods of Reference system monitoring. All were periods with no FAU / air conditioner operation. For the winter, we fit the equation to the entire period of available data, with fitted values determined for each 8h interval.

2.6 QUALITY ASSURANCE

2.6.1 System design elements relevant to quality assurance

There were several key elements of system design that promoted data quality. The design of having the same instruments measuring indoors and outdoors greatly reduced the potential for instrument drift to bias comparisons of indoor and outdoor time series. The dual sets of instruments enabled ongoing review of instrument response, with the assumption that performance was acceptable and reasonably in line with the prior calibration as long as the paired instruments remained closely aligned. Overlap in some of the particle instrumentation provided additional reference data. For example, if the two CPC 3787 units started to diverge in their response, the data from the CPC 3781 units provided relevant data to assess which instrument was more likely to be reporting accurately. When the paired instruments operated as designed and provided data in alignment, both the indoor and outdoor time series were measured at 1 min resolution for all parameters other than black carbon, which was at 4 min resolution. And very importantly to operational continuity, having two of each instrument meant that data collection could continue if one instrument failed.

2.6.2 Instrument calibration and operational quality assurance

As described previously, all particle instrumentation and the ozone analyzers were sent to the manufacturers to be calibrated prior to being deployed in our study. NO_X analyzers were zero and span-calibrated at 480 ppb just prior to the start of summer monitoring period. The analyzer used to measure SF_6 was span-checked prior to deployment and at several times throughout each season, and zero-checked during most system changes. Span values were checked using dilute mixtures from certified cylinders brought to the site in Tedlar bags. Performance of particle instruments was assessed by checking various diagnostics suggested in instrument manuals and by manufacturer service technicians.

2.6.3 Visual review of data

We developed a set of scripts for quickly downloading the data and plotting the raw data. These plots were grouped by instrument, and included both manifolds. This allowed us to review the data in near real-time and we remotely checked the data collected every 1-2 d during each monitoring event. This coarse review aimed to identify problematic conditions such as equipment malfunctions.

An extensive visual review of all data was undertaken using the plots presented in the first two groups of appendices. We visually checked the time series for each parameter of each system for the following potential issues, among others:

- Any short outdoor peaks not followed by an indoor peak
- Adequate delay of data analysis at beginning of monitoring period

- Peaks present in one channel but not nearby channels
- Unexplained indoor peaks or indoor peaks not associated with outdoor peaks.

2.6.4 Data analysis for quality assurance

We created scripts to download and assemble data into specific instrument files. These scripts would be applied at the conclusion of each monitoring period. These files included time series for each instrument that featured intermittent indoor and outdoor profiles. As a part of the instrument inter-comparison step described in the data analysis section, we would produce a set of plots showing the time series of the individual instrument adjustments. Gradual trends indicate an instrument that needs maintenance; sudden and large changes often indicate the fitting routine had a problem with the comparison through a transitional period. These short duration issues were typically resolved by an adjustment of the LOESS fitting parameters for the event.

During this stage of inter-comparison we would notice single instruments that abnormally drifted away from the other (or dropped out completely). This necessitated using a single instrument for at least a portion of the week, if not the entire week.

2.6.5 Replication of experimental conditions

Systems were operated to assess performance for outdoor particles over multiple days, up to roughly a week, during summer and fall/winter seasons. The only true replicate of a period of operation was for the Reference system, which was operated over two periods in summer. However, if one recognizes that an estimate of indoor/outdoor performance can be calculated for each discrete diurnal period of operation, then the system/season monitoring periods contain from 3 to 7 replicates each. Tables in appendices provide results by diurnal period.

The evaluation of system performance for indoor-generated particles occurred on only occasion for most systems, with a replicate occurring only for the Reference system.

The VOC performance assessment included collection of replicate samples during each day of measurements and either 2 or 4 days of measurements for each system that was evaluated.

2.7 ESTIMATION OF ANNUAL ENERGY USE

Because each system was only operated for about two weeks: one in the summer and one on the winter, it was not possible to measure annual energy use. Due to changes in weather conditions between weeks it was also not possible to obtain relevant estimates of relative energy consumption from the field data. To estimate annual energy use, we used simulations whose inputs, such as fan power requirements for the ventilation systems, were informed by the house used in this study and previous investigations of ventilation system related energy use.

The use of enhanced pollutant removal equipment in a home can increase energy consumption. The incremental energy use ranges from close to zero for a low pressure drop filter on a supply ventilation system or on an FAU without a runtime controller, to very large energy use for systems that operate the FAU for many hours beyond those needed only for heating and cooling. The extra energy consumption of various enhanced pollutant removal systems was estimated by considering the following elements: (1) the energy load associated with operating the FAU for more hours for enhanced pollutant removal and/or as part of a supply or balanced ventilation system; (2) increased fan power required to overcome increased flow resistance of

inline higher efficiency filters, (3) other energy required to operate air cleaning devices, including the ESP of System B and the bypass HEPA + Activated Carbon unit of System G.

To estimate the incremental operation of a FAU blower for pollutant removal or ventilation, we must first determine the baseline run-time for heating and cooling. To estimate incremental run-times, we analyzed data from simulations that were constructed for a study of the impacts of adding ventilation requirements to California's Title 24 building code (Walker et al., 2005; Walker and Sherman, 2006). The simulations – conducted with the REGCAP heat transfer, airflow, and moisture simulation model – provide minute-by-min accounting of many variables including heating and cooling system operation (ibid) Simulations were conducted for 2005 Title 24 prototype homes including a 1761 ft^2 home under various ventilation set-ups in several California climate zones. Although that house is larger than the test house, the runtime operation should be similar since the heating and cooling systems are sized to the demand. The simulated home included a typical efficiency (2 cfm/W) central air handler / FAU blower, and the HVAC fan power for each house was set according to industry standards for equipment sizing that is based on the climate. Simulations included the effect of additional supply fan and central blower fan heat on heating and cooling loads. The simulations were conducted for California climate zones 3, 10, 13, 15 and 16; these were selected as representing the range of climate zones where either central fan integrated supply (CFIS) or exhaust ventilation would be used. California's climate zones are shown in Figure 2.19. For the current assessment, we analyzed simulation results for a CFIS system that operates for a minimum of 20 min of every hour; this is often called "20/60 operation." Model output from these simulations includes FAU operating times attributed to heating, cooling and ventilating.

Climate Zone	City
1	Arcata
2	Santa Rosa
3	Oakland
4	Sunnyvale
5	Santa Maria
6	Los Angeles
7	San Diego
8	El Toro
9	Pasadena
10	Riverside
11	Red Bluff
12	Sacramento
13	Fresno
14	China Lake
15	El Centro
16	Mt. Shasta

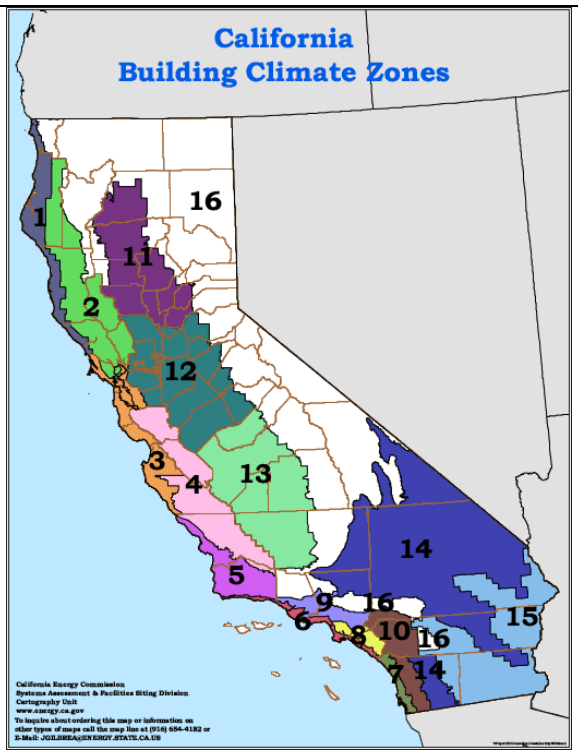

Figure 2.19. California climate zone map.

To estimate the incremental hours for 20/60 operation, we looked at the operating times for the reference system that has no additional central forced air system (CFA) runtime. Table 2.6 summarizes these results and converts the number of minutes of annual operating time into hours. The "Additional runtime CFIS" values were calculated by adding the difference between "reference heating + cooling" and "CFIS heating + cooling" to the CFIS ventilation values. This accounts for the extra heating and cooling time attributed to the additional ventilation loads of the CFIS ventilation system compared to the reference so that the additional runtime is now relative to the reference case. This additional runtime is what we need to calculate the additional FAU blower energy. The variability in this additional runtime across climate zones is quite small (standard deviation less than 3%) so it is reasonable to use an average value of 2400 hours per year in our calculation of additional central fan operation when a fan controller is used for 20/60 operation.

Table 2.6. Simulation based estimates of annual operating hours for central forced air system in typical new California homes in various California climate zones.[1]

Climate Zone	Reference heating + cooling hours	CFIS heating + cooling hours	CFIS ventilation, hours	Additional runtime of CFIS, hours	Additional runtime + heat + cool, hours
3	606	616	2440	2450	3056
10	709	752	2439	2482	3191
13	882	928	2351	2397	3278
15	988	1046	2287	2345	3332
16	870	887	2300	2318	3187
Mean	**811**	**846**	**2363**	**2398**	**3209**

[1] From Walker and Sherman (2006).

The values shown in column with heading "Additional runtime + heat + cool" include ALL hours of operation, i.e. including the hours for heating and cooling and the additional 20/60 operation. The standard deviation is also quite small (just over 3%) so it is reasonable to use an average value of 3200 hours to calculate the additional energy requirements for enhanced pollutant removal systems that operate whenever the CFA operates.

It is interesting to note that the large range in heating and cooling operating hours from 616 to 1046 did not result in a similarly large range of additional runtime. This is primarily due to how the cycling characteristics of the heating and cooling systems interact with the 20/60 timing. For a system that goes from 20 to 30 min of operation in an hour the time for heating (or cooling) increases by 50% but there would be no change to the 20/60 operation as in both cases the criterion for operating a minimum of 20 min out of the hour is met. This result is what allows us to use a single representative value for the additional runtime in the current study.

Relevant to the discussion below, we note that operating the FAU continuously for enhanced pollutant removal requires an additional 7949 hours of operation (8760 hours - 811 hours for reference heating + cooling).

The discussion below refers to power draws and airflows measured for system components installed it the test house and report in Table 2.3.

The estimated energy consumption for additional hours of FAU operation was calculated as the product of the incremental run time and 600 W operating power. This is approximately the measured baseline power consumption of the air handler in the test house and corresponds to 0.5 W/cfm, a commonly used estimate of the efficacy for a conventional permanent split capacitor (PSC) FAU motor.

We also calculated both baseline and incremental power consumption for an FAU with an energy efficient, brushless permanent magnet (BPM) motor. Since these FAUs have higher cfm/W at low air flows (and corresponding low system static pressures), it makes more sense to operate them continuously at lower speed than intermittently at higher speed, as we did for the mini-split in System F, which featured an ECM. When calculating power for the FAU with BPM, we assumed for simplicity that the operating schedule and airflow did not change for the reference system. And we assumed a fan efficacy of 0.375 W/cfm, corresponding to 450 W for all heating and cooling operation. During continuous operation at 400 cfm (1/3 of the intermittent airflow and 188 L/s), we assumed the FAU had the same efficacy as measured for the mini-split in System F, i.e. 0.175 W/cfm, and a power draw of 70 W. This power draw was

assumed to occur for 7949 hours per year. For System G, we considered a hybrid deployment with the BPM motor operating at the higher flow rate on a fan cycler. We did this to keep the energy use estimates in line with the pollutant removal performance. If the System G bypass were operated continuously it would have higher energy consumption but also better pollutant removal performance than measured and reported for this study.

The increase in fan power to overcome the pressure drop of higher performance filters was treated as follows. For the PSC motor, we assumed no change in power with a higher performance filter. In fact, there may be a small decrease in power as the higher pressure drop leads to lower airflows; but this effect was not included in this calculation. For the BPM motor, we estimated increases in power proportional to those reported by Walker and Lutz (2005). For the MERV16 filter of System D, we assumed an 8W increase (11.4% increase) and for MERV13 filter of System E, we assumed a 4W increase (5.7%) increase.

We accounted for filtration energy costs on the supply ventilation systems by assuming that, in the absence of enhanced filtration, these fans could achieve the same fan efficacy as the exhaust ventilation fan: 0.11 W/cfm. Thus, for the supply systems with MERV13 filtration, the incremental energy attributed to filtration was 2.2 W (0.17 - 0.11 = 0.06 W/cfm * 17 cfm) for the continuous operation and 6.7 W for intermittent operation. We note here that we used the supply fan efficacy measured for System D because the lower flow for Systems A and B was obtained by partially closing a damper to increase duct pressure. The energy cost for MERV16 filtration on the blended (higher airflow) System C was 22.8W (0.35 - 0.11 = 0.24 W/cfm * 95 cfm).

The energy costs of operating the ESP and HEPA bypass were calculated from the component power consumption data presented in Table 2.3.

3 RESULTS

3.1 PERFORMANCE FOR OUTDOOR PARTICLES

This section presents a summary of performance results for outdoor particles. The section includes examples series of appendix figures and tables that present complete results for each multi-day period of system operation. There is one appendix dedicated to each period. There was at least one period of operation for each system during cool to cold (fall/winter or FW) and warm to hot (summer or SU) seasons. Appendices are identified by season (FW or SU), ordered and numbered in chronological order within each season, and the names include the system identifier (A, B, C, etc.). The reference system is labeled as “R” and the portable air cleaners labeled as “PA” when operated with the automatic setting and “PM” when operated on medium setting. Periods when filters for systems A and E were taped to reduce or eliminate bypass are indicated with an extra “X”, as “AX” and “EX”. Table 3.1 lists the periods of operation during fall/winter and Table 3.2 lists the periods of operation for each system during summer.

Table 3.1. Fall and winter (FW) periods of system performance assessment for outdoor particles.

Dates (2014)	System	Appendix Name
2/21–2/27	Ref: Continuous exhaust ventilation; no enhanced filtration	FW-1-R
2/27–3/6	C: Continuous blended supply w/MERV16	FW-2-C
10/28–11/4	E: Continuous exhaust ventilation; MERV13 on FAU, 20/60 fan timer	FW-3-E
11/4–11/10	F: Continuous exhaust ventilation; Cont. MERV13 on mini-split fan unit	FW-4-F
11/11–11/17	A: Continuous supply w/MERV13	FW-5-A
11/18–11/25	B: Continuous supply w/MERV13; ESP on FAU, thermostat control.	FW-6-B
11/25–12/2	D: Supply ventilation + MERV16 on FAU, 20/60 fan timer	FW-7-D
12/2–12/8	G: Supply ventilation + HEPA bypass on FAU, 20/60 fan timer	FW-8-G
12/8–12/12	Portable air filtration unit set to Auto operation mode	FW-9-PA
12/12–12/15	Portable air filtration unit set to Medium speed operation mode	FW-10-PM
12/16–12/19	E: Continuous exhaust ventilation; MERV13 on FAU, 20/60 fan timer	FW-11-EX
12/19–12/23	A: Continuous supply w/MERV13	FW-12-AX

Table 3.2. Summer (SU) periods of system performance assessment for outdoor particles.

Dates (2014)	System	Appendix Name
6/6–6/12	E: Continuous exhaust ventilation; MERV13 on FAU, 20/60 fan timer	SU-1-E
6/12–6/17	A: Continuous supply w/MERV13	SU-2-A
6/18–6/22	F: Continuous exhaust ventilation; Cont. MERV13 on mini-split fan unit	SU-3-F
6/25–7/2	G: Supply ventilation + HEPA bypass on FAU, 20/60 fan timer	SU-4-G
7/2–7/9	Ref: Continuous exhaust ventilation; no enhanced filtration	SU-5-R
7/9–7/16	D: Supply ventilation + MERV16 on FAU, 20/60 fan timer	SU-6-D
7/16–7/23	Ref: Continuous exhaust ventilation; no enhanced filtration	SU-7-R
7/23–7/30	C: Continuous blended supply w/MERV16	SU-8-C
7/30–8/6	B: Continuous supply w/MERV13; ESP on FAU, thermostat control.	SU-9-B

3.1.1 Example results for outdoor particles: Reference system during summer

As an example of the material contained in appendices, and for the purposes of elucidating some common features of the data, this sub-section presents selected results from Appendix SU-6-D, pertaining to the Reference system operated over a roughly weeklong period starting on July 16, 2014 (7/16).

The first plot for each series presents the status of all relevant mechanical systems throughout the test period. Figure 3.1 shows that for the Reference system, the bathroom exhaust fan operated continuously to provide the general mechanical ventilation rate that has been required by California's Title 24 building code since 2008. The air conditioner (AC) and airflow through the forced air unit (FAU) operated in synch for this system; but they are shown separately because some systems operate the FAU on a regular schedule for filtration. The plot shows nearly continuous AC operation starting in the early afternoon of most days and cycling with decreasing frequency into the night.

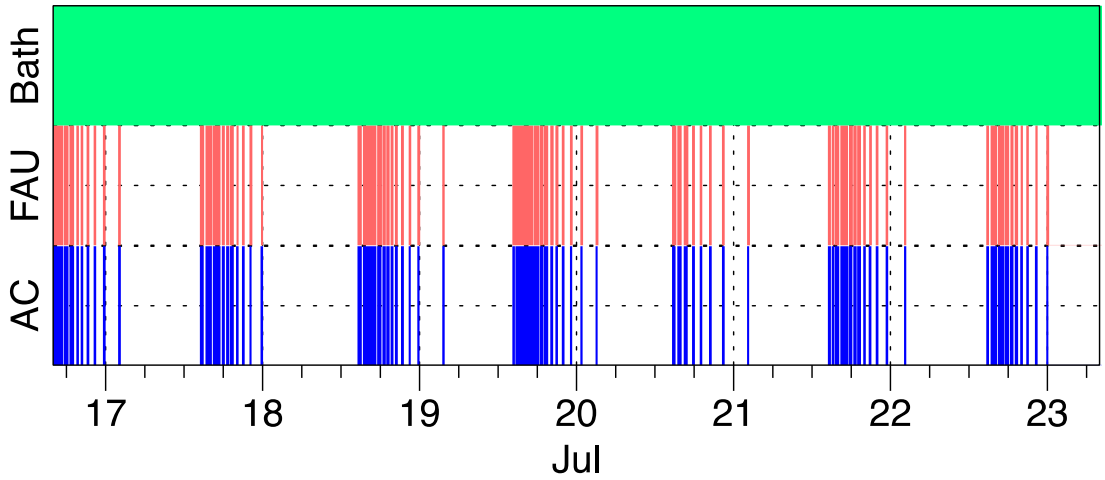

Figure 3.1. Operation of bath exhaust fan (low speed for continuous ventilation), forced air unit (FAU), and central air-conditioning (AC) during Reference System operation July 16-22, 2014. The filled areas indicate periods of operation.

The next plot for each system, presented here as Figure 3.2, provides outdoor and indoor environmental parameters and the time-resolved air exchange rate calculated from continuous measurements of the constantly released tracer gas. The top panel shows the nearly constant indoor temperature and diurnally varying outdoor temperature. The second panel shows that, for this operational period, the wind direction was consistently from the south (180º from North) and wind speeds were generally within the range of 1–6 m s^{-1} with hourly averages mostly within the range of 2–5 m s^{-1}. The air exchange rate varied from early morning lows of roughly 0.22–0.23 h^{-1} to late afternoon highs of 0.30–0.34 h^{-1}.

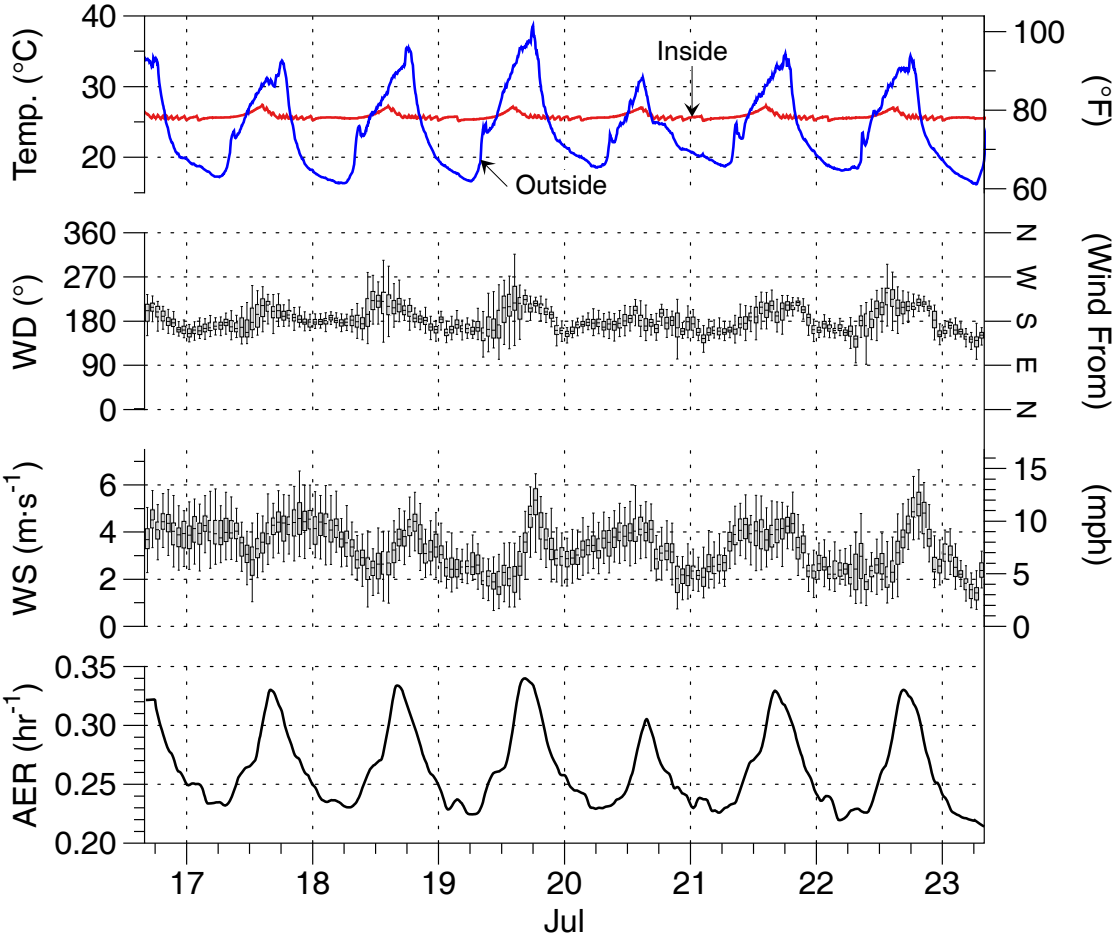

Figure 3.2. Environmental parameters during operation of Reference System, July 16-22, 2014. From top to bottom: indoor and outdoor temperatures, wind direction (WD) in units of degrees from North, wind speed (WS), and air exchange rate (AER). For WD and WS, the box for each hour shows the 25th, 50th and 75th percentiles of the measured values and whiskers extend 1.5X the interquartile range (75th–25th percentile values) above the 75th and below the 25th percentile values.

The next series of plots present examples of processed data for various particle size fractions, $PM_{2.5}$ mass, and black carbon. The first example, Figure 3.3, presents the number concentration of particles (PN) with aerodynamic diameters from 6 nm to 2.5 µm, as measured with the CPC 3787 units. The top and bottom of the grey band in the lower portion of the plot are the LOESS-smoothed, 1-min resolution time-series for outdoor and indoor concentrations. Also shown are time series with 1h and 24h time averaging (solid for outdoors, dashed for indoors), and the highest outdoor 1h and corresponding highest indoor 1h average during each day (triangles). The top section of the of plot shows the ratio of indoor to outdoor (IO) running 24h averages and the ratios of the highest 1h indoor to corresponding highest 1h outdoor concentrations each day. During this period, outdoor PN concentrations followed a consistent diurnal trend, with troughs in the early morning (generally between midnight and 6 am) and peaks in the late morning. The indoor time series followed the outdoor trend with a delay of a few hours, and at a substantially lower level owing to particle losses during air infiltration through the building shell and indoor deposition. The top of the figure shows that the 24h IO ratio was in the range of 0.10–0.15 throughout the period, and the IO ratios of the highest daily 1h indoor and outdoor concentrations (inverted triangles) were in the range of 0.02–0.14.

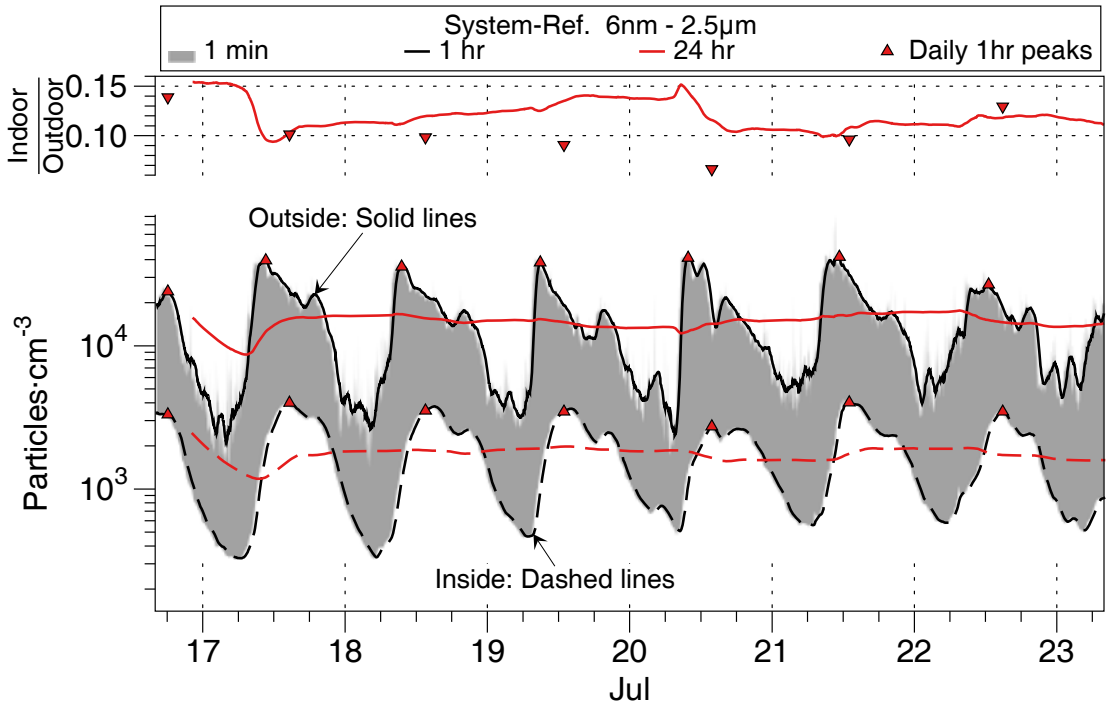

Figure 3.3. Number concentrations of 6 nm to 2.5 µm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014.

Figure 3.4 presents results for particles from 100 nm to 2.5 µm, as measured by the two CPC 3781 units with size selective inlets. Results in this figure and all subsequent pollutant time series are presented with the same format as described above for Figure 3.3. Particles larger than 100 nm followed the same diurnal pattern as those larger than 6 nm, but with substantially lower concentrations. IO ratios for 100 nm – 2.5 µm particles were substantially higher than those for 6 nm – 2.5 µm particles.

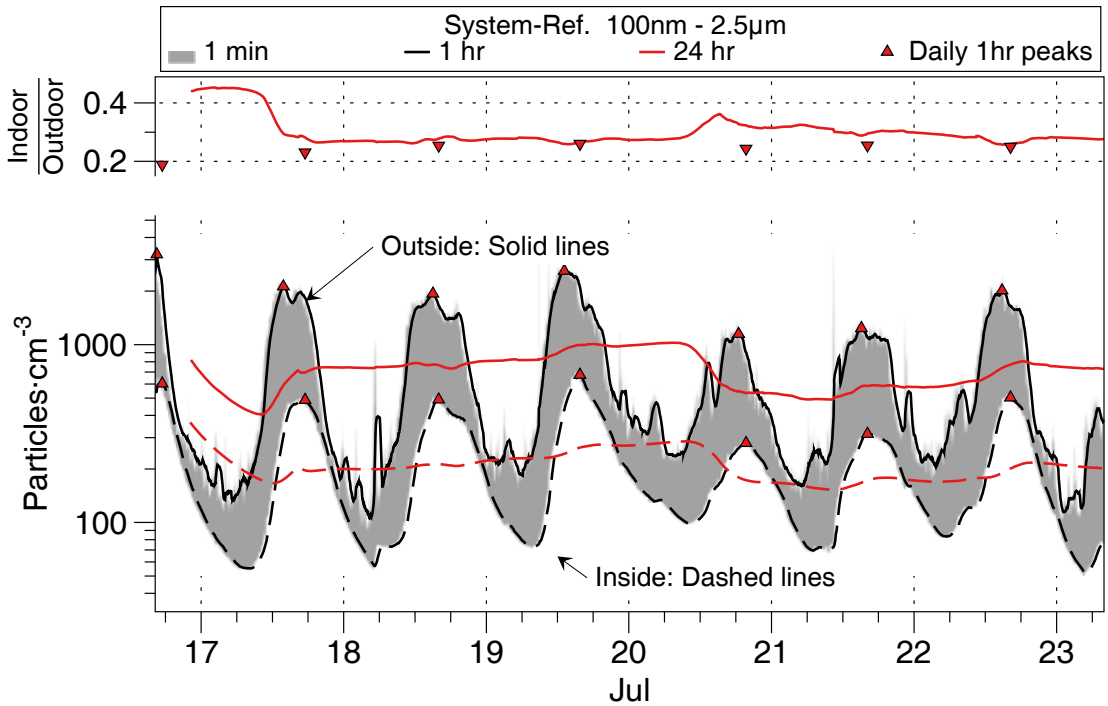

Figure 3.4. Number concentrations of 100 nm to 2.5 µm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014.

The next example, Figure 3.5, presents results for ultrafine particle number concentrations (UFP, 6–100 nm), obtained by subtracting the time series for 100 nm – 2.5 µm particles (measured by CPC 3781) from the time series for 6 nm – 2.5 µm particles (measured by CPC 3787). Comparing this figure to the prior figure indicates that most of the particles were in the ultrafine mode. IO ratios for this parameter were similar to those calculated for the all particles in the range of 6 nm – 2.5 µm.

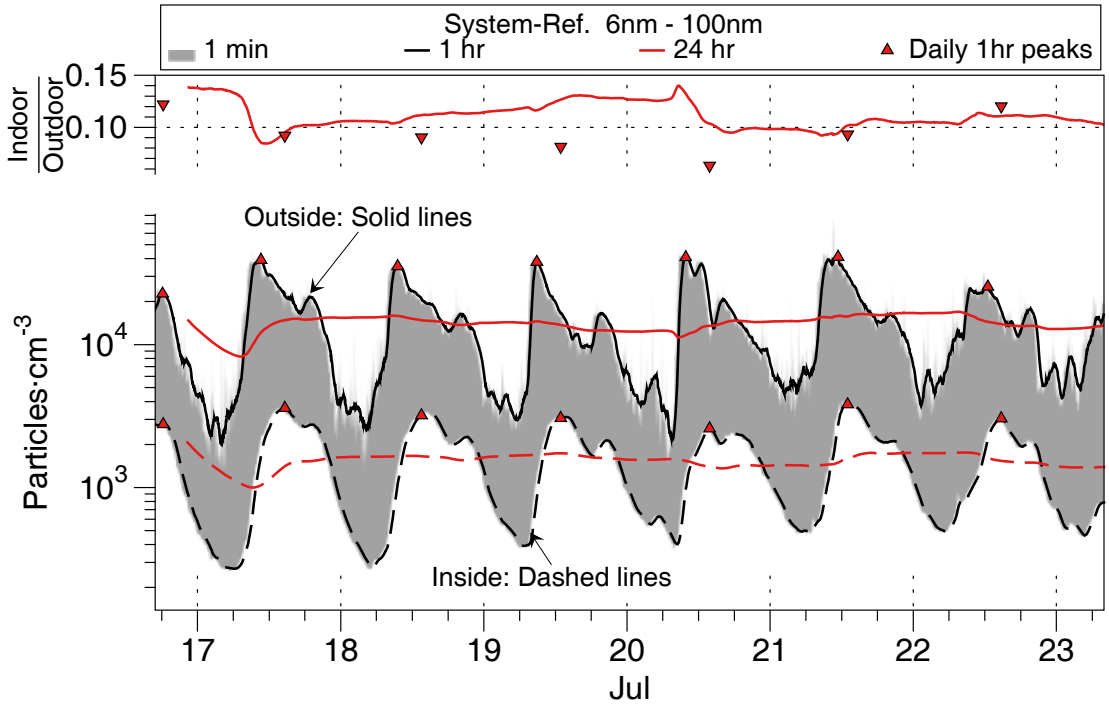

Figure 3.5. Number concentrations of 6–100 nm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014.

Figure 3.6 through Figure 3.8 present particle number concentrations in ranges derived from three of the channels of the MetOne 637 optical particle counter: 0.3–0.4, 0.5–0.7, and 1.0–2.5 µm diameter particles. The sixth channel of this instrument was set to measure particles larger than 2.5 µm as confirmation that the size-selective inlet was performing as designed (which it was). Looking across these plots shows a trend of decreasing 24h IO ratios as the particle size increases. The higher IO ratios of the 0.3–0.5 µm particles reflect lower loss rates (during penetration and from deposition) for these particles. The plots show a large magnitude, short duration event of high outdoor particle concentrations outside the home on the morning of July 18, with corresponding but dampened increase in indoor particles shortly after. The event produced daily highest 1h IO ratios much lower than the 1h IO ratios for other days. A smaller, but similarly timed event occurred for 0.5–2.5 µm particles on the following day and smaller events were observed late at night on July 19. Another feature of interest during this period is evident in the time series for 1.0–2.5 µm particles. On the mornings of July 21 and July 22, a researcher entered the home to change VOC samples. This activity produced an increase in the indoor concentrations of these large particles without a coincident increase in outdoor concentrations or smaller particles indoors. Since the resulting increase in the 24h average IO ratio is an artifact of the researcher activity, the 24h average data from this period were not used to calculate an average 24h IO ratio for this particle metric for this system.

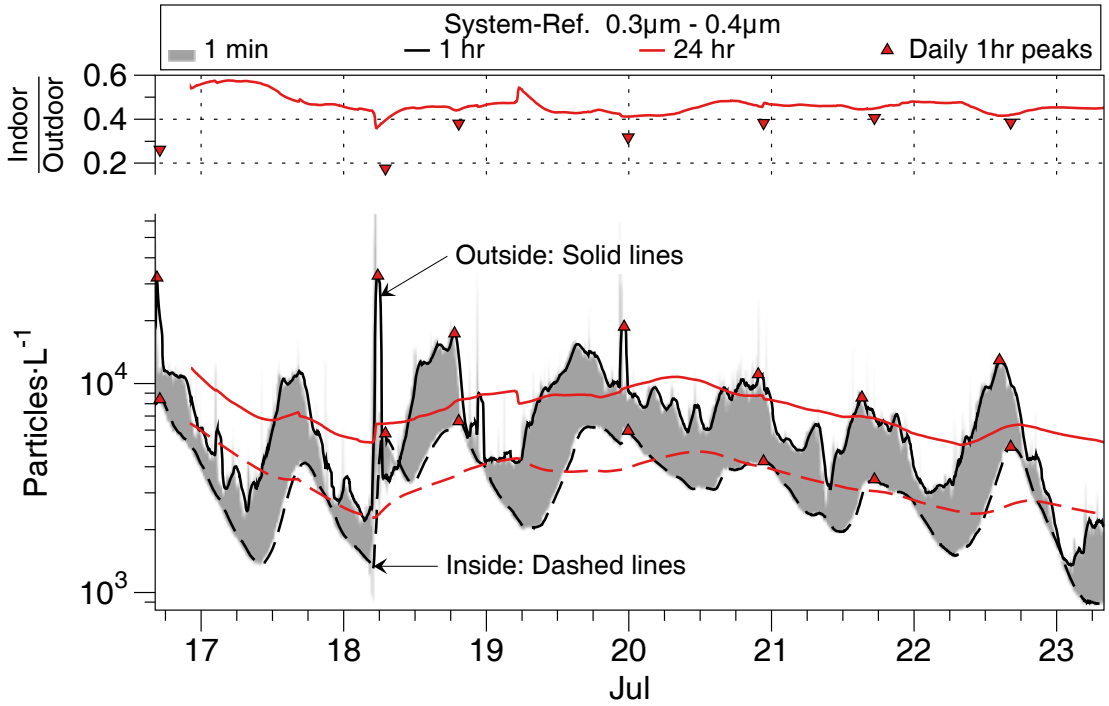

Figure 3.6. Number concentrations of 0.3–0.4 µm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014.

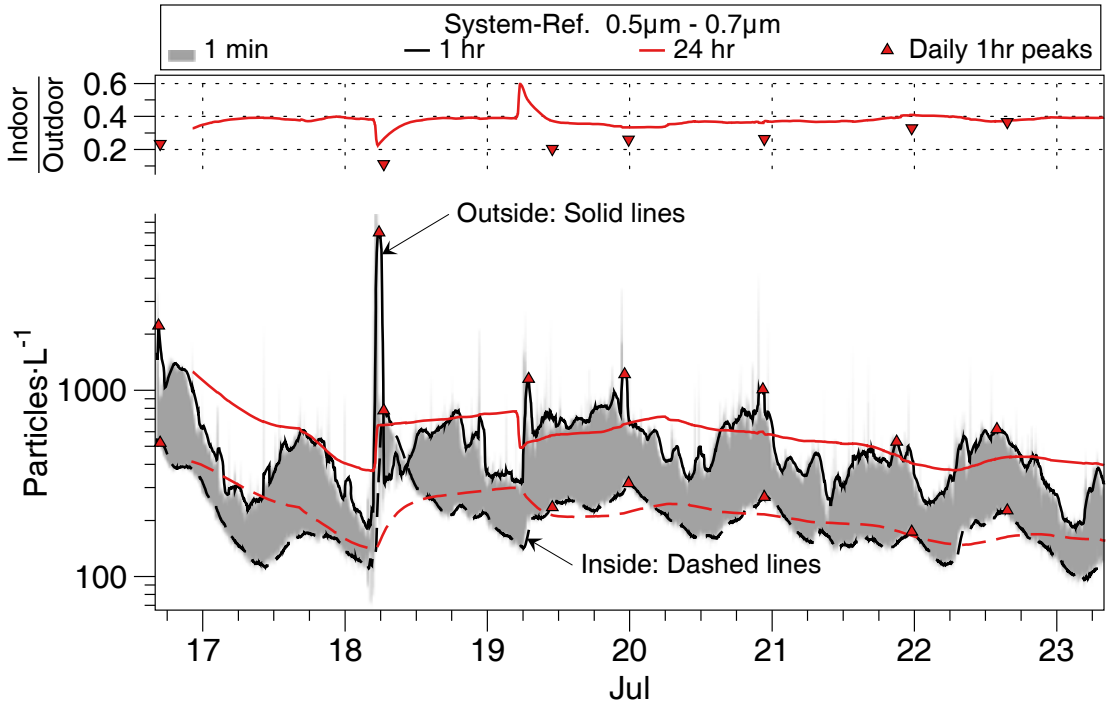

Figure 3.7. Number concentrations of 0.5–0.7 µm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014.

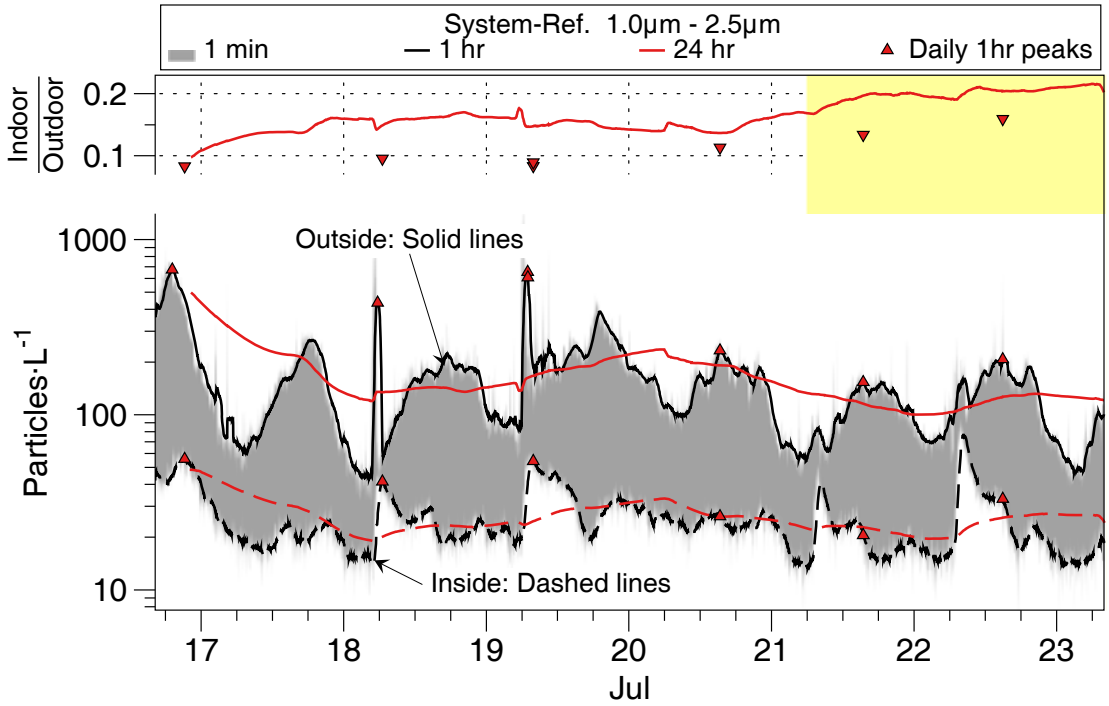

Figure 3.8. Number concentrations of 1.0–2.5 µm diameter particles measured outdoors and indoors during operation of Reference System, July 16-22, 2014.
Shaded area not used in analyses because researcher was present in the home in the morning of both days.

Figure 3.9 presents the black carbon (BC) concentrations as measured by the aethalometers. The mean 24h IO ratio for BC was similar to the same metric for the 0.3–0.4 μm particles. The presence of the sharp spike in the BC signal on the morning of July 18 suggests diesel particulate matter as a possible source of the spike.

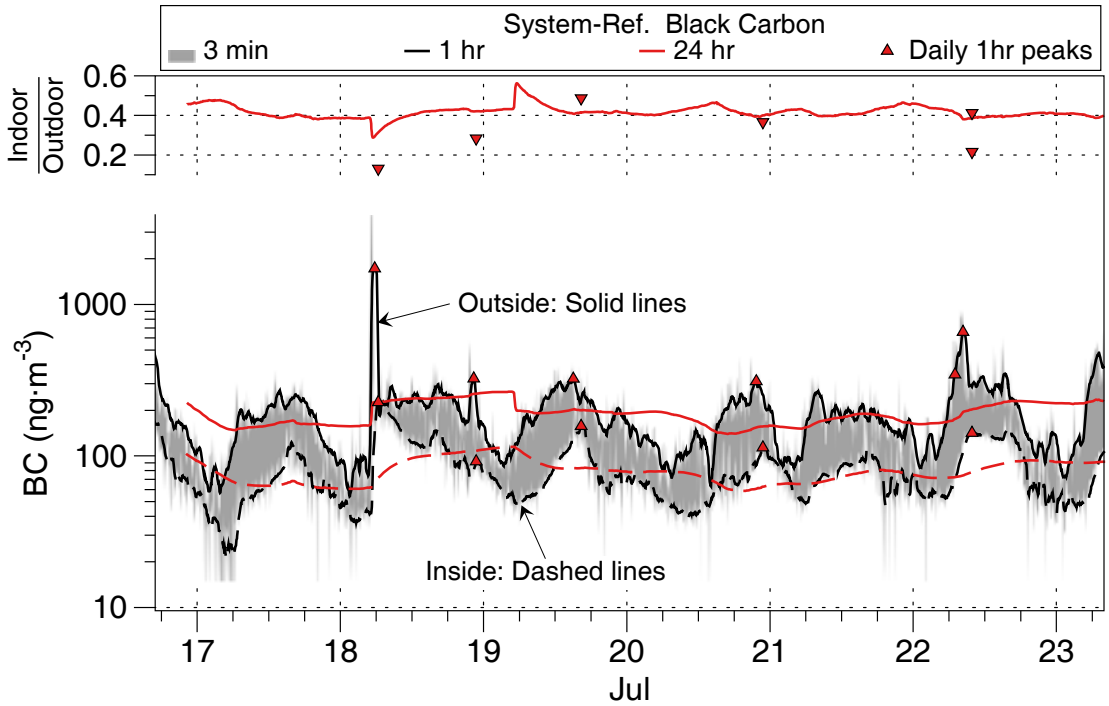

Figure 3.9. Black carbon concentrations measured outdoors and indoors during operation of Reference System, July 16-22, 2014.

Figure 3.10 presents an estimate of $PM_{2.5}$ concentrations from measurements of the DustTrak II 8530. A spike in outdoor concentration during the morning of July 18, consistent with the observed spikes in particles larger than 0.3 μm diameter and in BC, indicates mass concentrations more than 5x the observed increase in BC. The 1-min data in grey show the imprecision of individual DustTrak measurements at the relatively low mass values seen during this period, especially indoors. The minimum quantitation limit for a 1h average of DustTrak 1-min readings has been reported to be 4 μg m^{-3} (Wallace et al., 2011). And the DustTrak has a resolution of 0.001 mg m^{-3}, which translates to a lowest reported value of 1 μg m^{-3} for any concentration above 0. With many outdoor concentrations and all indoor concentrations appearing below the estimated QL, the DustTrak results should be regarded as only semi-quantitative during this period. DustTrak sensitivity was an issue for many monitoring periods, and especially limiting for quantifying performance of systems that drove indoor particle concentrations to very low levels.

Figure 3.11 presents estimated $PM_{2.5}$ mass calculated from particle number concentrations. These time series are much smoother than the DustTrak owing to the greater sensitivity of the particle counters at low concentrations.

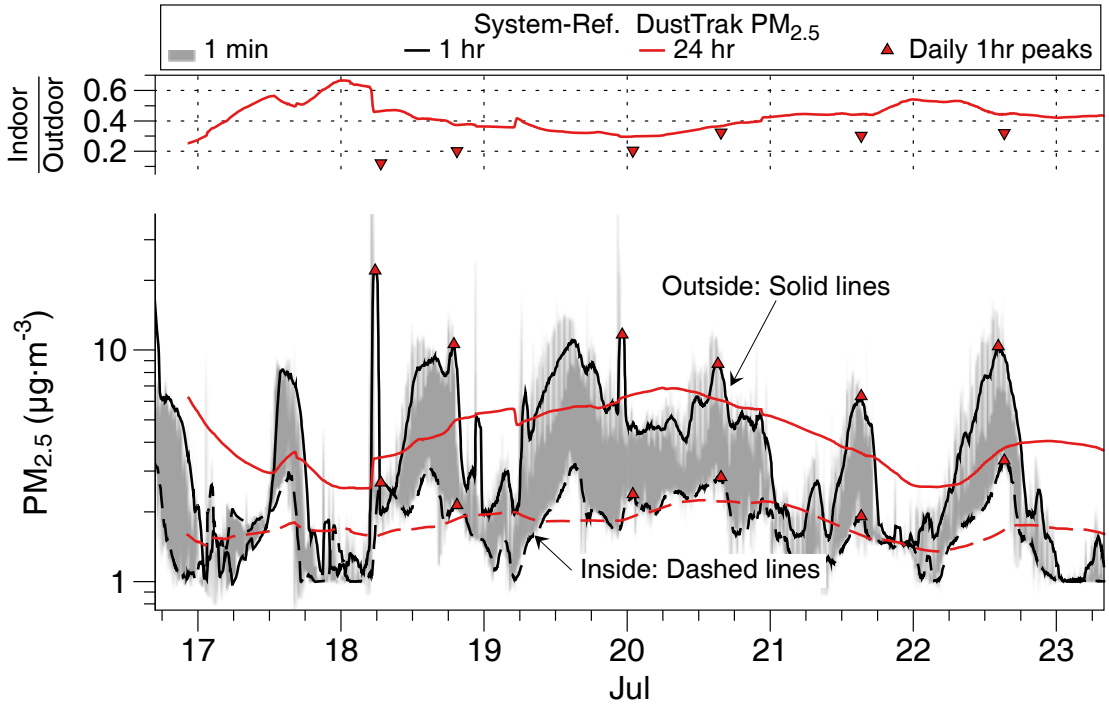

Figure 3.10. $PM_{2.5}$ reported by TSI DustTrak II 8530 measurements outdoors and indoors during operation of Reference System, July 16-22, 2014.

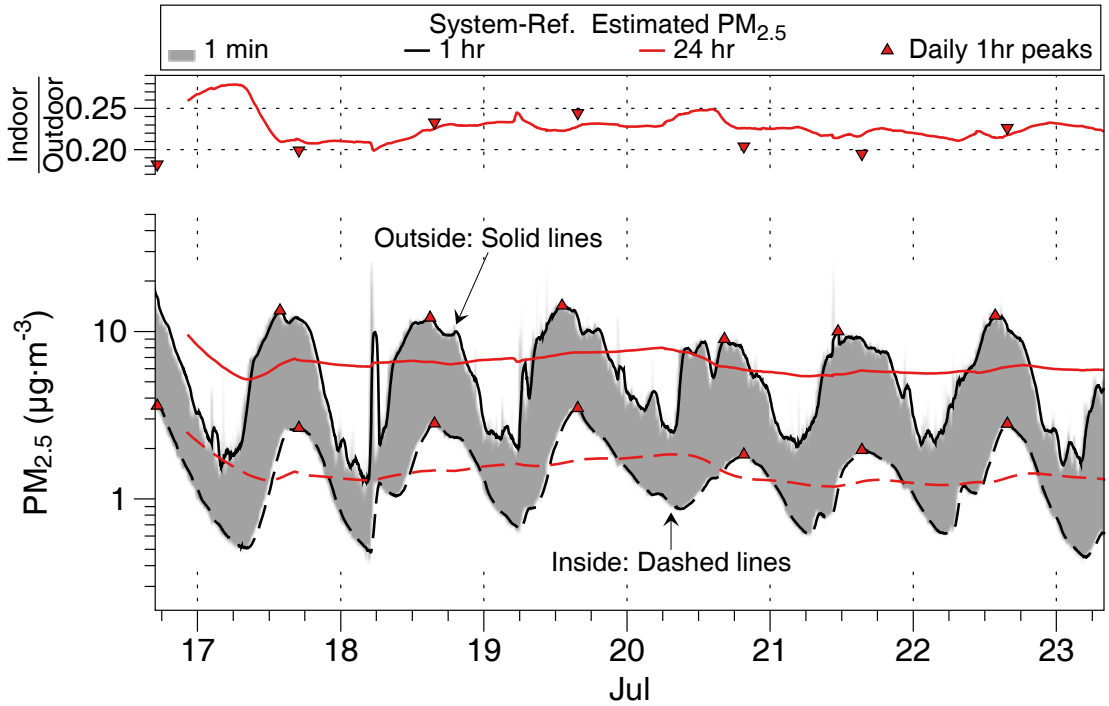

Figure 3.11. Estimated $PM_{2.5}$ calculated from size-resolved particle number concentrations measured by MetOne and CPC during operation of Reference System, July 16-22, 2014.

Table 3.3 presents an example of the tabular results presented for each measured parameter, in each appendix. Numerical results are presented by day, with days separated according to the diurnal pattern extant during the monitoring period. The mean value of 24h average statistics may not precisely equal the mean across all measured hours because some days have fewer than 24 hourly averages but received equal weighting (for simplicity) in the period averages presented in these tables. Table 3.3 presents results for PN from 6 nm to 2.5 μm. The alignment between the daily highest outdoor and indoor 1h average concentrations was imperfect, resulting in a variable time delay between the two measures.

Table 3.3. Example of summary results provided in appendices for each parameter each measured parameter for each multi-day period of monitoring. This table presents results for the number concentration of particles from 6 nm to 2.5 μm measured during operation of the Reference System, July 16-22, 2014.

Parameter	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Mean[1]	SD[1]
Outdoor mean	1.1E+04	1.6E+04	1.5E+04	1.3E+04	1.5E+04	1.7E+04	1.5E+04	1.9E+03
Outdoor SD	7.7E+03	1.2E+04	9.6E+03	9.2E+03	1.1E+04	1.2E+04	1.0E+04	1.5E+03
Indoor mean	1.7E+03	1.8E+03	1.9E+03	1.8E+03	1.6E+03	1.9E+03	1.8E+03	1.0E+02
Indoor SD	1.1E+03	1.3E+03	1.2E+03	1.1E+03	7.8E+02	1.2E+03	1.1E+03	1.6E+02
In/Out mean	**0.15**	**0.12**	**0.12**	**0.13**	**0.12**	**0.11**	**0.13**	**0.01**
High 8h Out	2.3E+04	3.0E+04	2.6E+04	2.3E+04	2.8E+04	3.1E+04	2.7E+04	3.2E+03
High 8h In	3.3E+03	3.4E+03	3.1E+03	3.0E+03	2.5E+03	3.3E+03	3.1E+03	3.1E+02
High 8h I/O	**0.15**	**0.12**	**0.12**	**0.13**	**0.09**	**0.11**	**0.12**	**0.02**
High 1h Out	2.4E+04	3.9E+04	3.6E+04	3.8E+04	4.1E+04	4.2E+04	3.7E+04	6.1E+03
High 1h In	3.3E+03	3.4E+03	3.1E+03	3.0E+03	2.5E+03	3.3E+03	3.5E+03	4.4E+02
High 1h I/O	**0.14**	**0.10**	**0.10**	**0.09**	**0.07**	**0.10**	**0.10**	**0.02**
Time of high 1h Outdoor	7/16 18:07	7/17 10:38	7/18 9:33	7/19 8:54	7/20 9:50	7/21 11:22		
Time of high 1h Indoor[2]	7/16 18:07	7/17 14:38	7/18 13:33	7/19 12:54	7/20 13:50	7/21 13:00		

[1] Refer to notes at beginning of appendix for start time on Day 1 and the time used to divide days. First and last days have <24h. Mean and SD across all days shown. [2]Occurring within 4h of highest 1h outdoor concentration.

3.1.2 Effectiveness of systems at reducing indoor concentrations of outdoor particles

This sub-section presents summary results for the effectiveness of each system at reducing indoor concentrations of outdoor particles. For each system, we present a plot showing the distribution of all hourly-averaged values of the 24h IO ratio for each measured component of the ambient aerosol. Each figure presents results for both FW and SU seasons.

Figure 3.12 shows that the Reference system was substantially protective of outdoor particles, though the degree of protection varied by particle size and, for some size fractions, by season. In both seasons, the greatest protection was afforded for ultrafine particles (6–100 nm diameter), with median and mean IO ratios of 0.1–0.2 (80-90% reduction). The lowest reductions – of roughly 50% – were seen for 0.3–0.4 μm particles. Performance was similar between seasons for 0.1 μm (100 nm) to 0.5 μm particles. Summer IO ratios were substantially lower than fall/winter ratios for the two largest size bins (0.7–1.0 and 1.0–2.5 μm particles), and slightly lower for UFP and estimated $PM_{2.5}$ mass. This may result from removal of the smallest and largest particles in the FAU, which operated for hours per day in summer for cooling but barely operated for heating in the fall/winter period. Analysis of particle decay rates following cooking – presented for the Reference and System A in Appendices IN-7-R and IN-2-A, respectively – indicate FAU removal rates of roughly 0.2 h^{-1} for UFP, 0.3–0.4 h^{-1} for 0.7–1.0 μm particles and 0.8–0.9 h^{-1} for 1.0–2.5 μm particles.

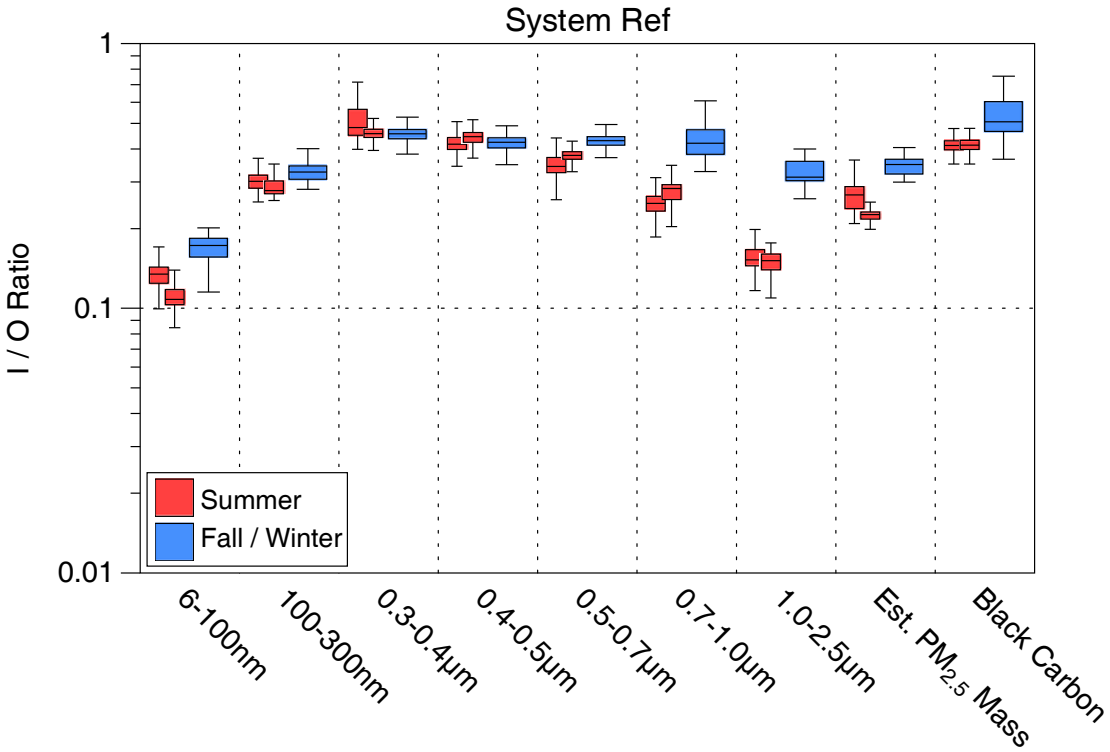

Figure 3.12. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for the Reference system during summer and fall/winter operation periods.

Figure 3.13 presents results for System A. The second (rightmost) result for each parameter during fall/winter is from the period when the system was operated with tape around the edges of the filter to assure minimal bypass. Across particle sizes, this system offered the least protection for 0.3–0.4 µm particles in summer (with a mean IO ratio of 0.63) and the greatest protection for UFP (mean IO ratios of ~0.2 in summer and fall/winter). The standard installation (left series of FW results) and the taped installation (to reduce bypass) gave similar results for almost all parameters. However, IO ratios for 0.3–0.4 and 0.4–0.5 µm particles were substantially lower when the filter had tape around the edges. The pattern of performance by particle size had some similarities but also some differences between seasons. Absolute IO ratios were similar between seasons for many of the particle sizes. Fall/winter ratios were substantially lower for 0.3–0.7 µm particles and a bit higher for 6–100 nm (UFP) and 1.0–2.5 µm particles, and for estimated $PM_{2.5}$ mass. The lower summer ratios for UFP and 1.0–2.5 µm particles may be explained by losses in the forced air system, as noted above for the Reference system.

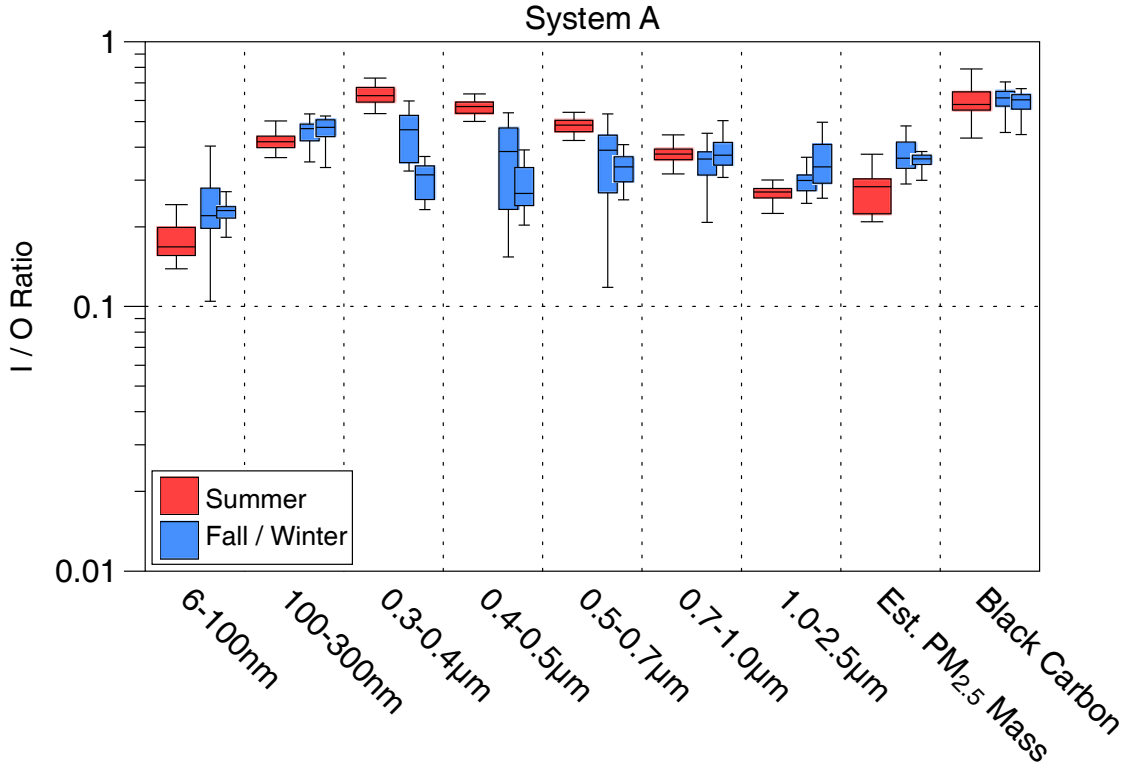

Figure 3.13. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System A during summer and fall/winter operation periods.

Figure 3.14 presents results for System B, which used the same supply ventilation with filtration (MERV13) as System A and featured an electrostatic air cleaner (ESP) in the FAU that operated when the forced air system was used for heating or cooling. As with the Reference and System A, there was less operation of the FAU for heating in fall/winter than for cooling in summer. But there were substantial periods of operation during the last three mornings and during the penultimate afternoon and evening of the roughly weeklong monitoring period. During each period of FAU operation (with ESP), indoor particle levels dropped sharply and substantially (see Appendix FW-6-B). For most parameters, there was a noticeable dip in the 24h running average IO ratio during the last two days of the monitoring period. And even the modest period of ESP operation during the FW period for System B produced lower IO ratios for most parameters for that system compared to System A and the Reference. Across particle sizes the longer periods of ESP operation in SU vs FW produced much lower IO ratios for the smallest and largest particles, and for $PM_{2.5}$ and BC. IO ratios for 0.4–0.7 µm particles were lower in FW compared to SU; but the seasonal differences for these particles sizes were much smaller for System B than for System A.

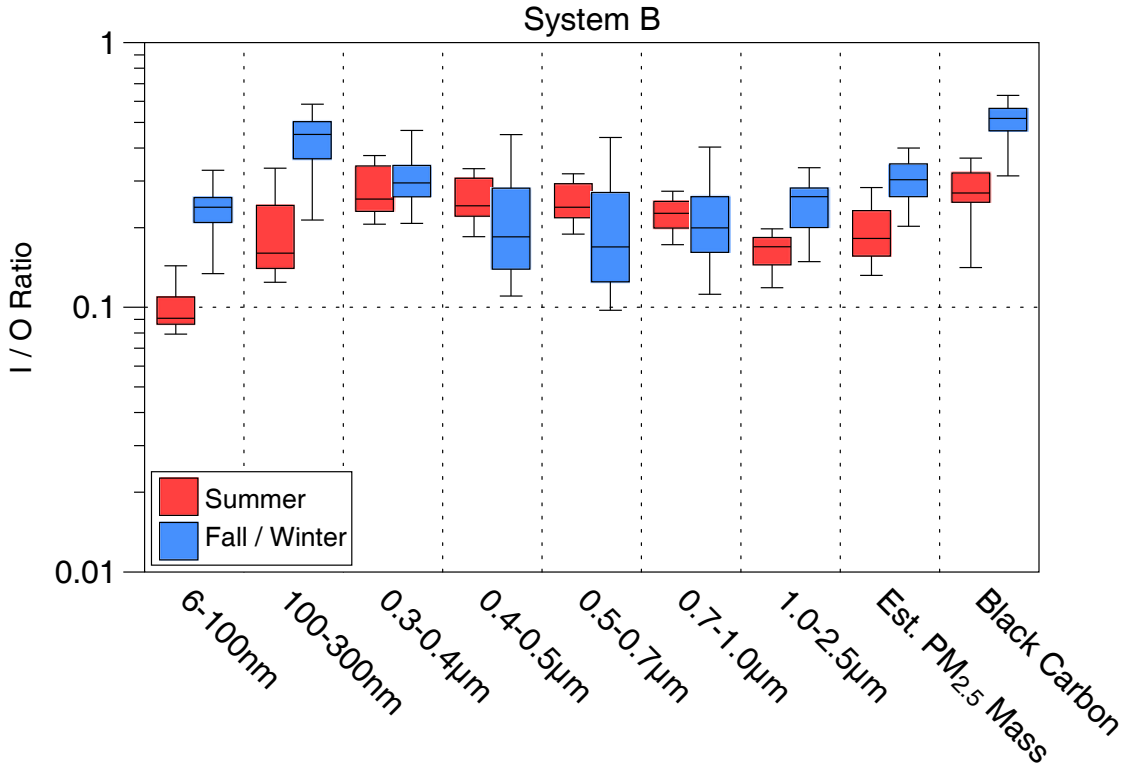

Figure 3.14. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System B during summer and fall/winter operation periods.

Figure 3.15 presents results for System C, which had a MERV16 filter on a continuous supply blended with air from indoors. For System C the summer pattern of IO ratios by particle size was similar to those observed for the Reference and Systems A and B: the highest ratios were observed for 0.3–0.4 µm particles and ratios decreased for smaller and larger particles. By contrast, the highest IO ratios for System C in FW were for 0.5–0.7 µm particles. With the exception of the largest size bin of 1.0–2.5 µm particles and BC, IO ratios for all other size bins and $PM_{2.5}$ were much lower in FW than in SU. The lower IO ratios of 1.0–2.5 µm particles in summer may result from removal in the FAU, which operated more in summer than winter, as noted above. The largest seasonal difference in IO ratios was seen for 0.3–0.4 µm particles: >0.05 in summer versus <0.01 in fall/winter. There was also a big difference in seasonal IO ratios for mass, with ratio of 0.035 in summer versus 0.01 in winter. The reason for lower FW ratios for other size fractions and $PM_{2.5}$ is not clear, though it is worth noting that they reflect relatively small differences in *removal effectiveness*. For example, removal effectiveness for 0.3–0.4 um particles was 94% in summer and 98–99% in fall/winter. The much higher IO ratios for BC relative to other parameters may be explained in part by lack of instrument sensitivity, as operated, to resolve the very low indoor concentrations resulting in both seasons. (We emphasize "as operated" because the instrument is capable of resolving much lower concentrations when operated with longer sample durations.) In summer, the issue was a combination of low outdoor BC concentrations and system effectiveness leading to extremely low indoor BC. In fall/winter, outdoor BC concentrations were higher but sensitivity for indoor BC was more limited owing to the 1 min sample durations used during the initial winter period of operation.

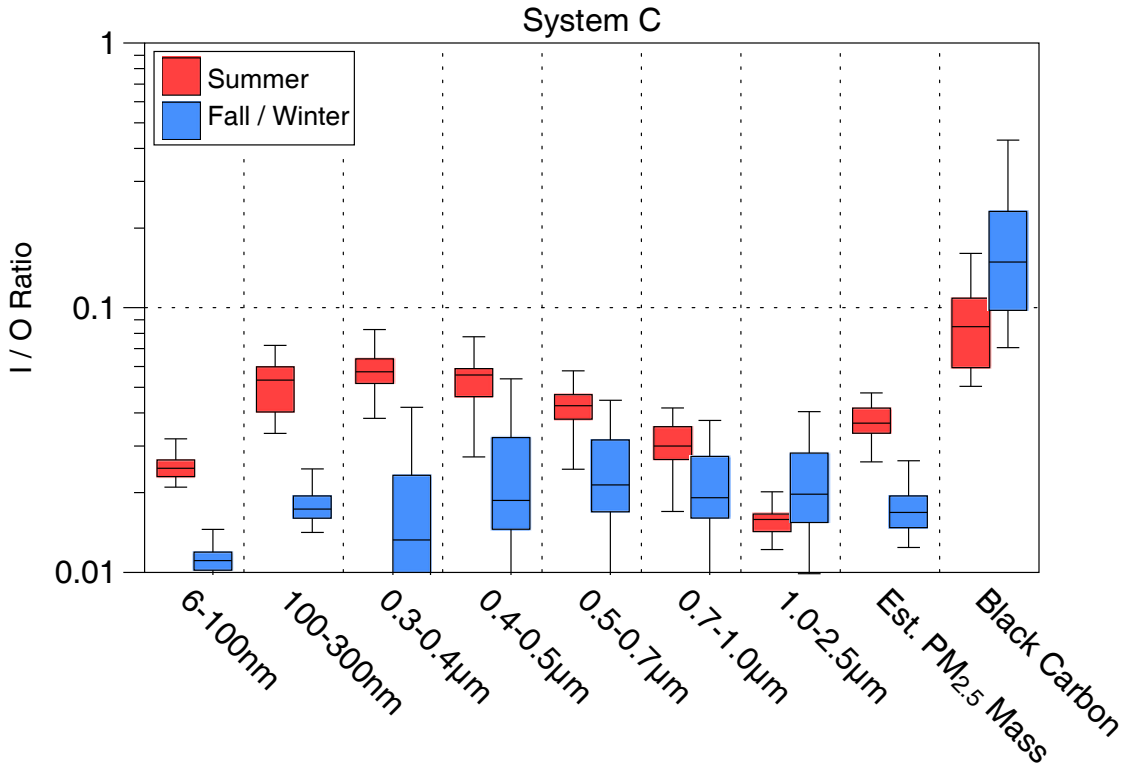

Figure 3.15. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System C during summer and fall/winter operation periods.

Figure 3.16 presents results for System D, which featured a MERV16 filter on the FAU return with a fan timer to operate the FAU for at least 20 min of each hour and a MERV8 filter on the supply ventilation. For this system, the highest IO ratios were observed for 100-300 nm particles. The largest seasonal differences in IO ratios were seen for 0.4-0.7 um particles and for BC, which had much lower IO ratios in FW vs. SU. The summer result for BC may be biased high because outdoor BC was low that week and indoor BC were below the QL and assigned a value of one half the QL. Ratios were similar between seasons for other size fractions including 1.0–2.5 um particles. Median IO ratios were below 0.04 (96% removal) for all size fractions – though not for BC – in both seasons.

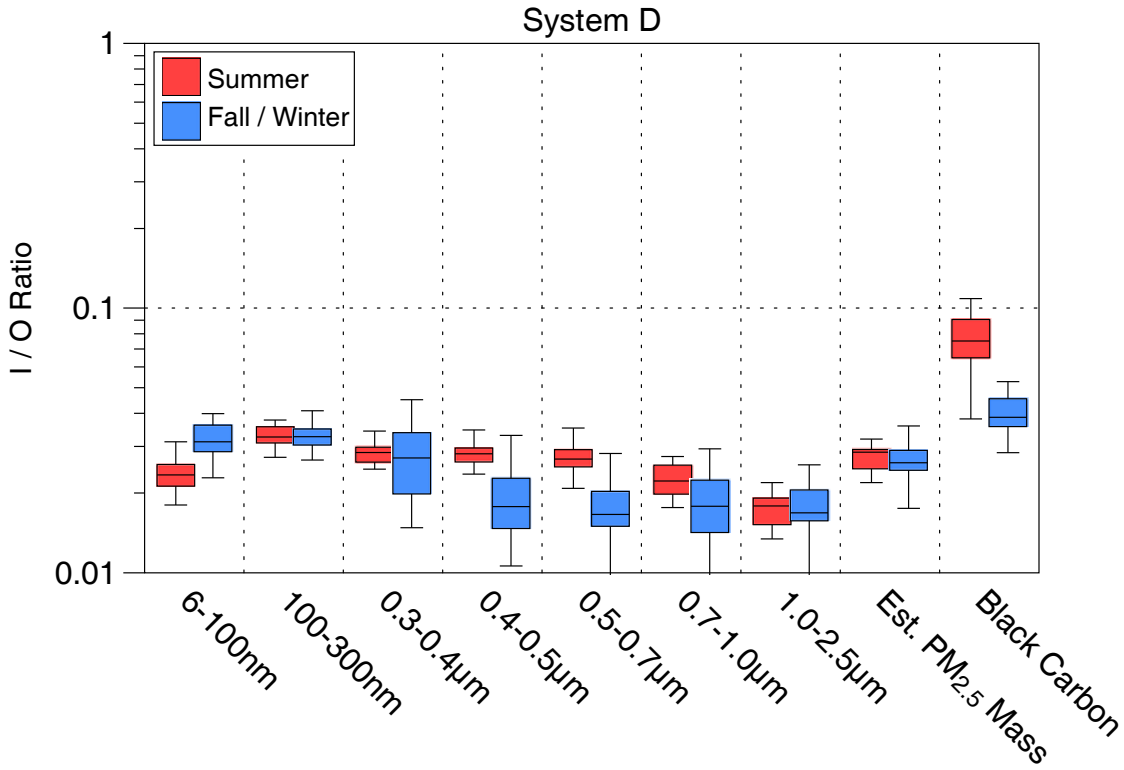

Figure 3.16. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System D during summer and fall/winter operation periods.

Figure 3.17 presents results for System E, which featured a MERV13 filter on the FAU return with a fan timer to operate the FAU for at least 20 min of each hour. The second (rightmost) result for each parameter during FW is from the period when the system was operated with tape around the edges of the filter to assure minimal bypass. The pattern of IO ratios by particle size was similar to most of the other systems, with the highest ratios for 0.3–0.4 um particles in SU and either 100-300 nm or 0.3–0.4 um particles in FW. Median IO ratios were similar between seasons for all size bins and even for $PM_{2.5}$ and BC. Distributions of 24h running average IO ratios were much broader in the first FW period for several size bins; these variations result from more rapid changes in outdoor particles levels during that period of operation, as shown in Appendix FW-3-E. Taping around the edges of the filter did not have a substantial impact on performance, as indicated by the similar IO ratios across size bins in the two periods of FW monitoring.

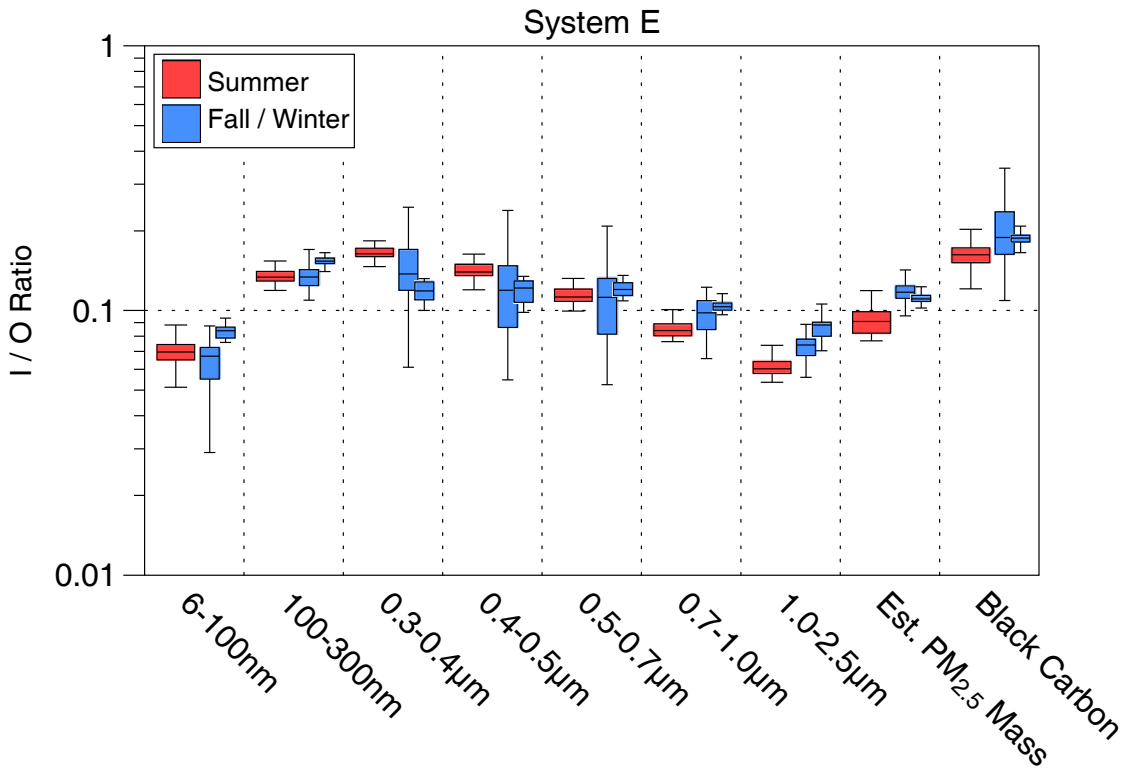

Figure 3.17. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System E during summer and fall/winter operation periods..

Figure 3.18 presents results for System F, which had MERV13 filtration on the mini-split with the fan operating continuously at low speed. The pattern of IO ratios by particle size for System F was similar to the pattern for System E. As with several other systems the median IO ratio was lower in FW than SU for 0.4–0.7 µm particles, but the differences were smaller for F than for some other systems.

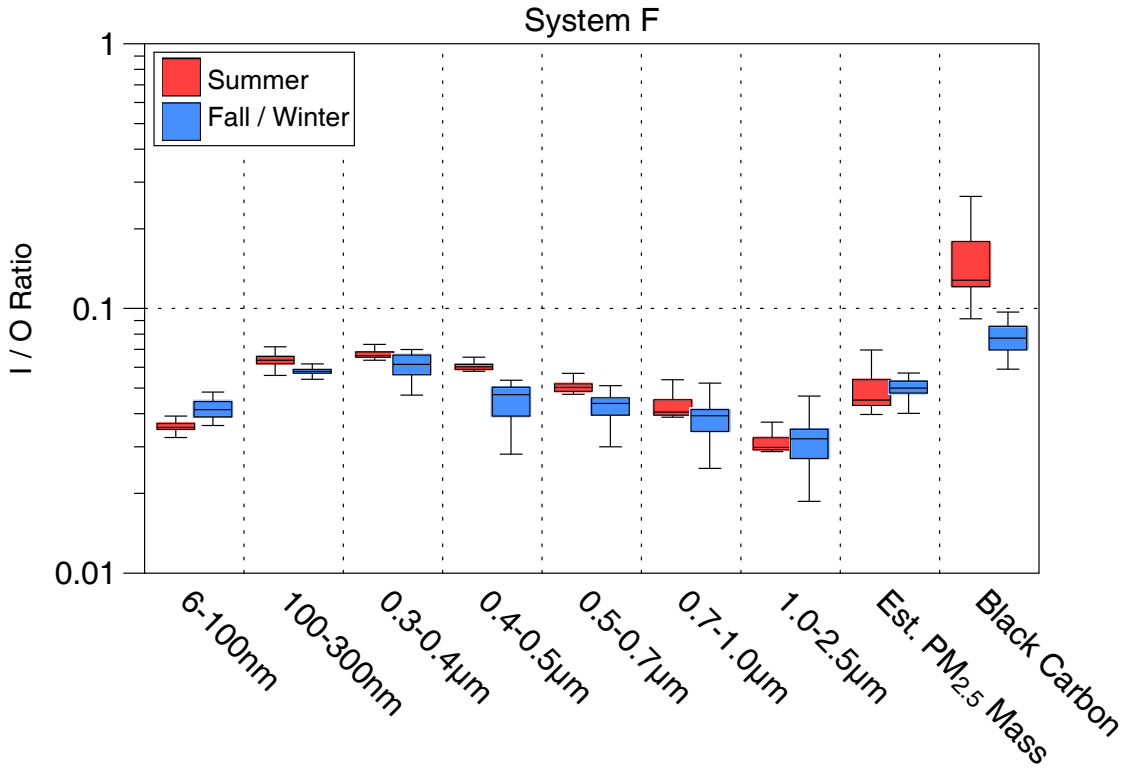

Figure 3.18. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System F during summer and fall/winter operation periods.

Figure 3.19 presents results for System G, which had a HEPA filter on a bypass loop in the FAU return and a fan timer; supply ventilation with a MERV8 filter was provided intermittently during periods of FAU operation. The pattern by particle size was similar for System G as for other systems, with the highest summer ratios observed for 0.3–0.4 µm particles and decreasing ratios for smaller and larger particles. Ratios for 0.3–0.7 µm particles were much lower and more variable in winter and ratios for 1.0–2.5 µm particles were much lower in summer. Ratios for estimated $PM_{2.5}$ were similar in the two seasons.

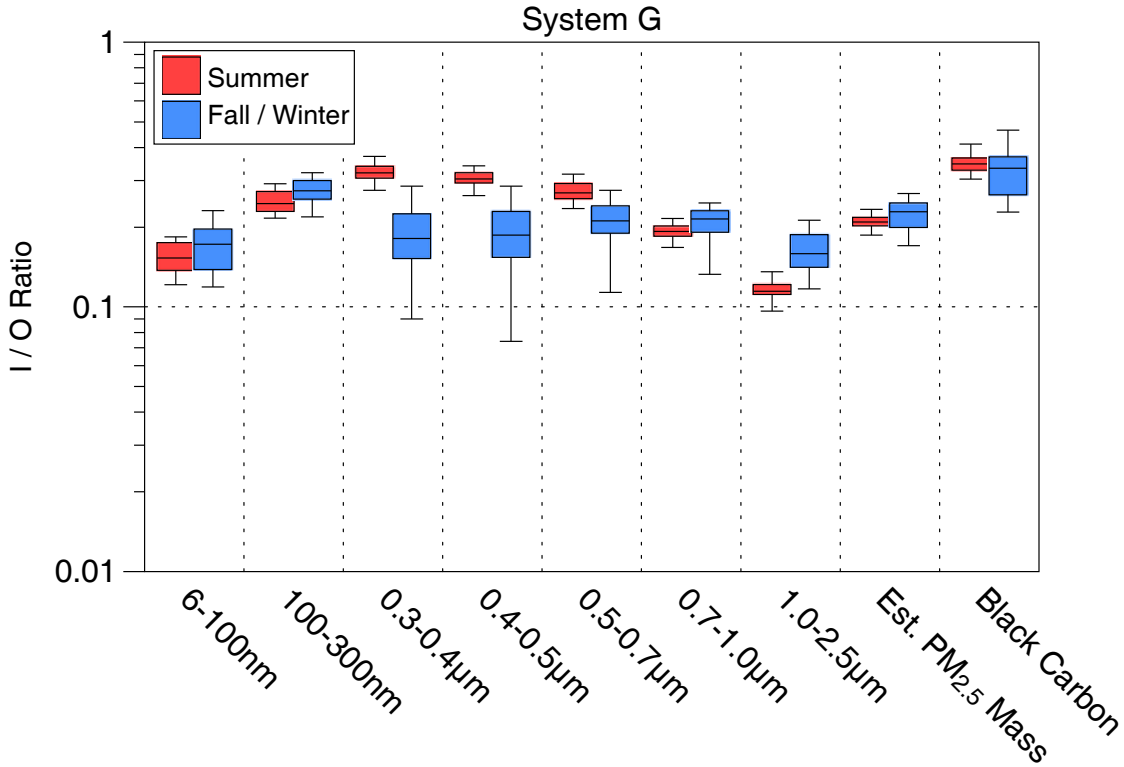

Figure 3.19. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for System G during summer and fall/winter operation periods.

Figure 3.20 presents results for the portable HEPA filter units, with the left set of boxes reflecting operation on automatic setting and the right set reflecting operation on medium speed. The continuous medium setting resulted in substantially lower median IO ratios across all size bins along with much less variation of IO over time.

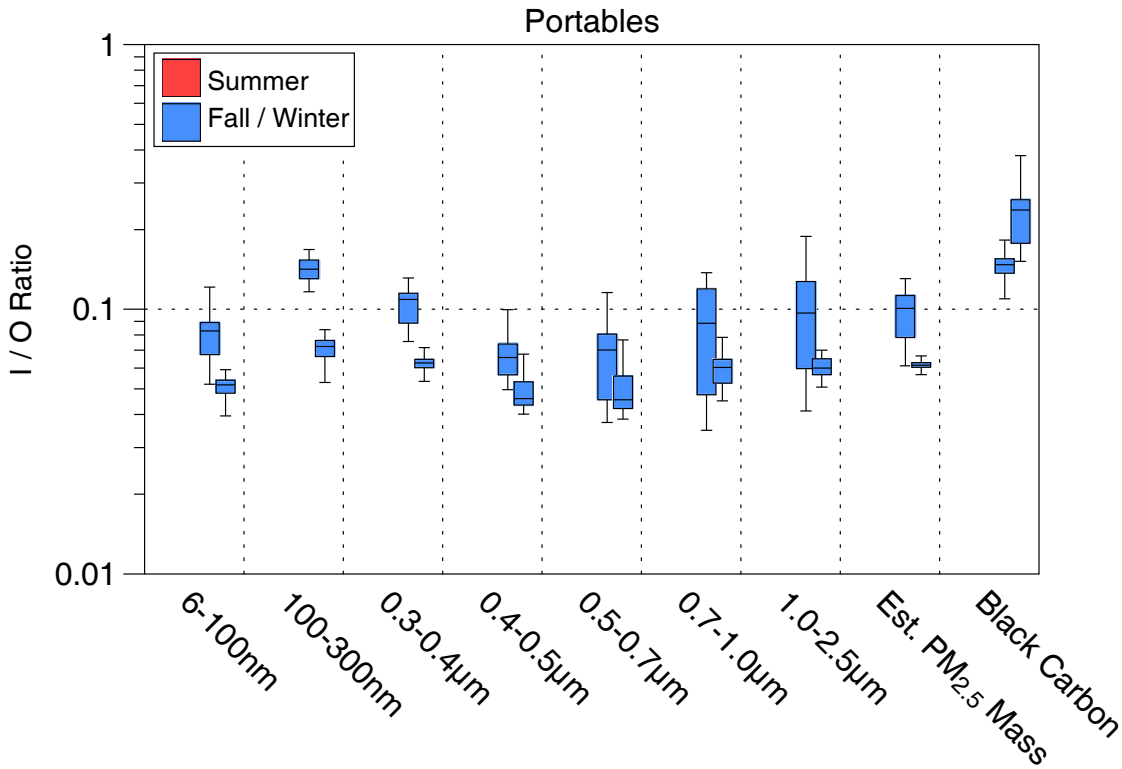

Figure 3.20. Distribution of 1h averages of the running 24h average indoor/outdoor ratios for Portable air filtration units during summer and fall/winter operation periods.

3.1.3 Comparison across systems – performance for outdoor particles

The relative performance of the tested ventilation and enhanced pollutant removal systems at reducing time-averaged indoor concentrations of outdoor particles can be assessed for each measured parameter by comparing the detailed system results presented above in Figure 3.12 through Figure 3.20. Provided below is a series of figures and tables that present results by parameter to facilitate comparisons across systems. The first two figures present time-averaged results over the seasonal monitoring periods; these are most relevant to considerations of chronic exposure impacts. Figure 3.21 presents the 24h average IO ratios for three particularly health-relevant characteristics of ambient particulate matter: $PM_{2.5}$ mass, as estimated from size resolved particle number concentrations, UFP, and BC. Figure 3.22 presents percent reductions (indoor relative to outdoor) for $PM_{2.5}$ mass, UFP, and BC. Discussion of the results is interspersed among the figures and tables.

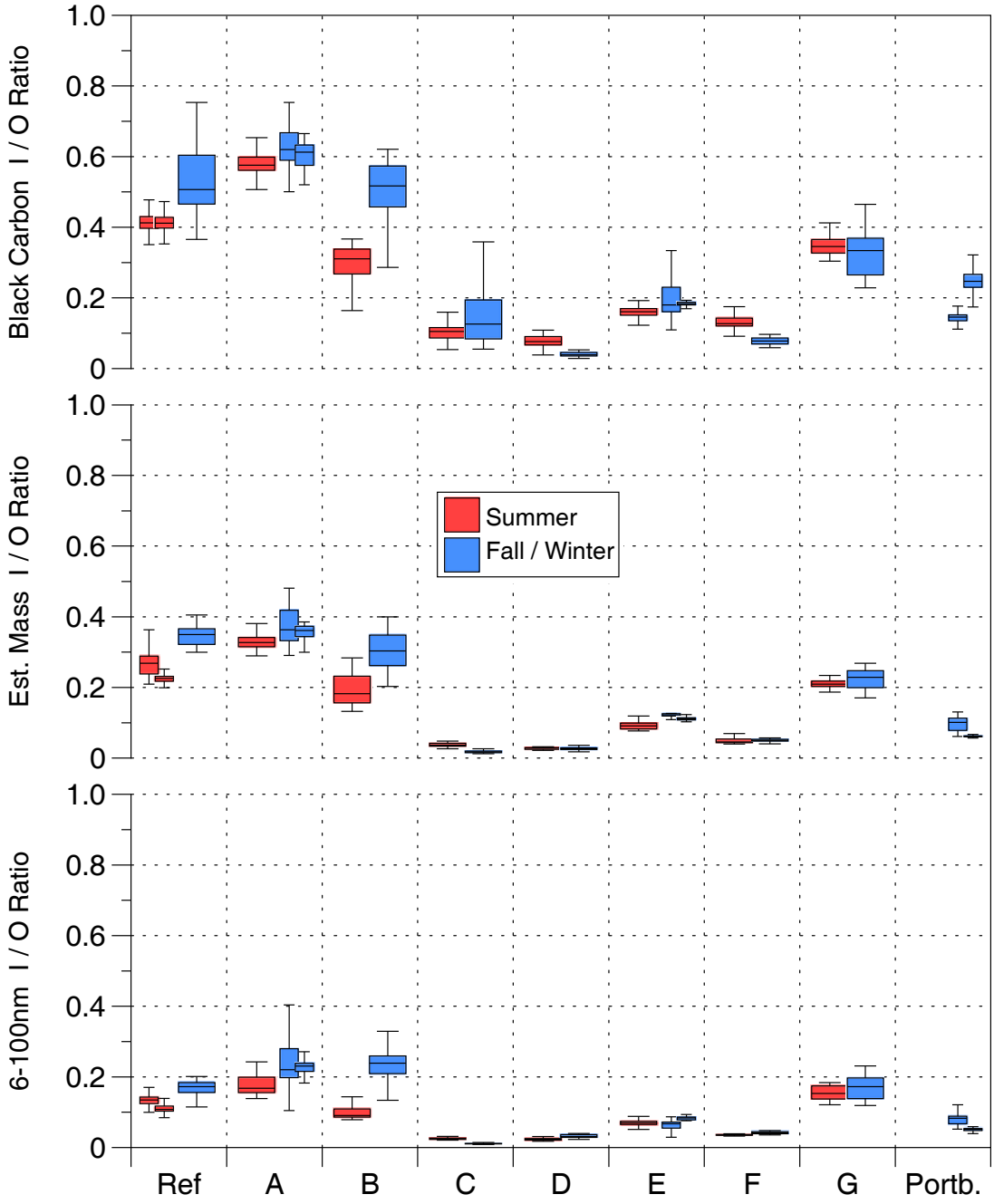

Figure 3.21. Distribution of running 24h average indoor/outdoor ratios for black carbon, estimated $PM_{2.5}$ mass, and ultrafine particles (6-100 nm) for each system operating over multi-day periods in fall/winter (FW) and summer (SU) seasons.

Several broad features of the experimental results are apparent in Figure 3.21. A comparison across parameters indicates substantially greater reductions (lower IO ratios) were achieved for UFP as compared to $PM_{2.5}$, with substantially lower reductions for BC. These differences are most prominent for the systems that achieved the lowest particle removal, namely the Reference and Systems A, B and G. Comparing across systems, it is clear that C, D, and F provided the

greatest levels of protection against outdoor UFP, $PM_{2.5}$, and BC, with System E and the Portables filling the next tier of performance. As noted previously, the results for most parameter and system combinations were similar across the two seasons. But there were benefits from FAU operation that produced better overall performance in summer versus winter most prominently for System B (with ESP operating with FAU in summer), but also for System A and the Reference.

Quantitative results are additionally presented in Table 3.4 and Figure 3.22 as reductions of indoor compared to outdoor concentrations of outdoor-origin $PM_{2.5}$, UFP and BC. In the table, the standard deviation is across the diurnal intervals, as shown for the IO ratios in Table 3.3. These summaries present results for only the primary period of FW operation for Systems A and E; they do not include the shorter monitoring period in which the system was operated with the filter taped to mitigate the change of bypass. The summary results for Portables are for the period in which they were operated in Auto mode.

Table 3.4. Percent reduction of time-averaged indoor concentration compared to the time-averaged outdoor concentration of outdoor-origin $PM_{2.5}$ mass, ultrafine particles (UFP) and black carbon for each evaluation period; SD is the standard deviation across the mean values for distinct 24h diurnal periods of analysis within each period (refer to discussion of Table 3.3).

System	$PM_{2.5}$				UFP				BC			
	SU		**FW**		**SU**		**FW**		**SU**		**FW**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ref	73	4	66	3	87	1	84	3	58	3	48	10
A	67	3	63	5	82	3	76	8	40	9	38	6
B	81	5	70	5	90	3	77	4	73	7	50	8
C	97	0	98	0	97	0	99	0	92	3	84	10
D	97	0	97	1	98	0	97	0	93	2	96	1
E	91	1	88	1	93	1	93	1	84	2	80	7
F	96	0	95	1	96	0	96	0	86	4	92	1
G	79	1	78	3	83	1	83	3	65	2	68	5
Port	nd[1]	nd[1]	90	2	nd[1]	nd[1]	91	2	nd[1]	nd[1]	85	2

[1] No data.

In considering the results of Table 3.4, we start by noting the perhaps surprising performance of the Reference system. Although it lacked any enhanced pollutant removal technology – other than a tight envelope, as required by California's building code – the Reference system with exhaust ventilation provided substantial reductions for in-home concentrations of outdoor particles, yielding outdoor to indoor reductions of 66–73% for $PM_{2.5}$, 84–87% for UFP and 48–58% for BC across the two seasons. System A, with MERV13 filtration on continuous supply ventilation, performed a bit worse than the Reference for all three parameters, providing reductions of 63–67% for $PM_{2.5}$, 76–82% for UFP, and 38–40% for BC. System B, with the

same ventilation system as A and an ESP on the FAU, performed slightly better overall than System A in winter, with reductions of 77% for UFP, 70% for $PM_{2.5}$ and 50% for BC. And the ESP operating several hours per day as the FAU provided summer cooling produced substantially better results: reductions for System B in summer were 81% for $PM_{2.5}$, 90% for UFP and 73% for BC. The installed systems that provided the best protection for outdoor particles were C, D, and F. These systems – which included two with MERV16 filtration on supply ventilation (C and D) and one with MERV13 filtration on a continuous recirculating flow through the mini-split fan unit (F) provided indoor concentrations that were lower than outdoors by 95-98% for $PM_{2.5}$, by 96-99% for UFP, and by 84-96% for BC across SU and FW seasons. The next-best installed system was E, which provided MERV13 filtration through the conventional FAU and operated intermittently with a fan timer. System E achieved indoor concentrations of UFP, $PM_{2.5}$ and BC that were 93%, 88-91% and 80-84% lower than outdoor levels over time. System G, with supply ventilation and a HEPA bypass on the FAU return operating intermittently with fan timer, performed similarly to the Reference for UFP, but showed moderate improvements for $PM_{2.5}$ mass and BC. During limited testing in FW, the two portable air filtration units with HEPA filtration achieved performance for UFP and $PM_{2.5}$ that was similar to System F when the portables operated continuously on medium airflow setting. When operated on automatic setting, performance was similar to System E for UFP, $PM_{2.5}$ and BC.

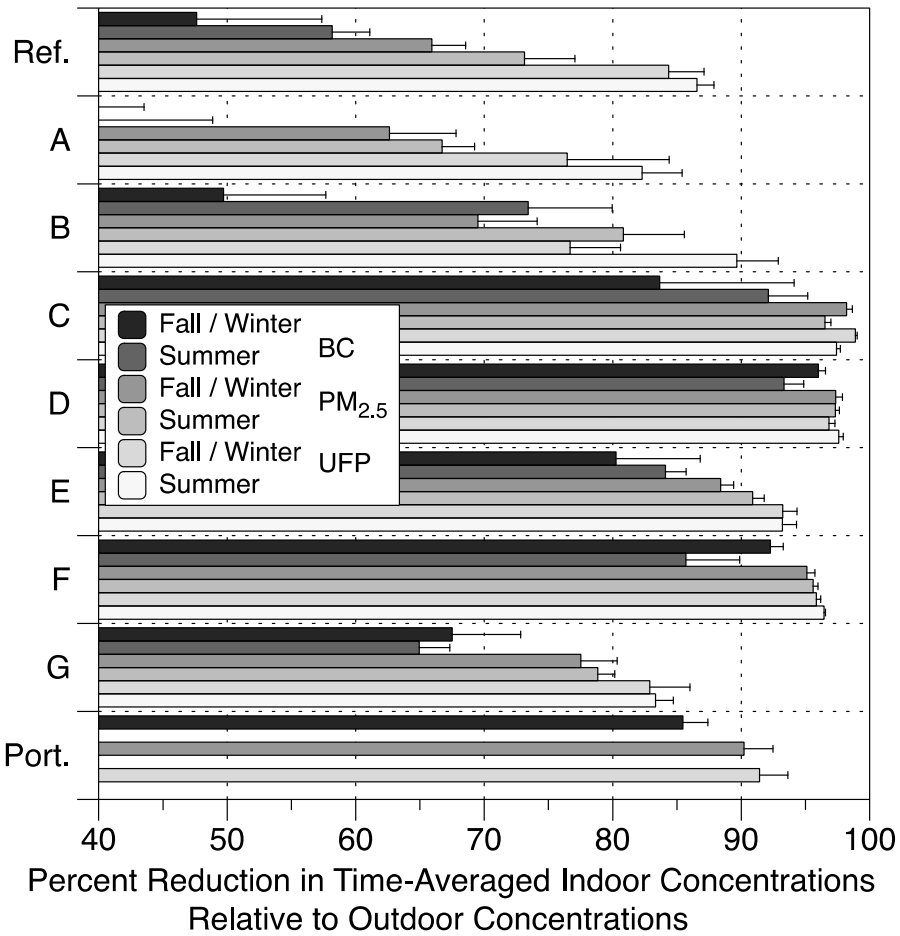

Figure 3.22. Effectiveness of each system, expressed as the reduction in the time-averaged indoor concentration compared to the time-averaged outdoor concentration of outdoor-origin black carbon (BC), $PM_{2.5}$ mass and ultrafine particles (UFP) over each evaluation period.

The next series of figures and tables present results that inform the protection provided for daily peak (highest 1h) in-home exposures to outdoor particles. Figure 3.23 presents the mean and standard deviation of highest daily 1h IO ratios for estimated $PM_{2.5}$ mass and UFP. Table 3.5 presents the reduction of the daily highest 1h outdoor-origin $PM_{2.5}$ mass and UFP for indoors relative to outdoor concentrations. The hourly results are not presented for BC both because the health concerns related to BC are more related to chronic exposure and because the BC data as collected in this study are less suited to analysis of peaks than they are to 24h and longer ratios. The IO ratios for the corresponding highest daily 1h indoor and outdoor "peaks" were lower than the 24h IO ratios for almost all systems and parameters, including the Reference system. This results primarily from pollutant concentrations indoors being smoothed relative to outdoors, meaning less pronounced peaks.

The best systems for reducing short-term concentrations were systems C, D, and F, all with 95% or greater reductions, followed by System E and the portable air filters. For the Reference system, the highest indoor hourly $PM_{2.5}$ concentrations were lower than the highest outdoor hourly $PM_{2.5}$ concentrations by 77-78%. System A had somewhat higher 1h IO ratios compared

to the Reference, corresponding to a 70% reduction. System B had lower 1h IO ratios in SU than FW, corresponding to 85% and 71% reductions of outdoor $PM_{2.5}$, respectively.

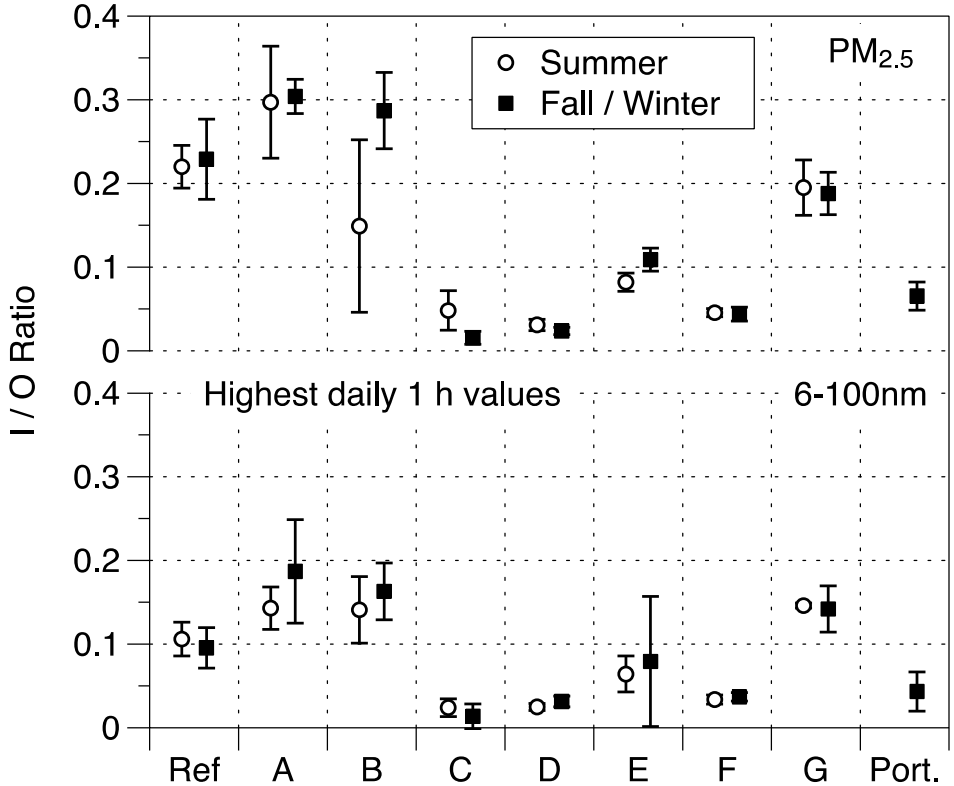

Figure 3.23. Ratios of highest daily 1h indoor to corresponding highest 1h outdoor concentrations for $PM_{2.5}$ mass and ultrafine particles (6-100 nm) for each system operating over multi-day periods in fall/winter (FW) and summer (SU) seasons. Results are provided as mean and standard deviation across days.

Table 3.5. Reductions (%) in highest daily 1 h indoor concentrations compared to corresponding highest daily 1h outdoor concentration of outdoor-origin $PM_{2.5}$ mass and ultrafine particles (UFP) over each evaluation period; mean and standard deviation across distinct 24h diurnal periods of analysis within each period (refer to discussion of Table 3.3).

System	$PM_{2.5}$				UFP			
	SU		**FW**		**SU**		**FW**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ref	78	3	77	5	89	2	90	2
A	70	7	70	2	86	3	81	6
B	85	10	71	5	86	4	84	3
C	95	2	98	1	98	1	99	1
D	97	1	98	0	98	0	97	1
E	92	1	89	1	94	2	92	8
F	95	0	96	1	97	1	96	1
G	81	3	81	3	85	0	86	3
Port	nd[1]	nd[1]	93	2	nd[1]	nd[1]	96	2

[1] No data.

3.1.4 Measured Air Exchange Rates

The air exchange rate is a variable that impacts indoor concentrations of outdoor particles. Higher AER brings outdoor particles indoors more quickly, which can increase concentrations as the removal processes are time-dependent. In general, since this house had a tight envelope and mechanical ventilation was provided in each system at a similar design rate, large variations in AER were not expected. Figure 3.24 presents a summary of the time-averaged AERs measured for all system monitoring periods, across both seasons. In the summer, the mean AER across tested systems was 0.27 $h^{-1}$with a standard deviation of 0.03 h^{-1} and a range of 0.21–0.31 h^{-1}. In the winter, the mean AER across tested systems was 0.29 $h^{-1}$with a standard deviation of 0.05 h^{-1} and a range of 0.22–0.35 h^{-1}. This figure shows that there were substantial variations in the AERs, even for systems that used the same ventilation equipment (e.g. Ref, E, and F). These result from variations in temperature and wind driving forces. It is interesting to note that several of the systems which featured very good performance for outdoor particles – namely D, E, F, and the Portable HEPA units – all had AERs that were in the top half of the range.

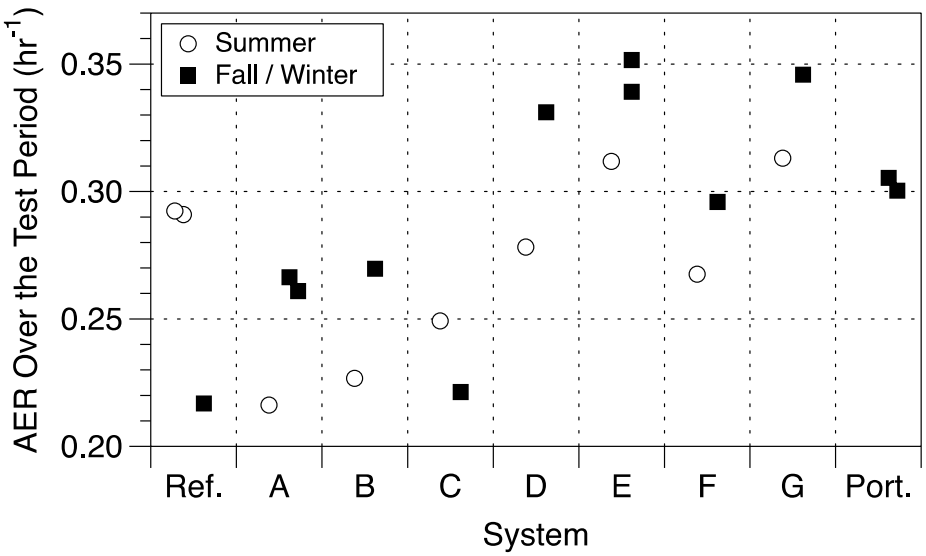

Figure 3.24. Time-averaged air exchange rate for each multi-day period of system operation. Calculated as the airflow and AER that produced the measured time-averaged concentration of indoor-emitted tracer gas over the duration of the monitoring period. For systems that were operated over two different periods in the same season, results are provided for each period of operation.

3.2 PERFORMANCE FOR OZONE

Analogous to the plots presented for particles in Section 3.1.1, Figure 3.25 presents an example plot of processed ozone data from the same period of Reference system operation. During this period, outdoor ozone varied diurnally with daily 1h peaks of 30-60 ppb and troughs between 10 and 20 ppb. Indoor ozone determination was limited by instrument sensitivity. This issue produces a potential bias in the 24h IO ratios, which may be lower than indicated.

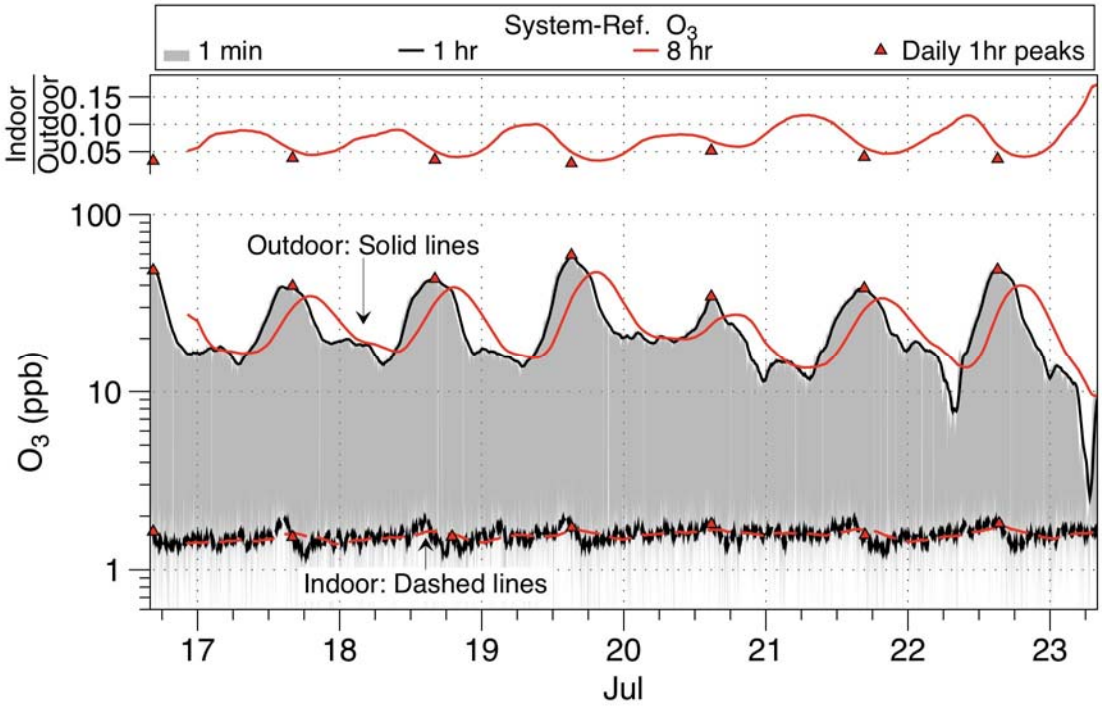

Figure 3.25. Ozone concentrations measured outdoors and indoors during operation of Reference System, July 16-22, 2014.

Summary results for measured ozone concentrations and system performance during the summer season are presented in Table 3.6. Performance was nominally very similar for all systems with valid data other than System B, which had substantially higher IO ratios and thus a lower protection factor for both 8h and 1h daily highs. The indoor/outdoor ratios of 0.03–0.04 for both the highest daily 8h and 1h concentrations for the Reference and Systems C and D are likely biased high because the indoor concentrations were often below the instrumentation quantitation limit (QL) of 1 ppb even during the daily high periods. Only System G had indoor daily high concentrations mostly above the QL, as indicated by the mean 8h and 1h values of 2.5 ppb. The second period of Reference system monitoring had a slightly higher IO ratio because the highest daily outdoor values were lower. The explanation for the higher IO ratios for System B appears to be that the ESP included in that system was producing ozone. Figure 3.26 shows that indoor ozone concentrations increased during each interval of system operation. The production of ozone by an ESP has been reported by Poppendieck et al. (2014) and others. Since ozone is highly reactive with surfaces and the reported indoor concentration was measured near the return grille, it is possible that ozone concentrations could have been higher in other rooms of the house, e.g. in rooms with HVAC supply registers. In an occupied home, furnishings would provide more surfaces for ozone reactions and removal, and ozone concentrations resulting from the ESP consequently would be expected to be lower.

Table 3.6. Summary results for ozone.[1]

System (start)	Days	Highest 8h Outdoor		Highest 8h Indoor		High 1h Outdoor		Highest 1h Indoor		**I/O ratio of highest 8h**		**I/O ratio of highest 1h**	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	**Mean**	SD	**Mean**	SD
Ref (7/2)	7	60	10	1.9	0.2	72	9	2.0	0.2	**0.03**	0.00	**0.03**	0.00
Ref (7/16)	6	37	6	1.6	0.1	44	8	1.6	0.1	**0.04**	0.01	**0.04**	0.01
B	7	50	12	5.9	1.3	59	16	7.4	1.5	**0.12**	0.02	**0.13**	0.03
C	7	55	12	1.7	0.2	64	17	1.9	0.3	**0.03**	0.00	**0.03**	0.01
D	7	53	11	1.5	0.1	64	19	1.7	0.3	**0.03**	0.01	**0.03**	0.00
G	3	59	11	2.5	0.6	68	15	2.5	0.6	**0.04**	0.00	**0.04**	0.01

[1] Data unavailable for Systems E and F because of instrument problems.

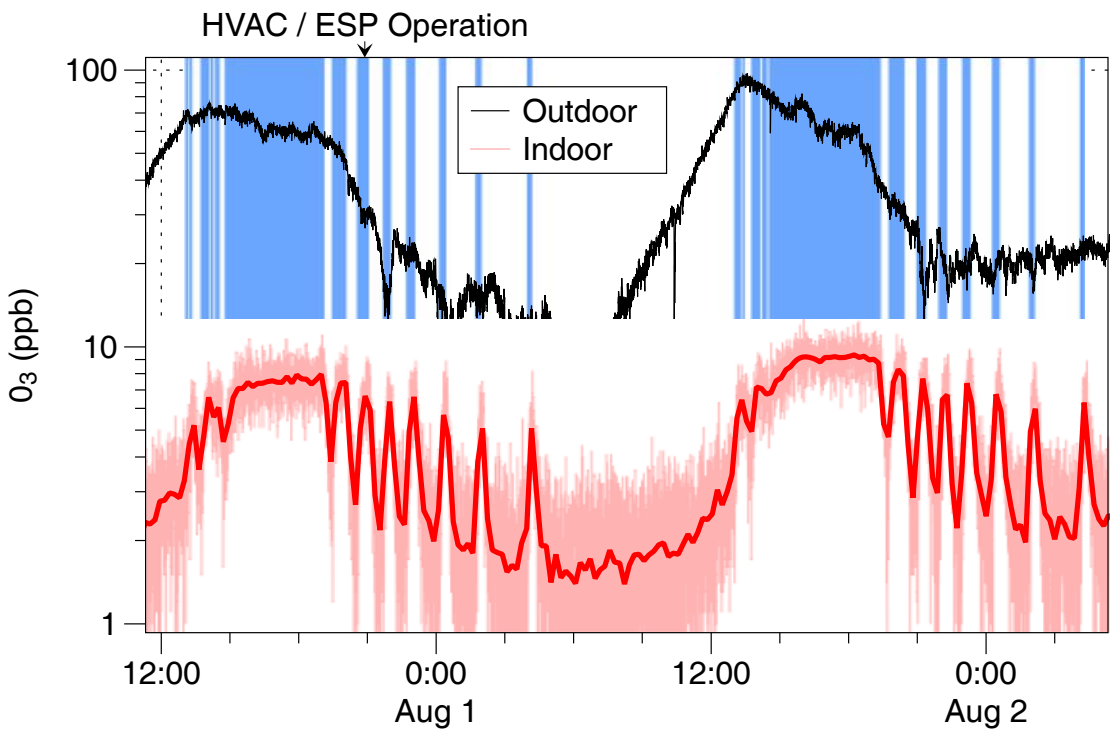

Figure 3.26. Time series of ozone concentration for System B indicating ozone production when the FAU with electronic air cleaner operated (shown in blue shading).
For indoor data, the figure shows both the minutely measurements – which are noisy because the concentrations are close to the quantitation limit – and a smoothed fit.

3.3 Nitrogen Oxides Measurements

Nitrogen oxides were measured with the goal of exploring whether there were variations in the ratio of indoor to outdoor NO and NO_2 as the various systems were used. Given the low outdoor concentrations and the relatively coarse field calibration of the instruments, the NO_X data were assessed to be unsuitable for quantitative assessment of percent reductions from

outdoors to indoors. The plots of NO_X data presented in summer appendices show that indoor NO_X was consistently lower than outdoor NO_X.

3.4 RESULTS FOR ENHANCED REMOVAL OF VOCS

This sub-section presents summary results for the VOC performance experiments conducted for the Reference and for Systems C, D, and G during the summer 2014 measurement campaign. The days of VOC sampling for each system are shown in Table 3.7.

Table 3.7. Days and dates (in 2014) of VOC sample collection for each system. Daylong samples initiated at approximately 7 am on the day noted.

Start day	Reference	System C	System D	System G
Thursday	-	-	7/10	6/26
Friday	-	-	7/11	6/27
Monday	7/21	7/28	7/14	6/30
Tuesday	7/22	7/29	7/15	7/1
Dates of System Test	7/16–7/23	7/23–7/30	7/9–7/16	6/25–7/2

Summary results for 30 individual VOCs are presented in Table 3.8. Compounds are grouped by functional groups, in the following categories: alkanes, aromatic hydrocarbons, carbonyls, alcohols, alkenes and siloxanes. Concentrations for most of the VOCs were determined by GC/MS analysis of sorbent tubes. Concentrations for three volatile carbonyls (formaldehyde, acetaldehyde and acetone) were determined by HPLC analysis of DNPH samplers.

Figure SU-10-1 (Appendix SU-10-VOC) graphically presents the concentrations of each compound measured in each System, with and without ozone scrubbers. These figures clearly demonstrate the value of using the scrubber to retain many compounds that were substantially impacted by ozone in the samples that were collected without scrubber. Summary results by compound in Table 3.8 are presented only for the samples with scrubbers

The average air exchange rate, temperature, relative humidity and dew point for each experiment are reported in Table SU-10-1 (Appendix SU-10-VOC).

3.4.1 Indoor and outdoor concentrations

The first two columns in Table 3.8 present average concentrations in the Reference system over the sampled period for each compound. It should be noted that hexane presents extremely high concentrations when measured with the scrubber, which are two orders of magnitude higher than those measured without the scrubber. Since all other alkanes show much closer values between those measured with and without scrubber, it appears that hexane was emitted by the scrubber (specifically, the plastic casing of the scrubbers). For that reason, hexane is not included in the analysis.

Table 3.8. Summary results for VOCs.

	Conc, Ref. (µg/m³)		IO ratio				Major	%ΔC		
	outdoor	indoor	REF	G	D	C	Sources	G	D	C
ALKANES										
Heptane	0.12	0.28	2.3	1.3	1.2	2.0	both	-69%	-84%	-1%
Octane	0.12	0.26	2.1	1.6	1.4	1.9	both	-12%	-62%	-5%
Decane	0.21	0.34	1.6	1.3	0.9	3.2	outdoor	-15%	-127%	317%
Dodecane	0.26	0.54	2.1	1.4	1.3	5.6	both	-6%	-43%	667%
AROMATICS										
Benzene	0.15	0.23	1.5	1.8	0.9	1.3	outdoor	-10%	-135%	-38%
Toluene	0.52	5.70	11.1	7.3	4.3	9.4	indoor	-29%	-53%	13%
Ethylbenzene	0.11	0.62	5.6	4.5	2.8	11.6	indoor	-31%	-51%	-6%
m/p-Xylene	0.34	1.31	3.9	3.2	1.8	4.0	both	-35%	-65%	-10%
o-Xylene	0.13	0.95	7.4	4.3	2.2	7.4	indoor	-37%	-67%	-9%
Benzene, 1,2,4-trimethyl-	0.19	0.32	1.7	0.8	0.9	1.4	outdoor	-156%	-121%	-32%
Benzene, 1,2,3-trimethyl-	0.04	0.08	1.9	0.9	1.0	1.5	outdoor	-127%	-105%	-29%
Benzaldehyde	0.20	2.34	11.8	8.1	4.0	9.3	indoor	-30%	-60%	-27%
Phenol	0.21	3.19	14.9	20.2	8.0	7.6	indoor	-14%	-20%	-21%
CARBONYLS										
*Formaldehyde**	2.71	116	*42.8*	*26.3*	*26.6*	*22.7*	indoor	*-8%*	*-7%*	*-17%*
*Acetaldehyde**	1.86	19.2	*10.4*	*7.7*	*7.4*	*7.8*	indoor	*-8%*	*-24%*	*-9%*
*Acetone**	3.17	20.0	*6.3*	*4.1*	*3.0*	*3.3*	indoor	*-7%*	*-40%*	*-19%*
Butanal	0.19	2.37	12.6	12.3	9.1	12.4	indoor	-18%	-9%	-10%
Hexanal	1.50	89.2	59.4	30.3	30.3	34.8	indoor	-26%	-51%	-26%
Octanal	0.23	5.01	21.9	12.2	15.4	11.0	indoor	-7%	-42%	-12%
Nonanal	0.26	0.54	6.0	2.9	5.1	3.8	indoor	-4%	-12%	1%
ALCOHOLS										
2-Butoxyethanol	0.80	9.74	12.2	29.2	93.1	7.1	indoor	-20%	-23%	-27%
1-Hexanol, 2-ethyl-	0.23	5.26	23.0	7.6	8.5	16.3	indoor	-25%	-33%	-9%
ALKENES										
a-Pinene	0.16	13.0	80.4	13.6	24.2	39.6	indoor	-35%	-58%	-16%
Styrene	0.07	1.31	18.8	10.8	3.6	20.1	indoor	43%	-60%	20%
3-Carene	0.01	0.31	22.7	5.6	7.5	15.1	indoor	-41%	-64%	-18%
D-Limonene	0.09	1.18	13.0	no O[1]	4.9	10.9	indoor	-43%	-65%	-15%
g-Terpinene	0.01	0.06	5.5	4.2	no O[1]	14.3	indoor	-41%	-50%	8%
SILOXANES										
Cyclotrisiloxane, hexamethyl-	0.40	2.83	7.0	6.8	2.2	9.7	indoor	-28%	-54%	-15%
Cyclotetrasiloxane, octamethyl-	0.06	0.46	7.3	7.2	2.5	9.5	indoor	27%	-45%	10%
Cyclopentasiloxane, decamethyl-	0.10	2.53	24.5	40.8	15.9	41.5	indoor	913%	271%	1422%

[1]Outdoor sample below detection limit.

The sum of all concentrations ("total VOCs") measured in the Reference system is plotted in Figure 3.27. In outdoor samples, the total concentration of all VOCs was 14.5 µg m^{-3} for samples measured with the scrubber, from which 7.7 µg m^{-3} correspond to the three volatile carbonyls determined by DNPH/HPLC. Samples collected without the scrubber showed a total concentration of 2.7 µg m^{-3}, which amounts to ~40% of the VOCs determined with the sorbent tube method using the scrubber, i.e. not including the volatile carbonyls determined by DNPH/HPLC. This is consistent with inspection of values for several VOCs that we expected to be depleted on the sorbent tube by reaction with ozone (e.g., alkenes).

In indoor samples, the total concentration of compounds was 305 µg m^{-3} for samples measured with the scrubber, from which 155 µg m^{-3} correspond to the three carbonyls determined by DNPH/HPLC. Samples collected without the scrubber showed a total concentration of 147 µg m^{-3}, which is very close to the VOC concentration determined with the scrubber, after subtracting the carbonyls determined by DNPH/HPLC. This is consistent with the fact that, in the absence of high indoor ozone levels, the use of scrubbers indoors did not result in different concentrations for VOCs. Formaldehyde was the dominant carbonyl, and the compound present at the highest concentration (116 µg m^{-3}).

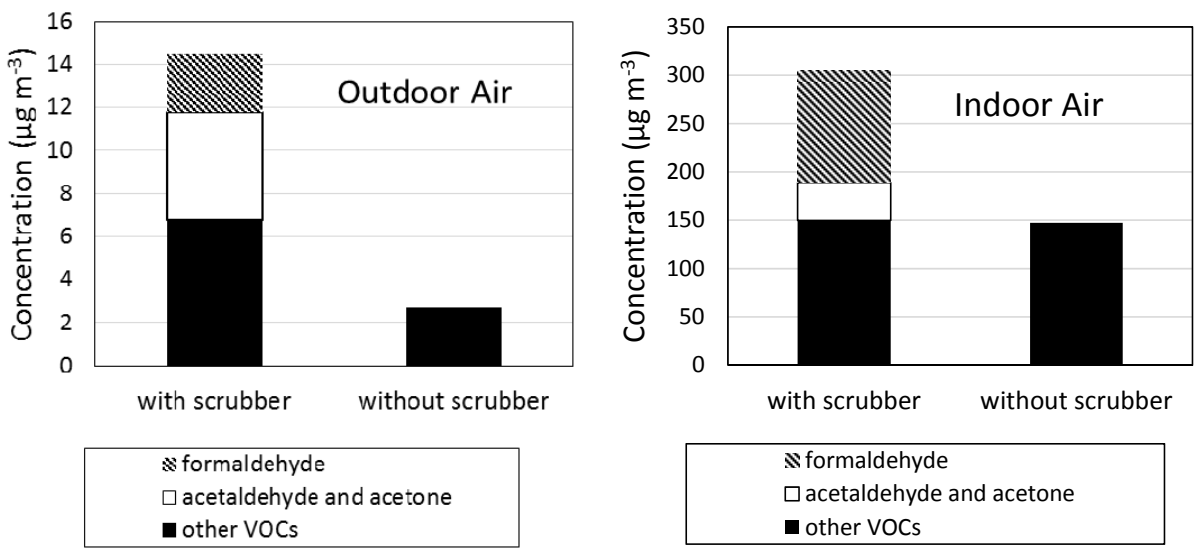

Figure 3.27. Total VOC measured in the Reference system outdoors and indoors, as labeled.
The volatile carbonyls formaldehyde, acetaldehyde and acetone were sampled only with ozone scrubbers.

3.4.2 Indoor/outdoor (IO) ratios

Table 3.8 reports values for IO ratio corresponding to each of the systems, with and without the ozone scrubber. Also, the nature of the source of each compound (indoor or outdoor) is reported in a separate column. The criterion used to assign the source was:

Mostly outdoor sources if IO < 2

Mostly indoor sources if IO > 5

Substantial contributions from indoor and outdoor sources if $2 \leq IO \leq 5$

From a total of 31 compounds reported, a majority (22 compounds) appeared to originate predominantly or fully from indoor sources. Five compounds (alkanes and aromatic hydrocarbons) were of outdoor origin, and four other VOCs from the same groups appeared to have substantial contributions from both indoor and outdoor sources.

IO ratios were determined for samples with and without the ozone scrubber. While in many cases there is overall good agreement between the two data sets, for some compounds the IO ratio corresponding to samples without scrubber were unrealistically high, due to the loss of analyte in the outdoor sample. For that reason, we report only results using the ozone scrubber.

It was observed that, for most compounds and all tested systems, the IO ratio was in general lower than that corresponding to the Reference system, indicating that indoor VOC levels were overall reduced by all three systems. In most cases, the IO ratios reported for Systems C, D and G were between 60% and 90% of those reported for the Reference System, suggesting a removal of up to **one third** of the VOCs present in indoor air.

Figure SU-10-2 (Appendix SU-10-VOC) illustrates the IO ratios determined for each group, with and without scrubber.

3.4.3 Relative reduction in indoor VOC concentrations due to air cleaning

Table 3.8 reports values for the relative difference in indoor concentrations between each system and the reference system, corresponding to the difference in differential concentrations, *%ΔC,* as defined in Section 2.5.4. This parameter was determined for each compound, with and without scrubber, for each of the three systems (C, D, and G). The same compounds for which data without ozone scrubber was deemed unreliable to calculate I/O ratios were not amenable to the calculation of *%ΔC*. Hence, those results were not taken into consideration.

These results are also presented in Figure SU-10-3 (Appendix SU-10-VOC). They provide for a first-order comparison between each system and the Reference system that assumes that sources inside the mixing volume of the home remain relatively constant during the sampling periods, but should capture any differences caused by the exhaust system pulling air through the building shell, where specific VOCs may be in higher concentrations. Overall, a net reduction (expressed as a negative value) was observed in *%ΔC* for most compounds, consistent with partial removal of pollutants by each of the systems. Alkanes showed mixed results, with net removal of three compounds by System D, but overall little removal or even increase in concentrations for Systems C and G. When outdoor concentrations were subtracted from indoor levels, results corresponding to Systems D and G showed net removal for all alkanes. Aromatic hydrocarbons, carbonyls, alcohols, most alkenes and most siloxanes were effectively removed by all three systems.

Overall, System D seemed to show better performance than the other two systems in removing VOCs. It should be noted that this initial observation is made only on the basis of comparing average concentrations, and does not take into account the fact that each system operated under different recirculation regimes and air flows. Comparing concentration changes, as done here, provides a useful first-order outcome that enables comparison across systems. It is important to note that system performance depends both on the removal efficiency of the air cleaning material and the number of times that air is passed over the air cleaning material.

Table 3.9 summarizes the airflow conditions corresponding to each of the studied systems. We define the recycle ratio as a measure of the capacity of each system, corresponding to the number of times the air can be processed by the air cleaning system before being removed from the room by ventilation. The recycle ratio is calculated as the ratio between the airflow going through each system, F_S, and the airflow through the house, F_H, given by the air exchange ratio (ACH). Systems G and D operated 20 minutes per hour; for that reason, the hourly average for their recycle ratio is a third of the value measured when the system was in operation. System C operated continuously. While systems G and C performed at a comparable recycle ratio, system D had a higher capacity (by a factor of 5-6 with respect to the other systems). Hence, the better performance observed for system D can be attributed primarily to its higher capacity, rather than to intrinsic properties of the air cleaning media.

Table 3.9. Airflow conditions for each of the VOC removing systems.

SYSTEM	F_S	ACH	F_H	Recycle ratio	
	$m^3 h^{-1}$	h^{-1}	$m^3 h^{-1}$	During system operation	Hourly average
G	306	0.31	98	3.1	1
D	1711	0.28	89	19	6.4
REF		0.29	92		
C	123.5	0.25	79	1.6	1.6

3.5 PERFORMANCE FOR INDOOR-GENERATED (COOKING) PARTICLES

3.5.1 Example results for indoor-generated (cooking) particles: System D

System performance for indoor particles was assessed using the stir-fry cooking procedure described in in Lunden et al., (2014). The stir-fry procedure took roughly 5 min and occurred in synch with the hourly cycle of operation for any system that included intermittent operation of pollutant removal and ventilation.

Complete results for each experiment featuring indoor particles from cooking are presented in a series of appendices. The naming convention for these appendices includes “IN” to indicate they are for indoor-generated particles, and a number to indicate chronological order and the system identifier (A-G, R). Each appendix presents a series of figures showing the time series for the inert tracer and for each pollutant with valid data.

This section presents as an example the series of figures from Appendix IN-6-D, which shows results for System D obtained from an experiment occurring on July 16, 2014. As a reminder, System D featured supply ventilation and MERV16 filtration on the FAU return, with operation of both systems controlled by a fan timer to occur for at least 20 min of each hour. Since the thermostat was set to not initiate operation during this experiment, the system operated exclusively on the 40 min off / 20 min on schedule.

Figure 3.28 presents the time series of SF_6 concentrations in the test house, starting just before cooking and continuing through two cycles of intermittent FAU operation with supply ventilation. Stir-frying of green beans occurred during the first shaded interval, at 9:02 am. Most of the cooking experiments were preceded by a supplemental injection of SF_6 tracer gas to

provide fine resolution of the air exchange rate during the different phases of system operation, as shown in this figure. Injection occurred prior to the display interval. The figure shows the fitted first order decay rate during each interval. The start of the fit during the first interval in this case was delayed for several min because the initially steeper decay was thought to reflect some mixing throughout the house rather than purely the outdoor air exchange rate. The tracer time series shows the higher AERs that occurred during system operation and the lower AERs during the intervals without mechanical ventilation. A timer operated the central air handler for the last 20 min of each hour starting with the initiation of cooking. Faster decay occurred during system operation because of intermittent ventilation supply connected to the forced air unit (FAU).

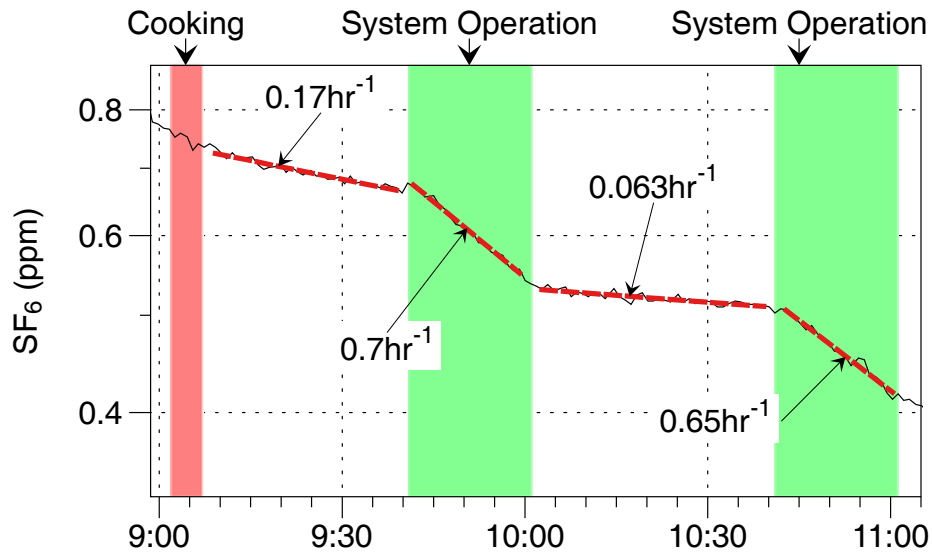

Figure 3.28. Time series of SF_6 tracer concentrations during cooking experiment with System D on July 16, 2014. (Refer to text for a detailed description.)

Figure 3.29 presents the number concentration (PN) of 6 nm to 2.5 µm particles collected with the single CPC 3787 that was operational during this experiment. This figure shows the much higher decay rates that occur when the FAU with MERV16 filtration is operating compared to the intervals of no FAU operation. The decay rate for this metric just after cooking and before the first interval of system operation were typically very high though not precisely in line with the value shown in this figure. During this experiment, outdoor PN was higher than indoor from the first period of system operation onward. It is important to note, however, that for System D, the 24h average IO ratio for 6 nm to 2.5 µm particles is <0.03. Thus, for an outdoor concentration of roughly $4x10^4$ particles cm^{-3} the indoor concentration would be $<1.2x10^3$ particles cm^{-3}. The indoor particle concentration is well above this level until the very end of the second period of system operation, therefore the additional ventilation as shown above did not contribute significantly to indoor particle concentrations compared to the cooking event.

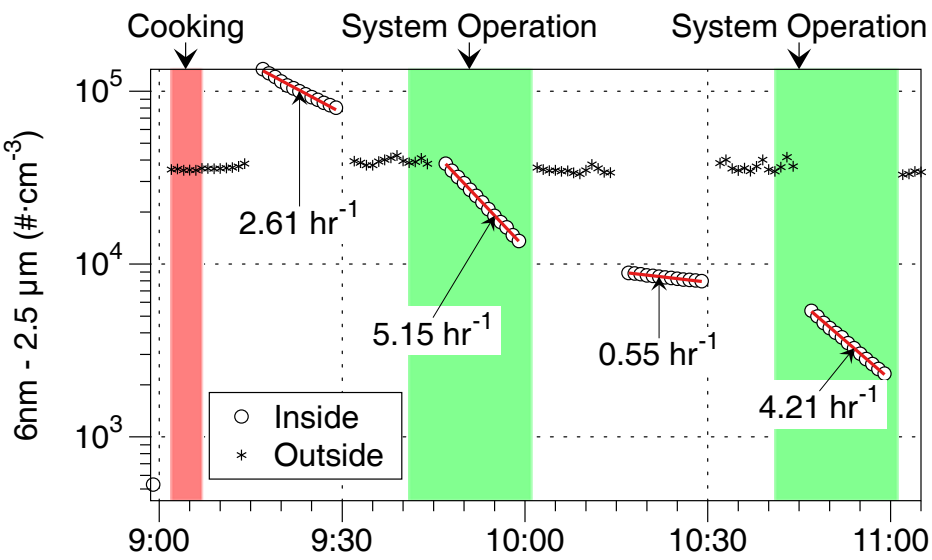

Figure 3.29. Time series of number concentration of 6 nm to 2.5 µm diameter particles during cooking experiment with System D on July 16, 2014.
Data shown for only one of two CPC3787s. The other unit had a wick problem during this experiment. Data gaps for inside and outside time series correspond to periods when the CPC3787 with a wick problem was monitoring in each location. Fitted decay rates during each period reflect sum of all particle transformation and removal mechanisms including growth, ventilation, deposition and filtration.

Figure 3.30 presents data for 100 nm to 2.5 µm particles, as reported by the CPC 3781 instruments with size selective inlets. This plot shows that a somewhat different first order decay rate results from fitting the data from each instrument. This is true both for the first interval before system operation and for the second interval of no system operation when the decay was expected to be more stable.

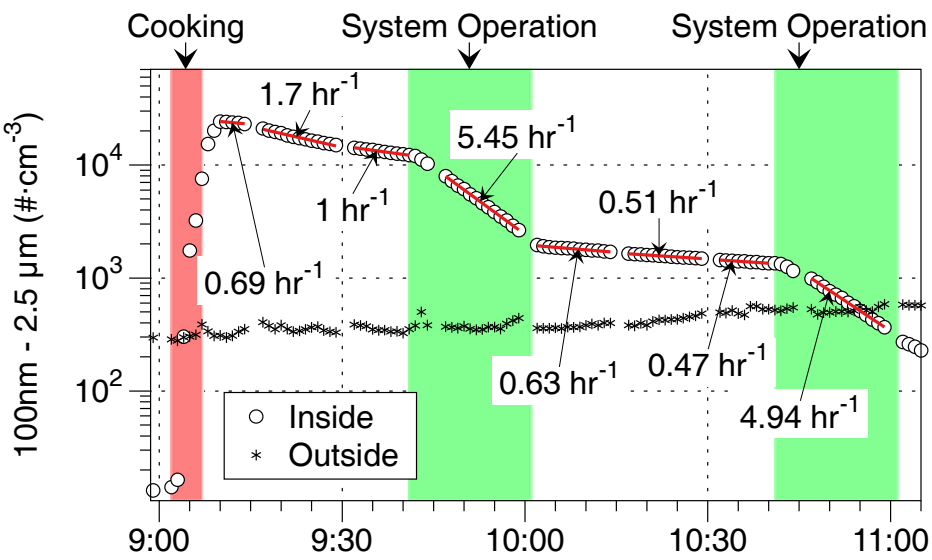

Figure 3.30. Time series of number concentrations of 100 nm to 2.5 µm diameter particles during cooking experiment with System D on July 16, 2014.
Fitted decay rates during each period reflect sum of all particle transformation and removal mechanisms including growth, ventilation, deposition and filtration.

Figure 3.31 presents the time series of 6–100 nm particles calculated as the difference between the preceding two data series. Results are presented as sequential indoor and outdoor series because only one CPC3787 was operational, as noted above.

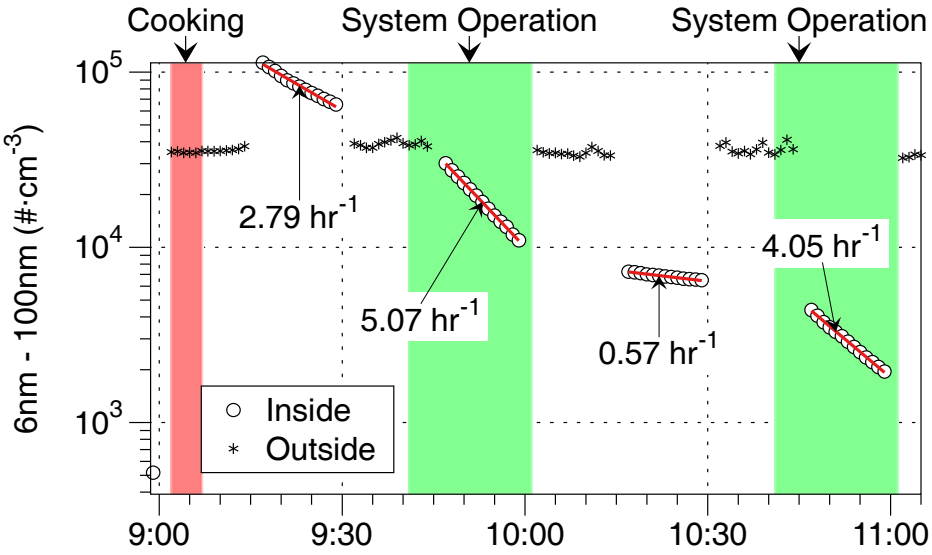

Figure 3.31. Time series of number concentrations of 6–100 nm diameter particles during cooking experiment with System D on July 16, 2014.
Data obtained by subtracting counts in range of 100 nm – 2.5 µm from counts in range of 6 nm – 2.5 µm. Data gaps for inside and outside time series correspond to periods when the CPC3787 with a wick problem was monitoring in each location. Fitted decay rates during each period reflect sum of all particle transformation and removal mechanisms including growth, ventilation, deposition and filtration.

Figure 3.32 presents the time series of 100–300 nm particles calculated as the difference between the CPC 3781 data and the combined particle counts from all size bins of the MetOne 637 optical particle counter. The figure shows three distinct decay rates starting from the peak after cooking. These data also indicate some modest variations in decay rate during the second interval of system non-operation.

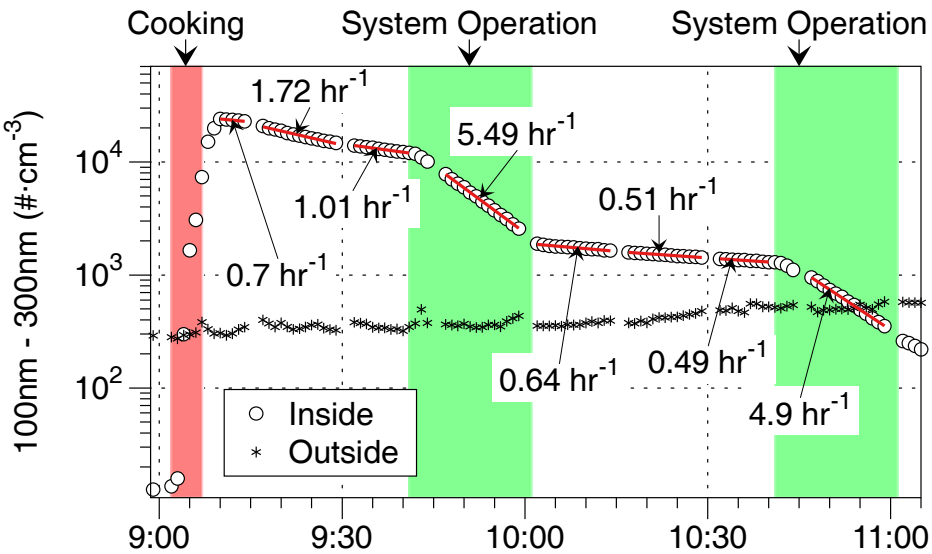

Figure 3.32. Time series of number concentrations of 100-300 nm diameter particles during cooking experiment with System D on July 16, 2014.
Data obtained by subtracting counts in range of 0.3–2.5 μm particles (MetOne 637) from the counts measured in the range of 100 nm–2.5 μm by the CPC3781 with size selective inlet. Fitted decay rates during each period reflect sum of all particle transformation and removal mechanisms including growth, ventilation, deposition and filtration.

Figure 3.33 presents the time series concentration for 0.3–0.4 μm particles. This plot shows *increasing* concentration for this particle size bin during the interval after cooking and before system operation. This phenomenon occurred for cooking experiments with Systems A, B, C and one of two Reference system experiments. We hypothesize that this results from smaller particles growing into the 0.3–0.4 μm size bin (from the 100–300 nm bin) by condensation of organic gases and water vapor that were released during cooking. The relatively low decay rate during the first period of system operation (compared to the second period of system operation) may reflect the contribution of ongoing growth into this size range during that time interval. While these details suggest that caution should be exercised when considering the generalizability of the fitted decay rates to other indoor particles, it is important to also recognize that complex particle dynamics occur following many indoor particle generation events.

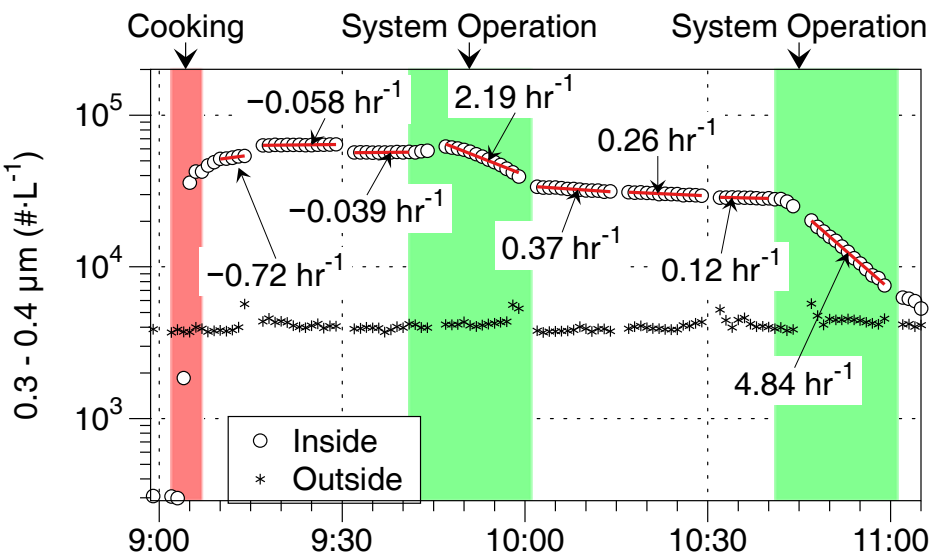

Figure 3.33. Time series of number concentration of 0.3–0.4 µm diameter particles during cooking experiment with System D on July 16, 2014.
Fitted decay rates during each period reflect sum of all particle transformation and removal mechanisms including growth, ventilation, deposition and filtration. Disconnected data during period just after cooking are from the two instruments switching between indoors and outdoors and may reflect small differences in the sampling efficiency at the lower cut point that is particularly sensitive to rapidly changing particle size distributions from the indoor source. Negative decay during this period indicates that particles in this size bin are increasing.

Figure 3.34 presents results for 0.4–0.5 µm particles. The small increase in particles during the first fitted time period just after cooking suggests there could be growth into this size bin as seen for the 0.3–0.4 µm particles, but at a much lower magnitude. By the second set of data used for fitting, the decay rate is solidly positive (decreasing concentrations). However, the fitted decay rates during this interval are a bit lower than those during the second interval of system non-operation, suggesting the possibility of a small amount of ongoing particle growth.

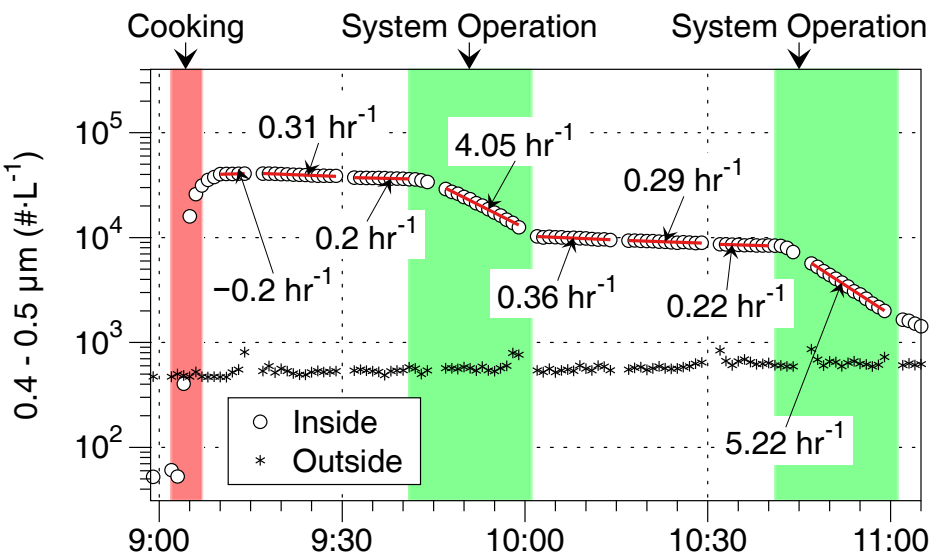

Figure 3.34. Time series of number concentration of 0.4–0.5 µm diameter particles during cooking experiment with System D on July 16, 2014.
Fitted decay rates during each period reflect sum of all particle transformation and removal mechanisms including growth, ventilation, deposition and filtration.

The time series for 0.5–0.7, 0.7–1.0, and 1.0-2.5 µm particles, which are presented in Appendix IN-6-D, show decay rates through all intervals increasing with particle size. The appendix also presents results for $PM_{2.5}$ mass concentrations based on the DustTrak.

Figure 3.35 presents the time series of $PM_{2.5}$ mass estimated from particle number concentrations. This figure shows that indoor $PM_{2.5}$ concentrations from cooking reached a peak that was more than 2 orders of magnitude larger than outdoor levels during this experiment; but over the two hourly cycles of intermittent operation of System D the indoor concentrations dropped to within a factor of 2 of the outdoor levels. $PM_{2.5}$ decay rates during system operation were 5.5 h^{-1}.

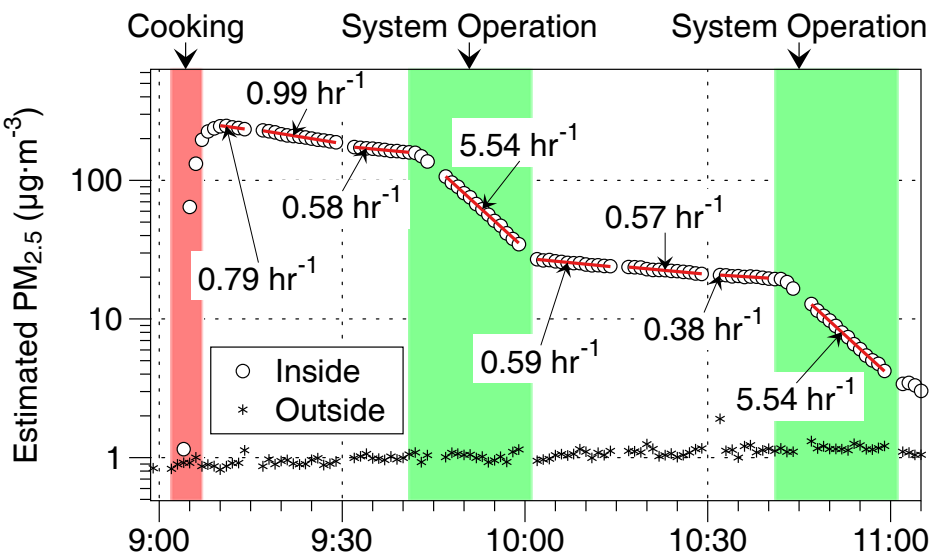

Figure 3.35. Time series of estimated $PM_{2.5}$ concentration calculated from size-resolved particle number concentrations during cooking experiment with System D on July 16, 2014.
Refer to Methods section for details on this calculation. Fitted decay rates during each period reflect sum of all particle transformation and removal mechanisms including growth, ventilation, deposition and filtration.

3.5.2 Comparison across systems – performance for indoor particles

Summary results from the "as-tested" performance assessments for indoor particles are provided in the following two figures. Figure 3.36 presents system performance as the reduction in time-integrated concentrations relative to the Reference system, for each particle size fraction and for $PM_{2.5}$, over the first hour following cooking. Time integrated concentration is calculated as the integral of the measured concentration × time over a 1h period starting at the peak concentration just following cooking. Time-integrated concentration is a predictor of the exposure that would occur for a human occupant in the home at this time. The entry marked "Ref" was the second of two indoor particle experiments conducted with the Reference system and it is compared only to the first Reference system. All other entries are compared to the average exposure values calculated from the two Reference experiments. The plot unsurprisingly shows very similar performance for Systems A and B as for the Reference, because the enhanced filtration on those systems is on the supply stream; they provide no more protection for indoor-generated particles than is provided by the Reference system. Deviations from 0 in the percent reduction results for these three systems indicate the repeatability of the approach, as these are effectively replicates. The negative values reflect lower reductions relative to the Reference system. The small recirculation flow through System C (for blending/tempering) is too small to provide a benefit to indoor particle concentrations and exposures. Systems D, E, and G all provide moderate increments of benefit over the Reference system. A much larger exposure reduction benefit was observed for System F and for the Portable units, both of which featured continuous operation throughout the hour following cooking.

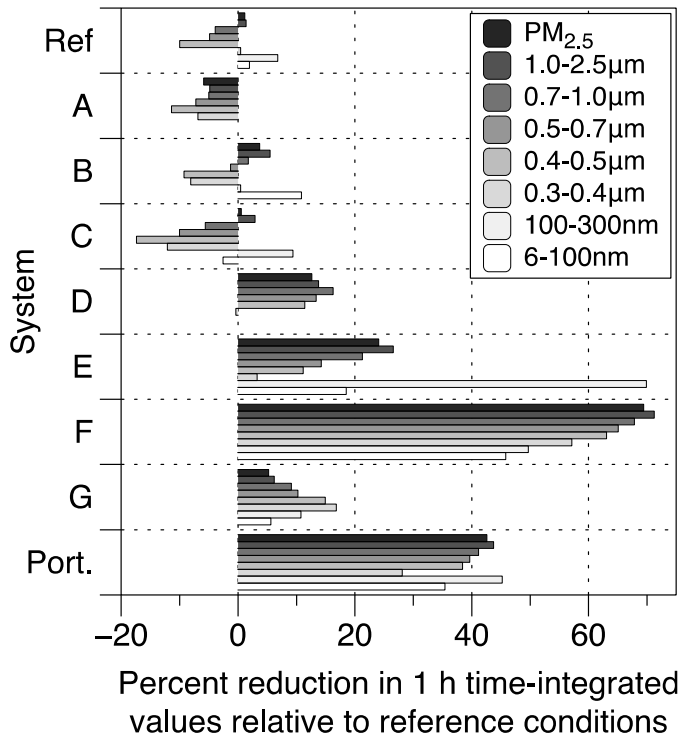

Figure 3.36. Percent reduction in time integrated concentration over 1 h following cooking, relative to reference conditions.
The 1h duration starts from the peak concentration just after a scripted cooking event. These results represent the minimum benefit for Systems D, E, and G, whose intermittent enhanced filtration was set to operate for the last 20 min of the hour following the cooking event. Results shown for "Ref" are the differences between two tests with the reference system.

The "as tested" performance experiments for indoor particles provide an estimate of the minimum benefit because the intermittent period of system operation occurred only at the end of the hour. For the first 40 min following cooking particle generation, the intermittent systems were effectively identical to the Reference. To assess the maximum potential benefit, we considered that any enhanced pollutant removal system could be operated over the entire hour starting with cooking. Figure 3.37 presents results from this assessment for estimated $PM_{2.5}$ mass. The baseline exposure is for no operation of the central heating and cooling system, since even the FAU and ductwork without special filtration provide some particle reduction benefit. It is based on the fitted first order decay over 1h. Exposure for the other systems is based on first order decay at the incrementally higher rates observed during system operation, compared to no central FAU operation. Thus, even the Reference and System A show great improvement over the baseline since larger, more massive particles are removed at non-negligible rates by the FAU and ductwork. Systems B, D, E, and G also have the potential to provide very large benefits in reducing exposures to indoor generated particles. The small negative and positive values for Systems A and B "as tested" again (as in Figure 3.36) reflect repeatability of the approach since they are effectively the same as the Reference when operated for the indoor generated particles.

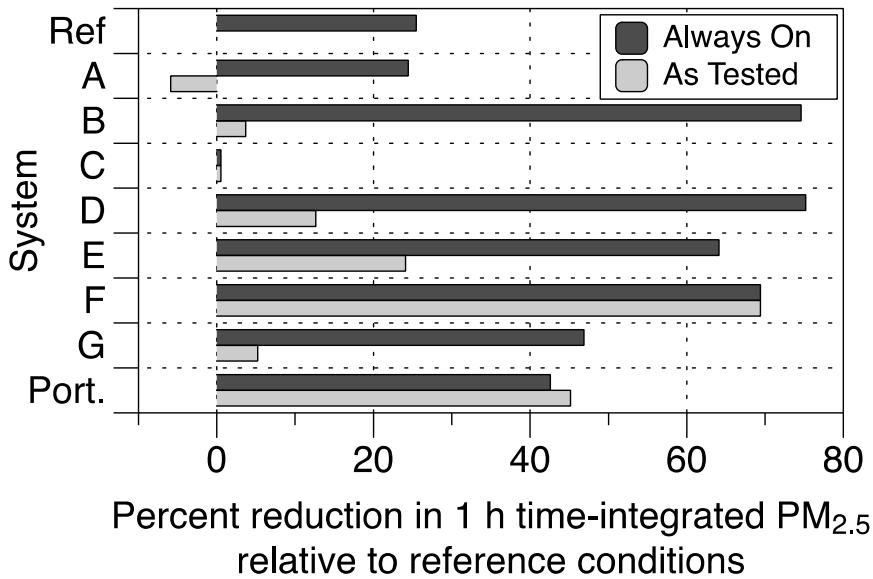

Figure 3.37. Estimated potential of systems to reduce time-integrated $PM_{2.5}$ concentrations over 1h following an indoor cooking event, assuming system operates continuously during the hour relative to a baseline Reference test[4].

3.6 SIZE-RESOLVED PARTICLE LOSS AND FILTER PERFORMANCE PARAMETERS

As an example of parameter determination from indoor time series data following cooking, the reader is referred to Figure 3.32, which shows the time series of 100-300 nm particles following cooking with System D. Indoor particle concentrations increased with cooking (shown in red shading starting just after 9:00 am) and reached a peak around 9:10 am. Decay rates of 1.7 h^{-1} and 1.0 h^{-1} were estimated from data intervals starting at roughly 15 min and 30 min following the start of cooking. The decay during the first period of system operation was estimated to be 5.49 h^{-1} and in the periods just before and after decay rates of 1.01 h^{-1} and 0.64 h^{-1} were calculated. We calculated the mean of the pre- and post-operating decay rates (0.83 h^{-1}) then subtracted this from the fitted rate during system operation to estimate the enhanced removal rate during system operation as 5.49 – 0.83 = 4.66 h^{-1}. The removal attributable to the higher quality filter was estimated by subtracting removal due to the higher air exchange rate at this time. That was determined as the difference between the SF_6 tracer decay measured during system operation (0.70 h^{-1}) and the tracer decay when the system was not running (mean of 0.17 h^{-1} and 0.063 h^{-1}, i.e., 0.12 h^{-1}), as shown in Figure 3.31. Thus, the removal rate attributed to enhanced filtration of System D was estimated as 4.66 – (0.70–0.12) = 4.08 h^{-1} for this particle size bin.

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[4] The "Ref" system in the figure was a repeated test of the reference system that was compared to the baseline reference test.

Results of the post-cooking time series data fitting are provided in Table 3.10 and Figure 3.38 below. Table 3.10 shows that for all particle sizes other than 0.3–0.4 µm, the apparent decay decreased over time following cooking. For 0.3–0.4 µm particles, there was a small net increase in concentration during each time interval. While it is beyond the scope of this project to fully understand these dynamics, we hypothesize that the cause is evaporation of organics and/or water vapor from the particles. The slow increase in concentration of 0.3–0.4 µm could result from larger particles losing mass / volume and winding up in that size range.

Table 3.10. Summary of calculated indoor decay rates following scripted cooking events.[1]

Period[2]:	~15-30 min			~30-45 min			~45–60 min		
Size bin	N	Mean	SD	N	Mean	SD	N	Mean	SD
6–100 nm	4	2.70	0.17	5	1.55	0.37	3	1.16	0.02
100–300 nm	4	1.48	0.42	6	0.95	0.29	3	0.68	0.20
0.3–0.4 µm	6	-0.03	0.24	6	-0.02	0.19	4	-0.01	0.13
0.4–0.5 µm	6	0.45	0.27	6	0.28	0.12	4	0.20	0.10
0.5–0.7 µm	6	0.77	0.22	6	0.46	0.09	4	0.30	0.09
0.7–1.0 µm	6	0.90	0.29	6	0.58	0.11	4	0.42	0.08
1.0–2.5 µm	6	1.32	0.29	6	0.82	0.11	4	0.61	0.05
Estimated $PM_{2.5}$	6	1.11	0.20	6	0.67	0.11	4	0.52	0.06

[1] Estimated by fitting of time series data following cooking from two experiments with Reference system and Systems A, B, D, and E. Some N values less than 6 because data were unavailable for a given metric / time interval combination. [2] Time intervals after the start of cooking.

Figure 3.38 shows the results of analysis to identify the filtration component performance for cooking generated particles. For all systems, the lowest removal rate was for 0.3–0.4 µm particles, and removal rates increased with particle size for particles larger than 0.4 µm diameter.

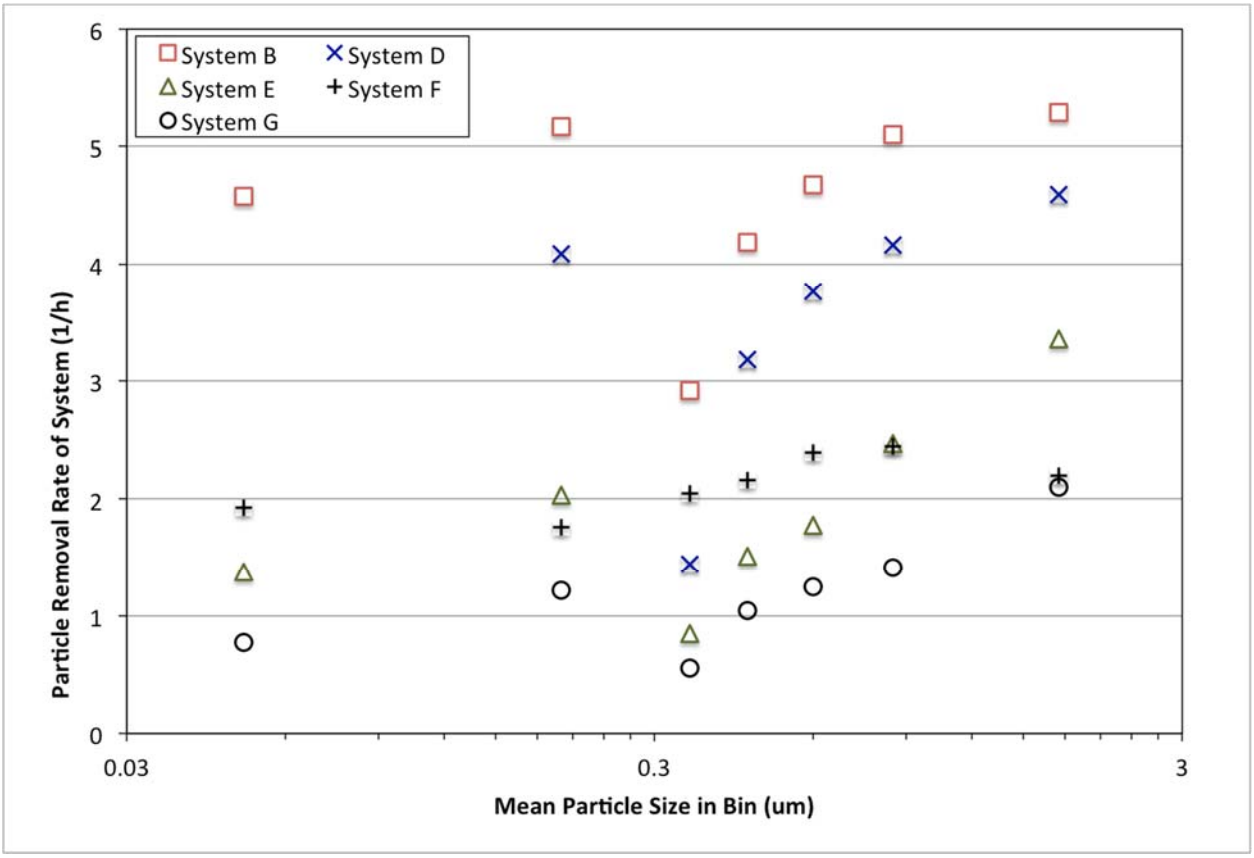

Figure 3.38. Particle removal rates attributed to system operation, estimated from time series data following scripted cooking events.
The result for each particle size bin is plotted at the arithmetic center of the bin. Results calculated only for the systems shown.

To determine filtration component removal rates for outdoor particles, we first conducted an analysis that used fixed deposition rates inferred from several of the cooking experiments. Figure 3.39 shows deposition rates for 0.3–2.5 µm particles from selected cooking experiments. Results from each experiment are placed at slightly different horizontal locations around the midpoint (linear) value of each size bin. These deposition rate estimates are from the last period of viable data from experiments with the Reference, and Systems A, D, and G. The data were selected from the following time intervals: Reference System, July 9, starting at 11:00; Reference System, July 23, 9:45-9:55; System A, 8:15-8:30; System D, 10:30-10:40; System G, 10:45-11:00. The reader is referred to the appendices that include plots of these data for more context. This figure also provides the central of three theoretical deposition curves presented by Lai and Nazaroff (2000) and data from deposition experiments presented in Abt et al. (2000), El Orch et al. (2014), Fogh et al. (1997), He et al. (2005), Howard-Reed et al. (2003), Long et al. (2000), Riley et al. (2002), and Thatcher and Layton (1995). Based on the range of values pulled from the cooking experiments, we created a curve that runs parallel to the Lai and Nazaroff theoretical curve and we used this line to select deposition rates at the mid-point of each particle size bin. These values are shown as stars in Figure 3.39.

The next step of this analysis was to use the deposition rates in Table 3.11 to determine penetration factors for outdoor particles coming indoors. To do this, we identified time intervals in the summer Reference system test when there was no FAU operation. This produced estimates of penetration factor by particle size shown in Table 3.11. The deposition and penetration factors in Table 3.11 were then fixed as the governing material balance (Equation 6) was fitted to indoor and outdoor time series when filtration systems were operating. This produced the estimated *system* removal rates shown in the top panel of Figure 3.40. These rates are translated to single-pass removal efficiencies (by accounting for airflow through the system) in the bottom panel of Figure 3.40. We note that the very low removal efficiencies estimated for the smallest particles is inconsistent with the expected performance profile. We were not able to conduct additional experiments or analyses to further investigate this finding.

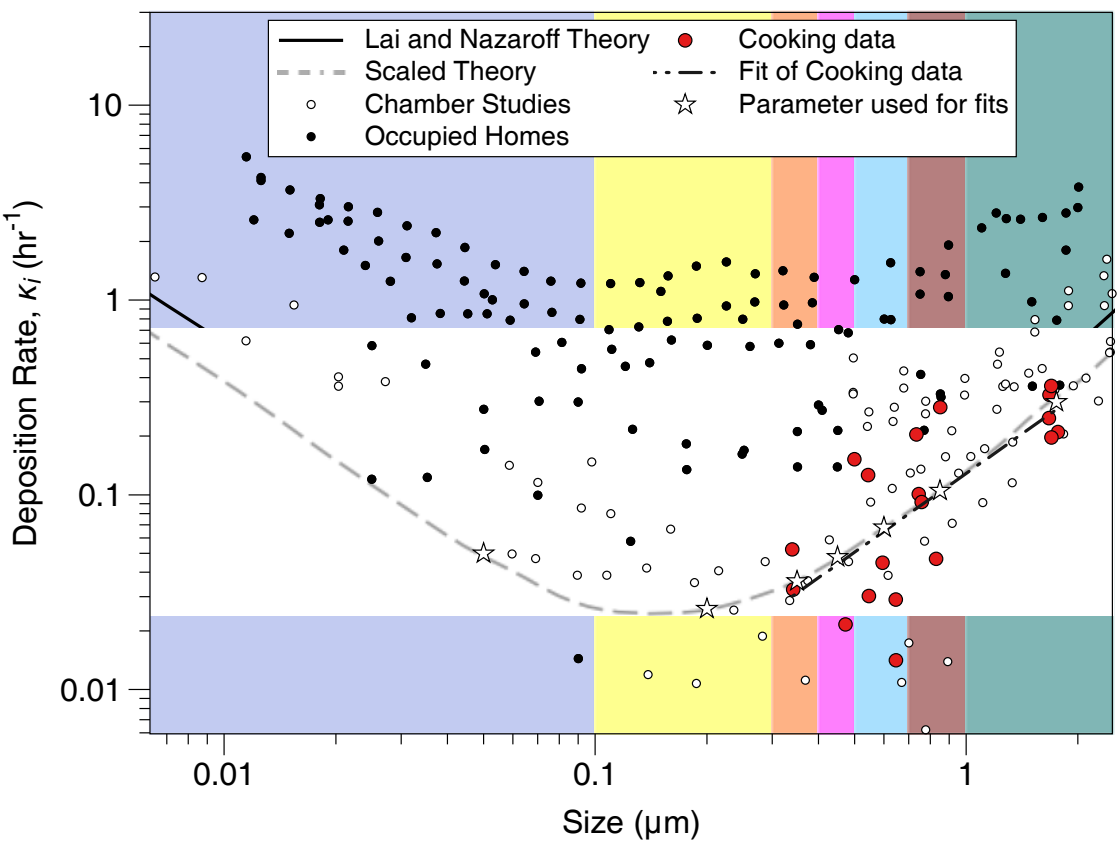

Figure 3.39. Selection of size-resolved deposition rates from indoor time series following cooking.

Table 3.11. Deposition and penetration factors used in fitting of time series data to get filtration parameters.

Particle Size	Deposition Rate (h^{-1})	Penetration Factor (unitless)
6-100 nm	0.05	0.13
100-300 nm	0.026	0.34
0.3–0.4 µm	0.036	0.49
0.4–0.5 µm	0.048	0.48
0.5–0.7 µm	0.068	0.48
0.7–1.0 µm	0.105	0.43
1.0–2.5 µm	0.3	0.41

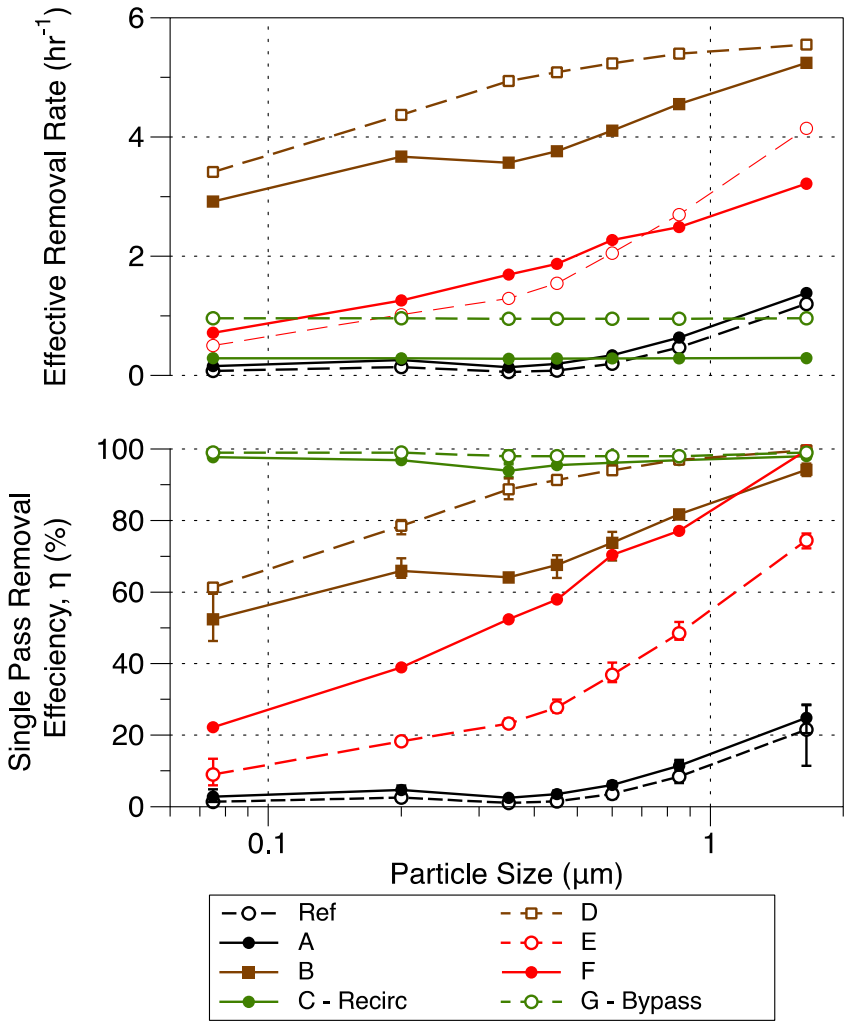

Figure 3.40. Estimated removal rates and efficiencies of recirculating air components of each system, based on stepwise fitting analysis that started with estimates of deposition after cooking.

The winter reference period occurred during a week when there was only a single, short interval of furnace operation. This provided an opportunity to isolate and fit deposition and penetration parameters. If the outdoor values are steady we cannot differentiate between low penetration and high deposition. The outdoor particle concentrations for many sizes varied by more than an order of magnitude over the period that we analyzed. This variability provided natural experiments to tease out the penetration and deposition values. We set up the LMFIT to solve for these parameters over a moving 8 h window over the entire week.

Results from the analysis that fit the governing material balance to simultaneously determine deposition and penetration values for outdoor particles are shown in the following series of figures. Figure 3.41 shows the fitted penetration efficiencies by particle size. The boxes and whiskers present the distribution of fits from the winter period and the circles present results from the six intervals of data fitting for summer. These penetration numbers indicate substantial loss / removal of particles as air infiltrations through the building envelope.

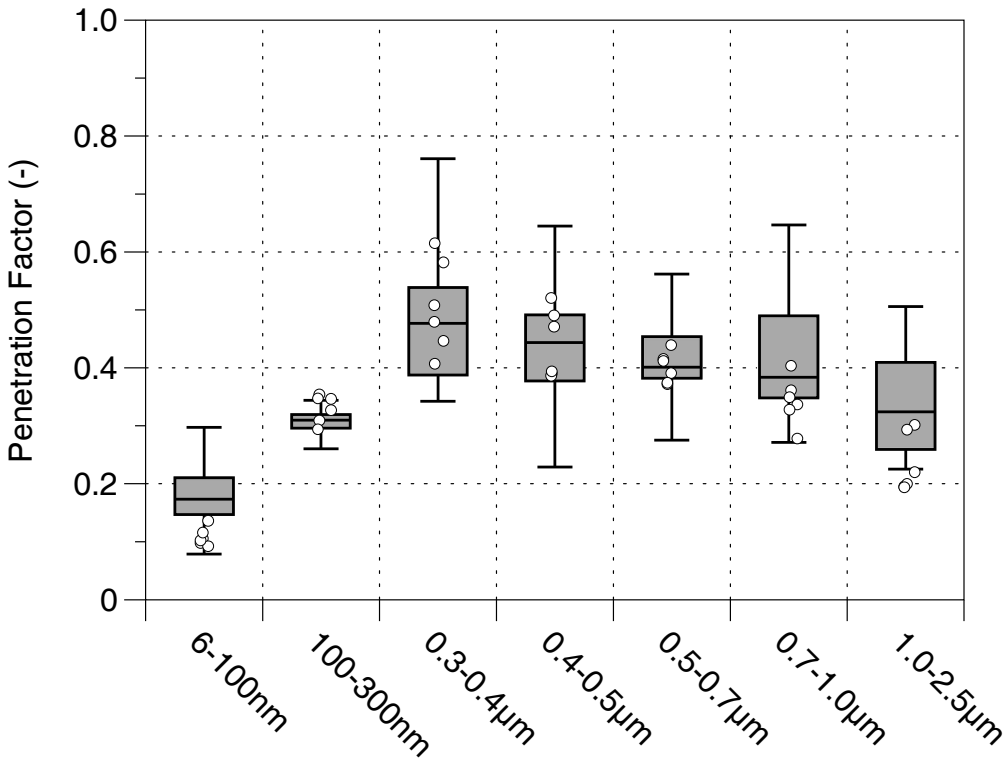

Figure 3.41. Penetration efficiencies estimated by fitting of time series data from the house configured with the Reference system, during periods when the forced air unit was not operating. The boxes and whiskers present the distribution of fits from the winter period and the circles present results from the six intervals of data fitting for summer

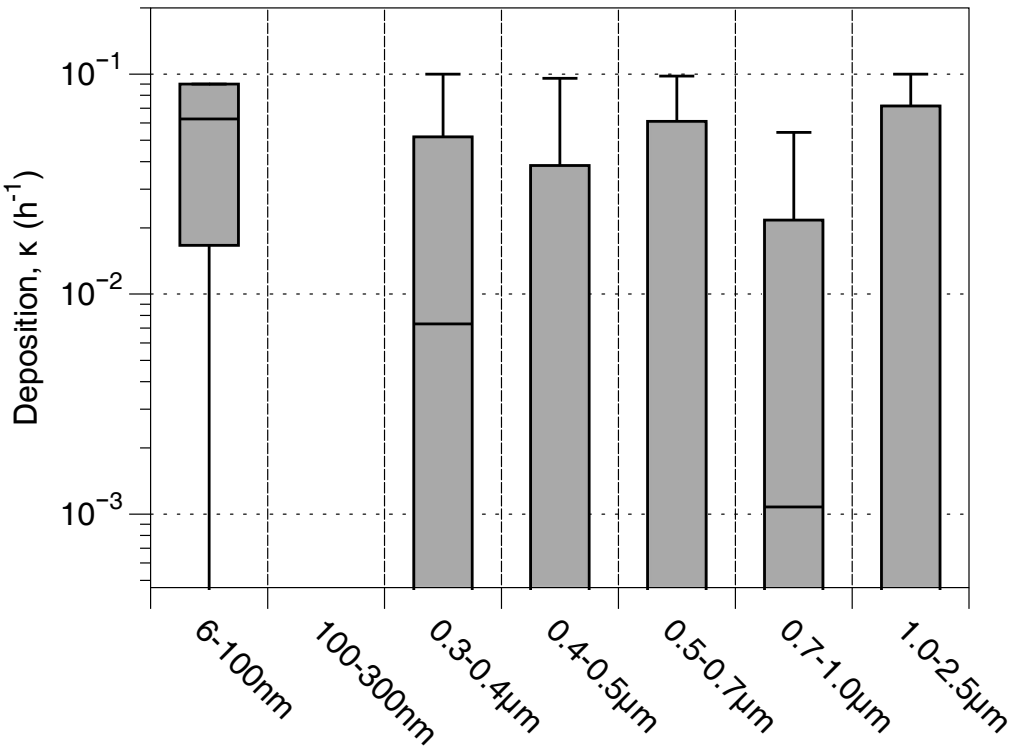

Figure 3.42. Indoor deposition rates estimated by fitting of time series data from the house configured with the Reference system, during periods when the forced air unit was not operating.

Figure 3.42 shows the fitted values of indoor deposition rate obtained from the series of 8h intervals over the winter monitoring period. The deposition rates were obtained from the same fits as the previously displayed penetration efficiencies. The key result here is that the deposition rate of outdoor particles inside the test house appears to have been extremely low across all particle sizes. No results are presented for 100-300 nm particles because the fitting program never provided a nonzero value of that parameter.

These fits for penetration values are close to what was determined from the analysis that started with deposition from cooking experiments. However, and importantly, the deposition rate determined from fitting to data related to outdoor particles appeared much lower than deposition rates determined from the cooking experiments. The difference is most pronounced for the largest particle size bin studied (1.0–2.5 μm), which had an estimated deposition of 0.3 h^{-1} from cooking experiment analysis and <<0.1 h^{-1} in the outdoor particle analysis. This difference should not have a substantial impact on the recirculating system removal rates determined for the 1.0–2.5 μm particles (Figure 3.40) since those rates are so much greater than even the higher deposition rate. Using the higher deposition rate determined from cooking particle experiments did, however, result in a substantially biased estimate of removal rate for outdoor particles of this size range for the filtered supply of Systems A and B. Fixing the deposition and penetration parameters to the values presented in Figure 3.41 and Figure 3.42 and fitting Equation 6 to the indoor and outdoor time series caused the calculated filter efficiency for 1.0–2.5 μm particles to increase from 21% to 52%.

Figure 3.43 shows the estimated single-pass system efficiencies for the supply systems and the effective source rates, presented as the product of the supply air exchange rate and 1-ε, where ε is the removal efficiency. The value shown for 1.0–2.5 µm particles for the MERV13 supply filter uses the deposition rates determined from fitting of outdoor particle data; all other values are from the stepwise fitting approach that started with deposition estimates derived from cooking experiments. The substantially higher removal efficiency for "penetration", i.e. for air infiltrating through the building shell with exhaust ventilation, relative to the MERV13 filtration on the supply reflects the lower indoor/outdoor ratios of the Reference compared with System A.

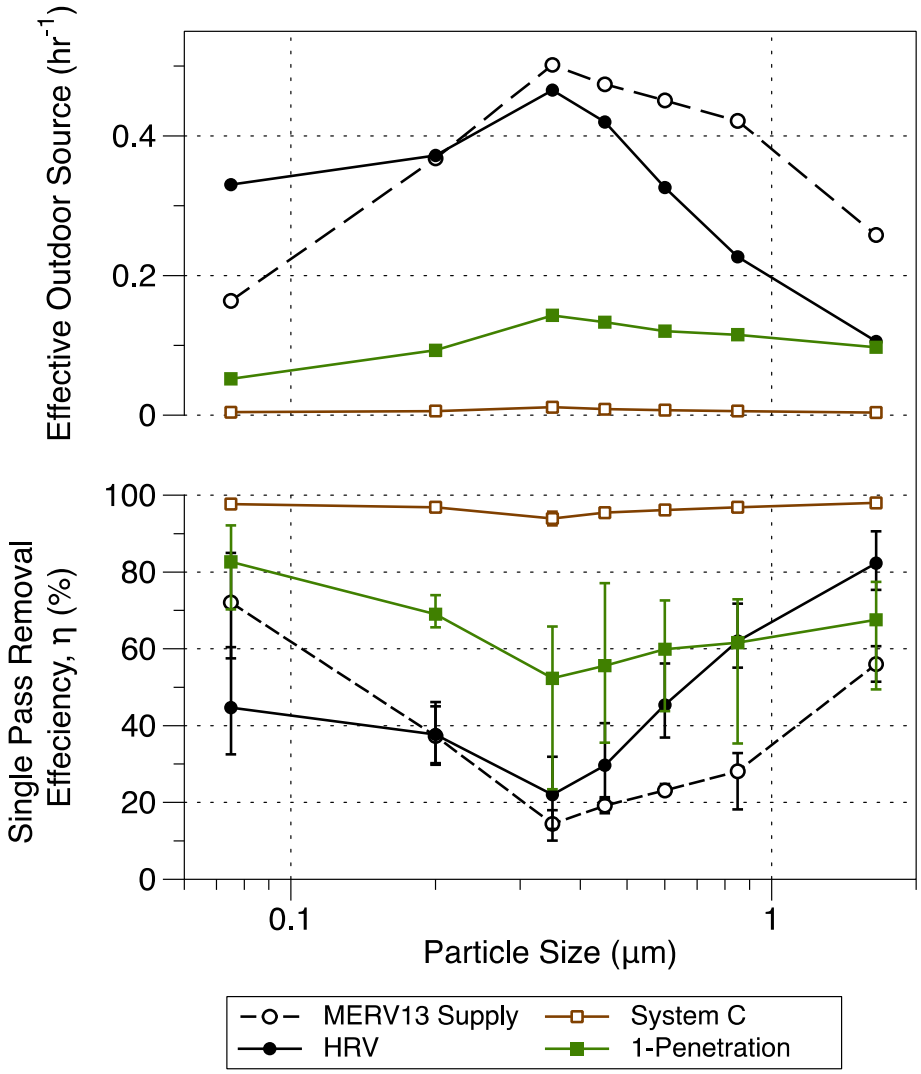

Figure 3.43. Estimated removal efficiency of particles entering home through various airflow pathways and the effective source rates for outdoor particles coming through these pathways.

3.7 Energy Use

Annual energy use estimates for the ventilation and enhanced pollutant removal systems evaluated in this study are presented in Figure 3.44. Details of the calculation methodology are

presented in Section 2.7. These estimates are for mid-2000s new homes compliant with Title 24 and the conditions represent something of a midpoint across California climate zones. Results would vary somewhat by climate zone and the specific characteristics of the home (including thermostat settings and other operational elements), all of which impact the baseline frequency and schedule of operation for the forced air system. The panel at left is for a conventional permanent split capacitor (PSC) FAU motor, as found in the test house. The panel at right is for a more energy efficient brushless permanent magnet (BPM) motor.

This figure provides several important insights. The most prominent is the jump in energy use that results when systems (D, E, and G) require routine operation of an FAU with PSC motor. The systems that have scheduled or continuous filtration only on supply fans (A-C) have much smaller energy penalties. This finding should be considered in the context that supply filtration can be very effective at reducing indoor exposures to outdoor particles (System C), but that design does not reduce exposures to indoor-generated particles. The Portable HEPA filtration units, which reduce exposure to both indoor and outdoor particles, require only a modest increase in energy use.

The panel on the right side shows that incorporation of an energy efficient blower motor reduces energy use for all systems, and has the biggest impact on the EPR systems that use the FAU. With a BPM motor in the FAU, installed Systems D and E –which provide substantial exposure reductions for both outdoor and indoor particles – require only about 600 kWh of extra energy per year.

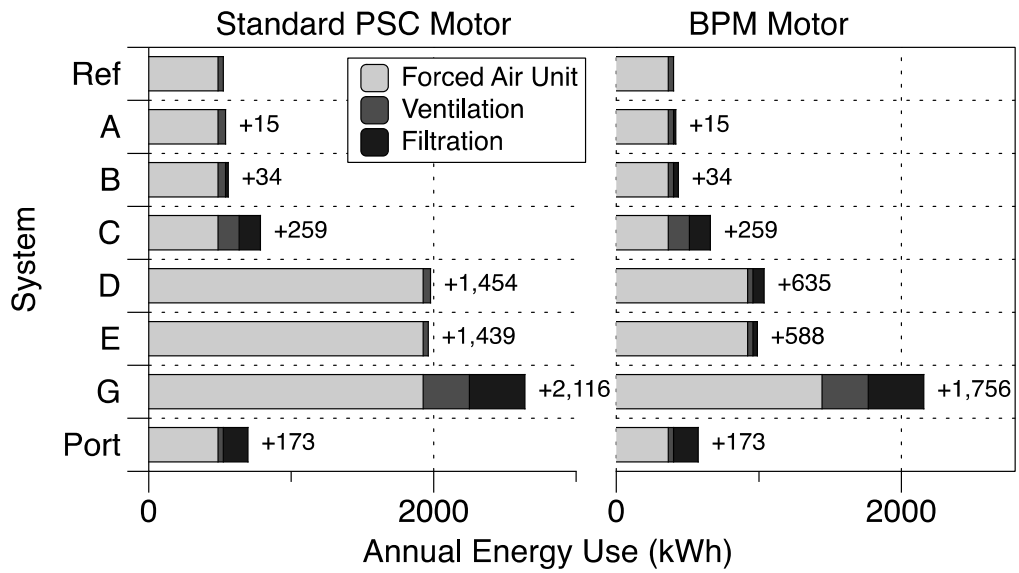

Figure 3.44. Estimated annual energy use of ventilation and enhanced pollutant removal systems evaluated in this study.
Results for the Reference system represent energy used to move air through the forced air system for heating and cooling along with energy to power the ventilation fan. Energy for thermal conditioning is not shown. Results for other systems include FAU fan energy for heating and cooling distribution plus any additional operation to accomplish enhanced pollutant removal. The panel at right presents estimates for a system with an energy-efficient, variable speed brushless permanent magnet motor. Refer to Section 2.7 for details.

This analysis does not provide an explicit estimate of the incremental energy cost for System F because the mini-spilt heat pump cannot be assumed to have the same baseline operating schedule as the conventional forced air system. With variable control of both heating/cooling and airflows, mini-splits typically operate over more min and hours than conventional systems. This is both because of the variable controls of mini-splits and also because conventional heating and cooling systems are often oversized and this is particularly true for energy efficient homes. Mini-splits and right-sized conventional systems that operate more of the time for heating and cooling will have a smaller incremental energy cost for the added operation time for enhanced pollutant removal.

Energy costs for all systems that use the forced air system would be lower if the enhanced pollutant removal operation occurred only when the home is occupied or about to be occupied. This control could be accomplished easily with a smart or learning thermostat.

3.8 FILTER IMPACTS ON AIRFLOW AND POWER CONSUMPTION

The effect of filter resistance on airflow and power consumption is displayed in Figure 3.45, which shows the FAU fan curves along with system curves representing the various filters, and Table 3.12. The two fan curves represent the two operating speeds of the FAU. Typical for this type of system, the fan was set at a higher speed for cooling than for heating. Fan curve data were obtained from the manufacturer's specification sheet. The system curves represent the combined resistance of the ductwork, FAU cabinet, cooling coils, and the filters. The actual flow delivered by a system is the intersection of the system and fan curves. We used filter curves from manufacturer specification sheets and adjusted the other resistance such that the combined resistance profile of the system curve matched the measured flow at the intersection with the fan curve for cooling mode. The close agreement between the measured heating mode airflow and the intersection of the fitted system curve with the heating fan curve provides some assurance that the system curve is correct.

The effect of resistance on airflow and power is presented in Table 3.12.The PSC-motor used in the FAU is essentially a constant speed motor. Adding resistance to this system produces lower flows. The least restrictive system was the MERV4 filter. The ESP had very little internal resistance (which, for an ESP, is determined by the distance between the charging grids), and it had essentially the same effect as the MERV4 filter on system performance. We show for comparison purposes the calculated airflow and fan efficacy of the MERV16 filter without the PuraGrid product, even though we did not test pollutant removal of this configuration. The 2.5 cm MERV13 filter was more restrictive than the deep pleat MERV16 and it cut the flow by 4.9%. Combining the PuraGrid cartridge with the MERV16 filter created the highest resistance, which cut the flow by 12.3%. The drop in flow (determined from system and fan curves) caused a drop in power consumption (measured) and the fan efficacy remained nearly constant.

It is important to note that for some FAU fans and installed ducting, the increase in resistance of a higher rated filter could result in a larger reduction in airflow. In cooling mode, a drop in flow causes a drop in cooling coil temperatures and cooling efficiency. If flow drops too much the coil temperature can drop below freezing and block airflow. Concerns about these effects inhibit HVAC contractors from installing or recommending filters that are rated for higher fine PM removal. While use of low resistance filters mitigates the risk of a problem developing, it is important and valuable to design or retrofit ductwork for low resistance irrespective of filtration.

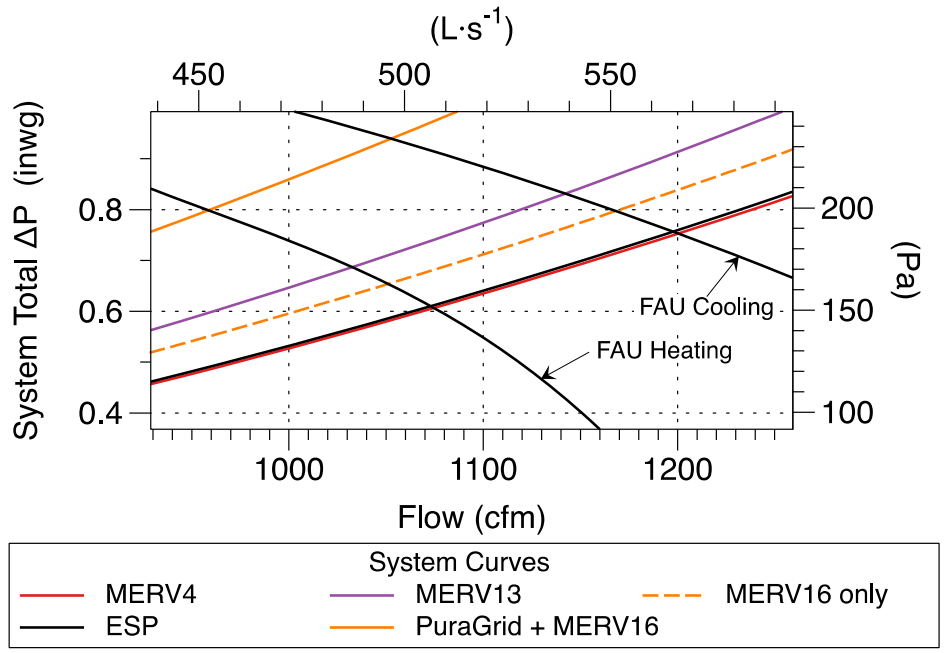

Figure 3.45. Intersections of forced air unit (FAU) fan curves and inferred systems curves based on product specification sheets and measured airflows.

Table 3.12. Calculated effect of filters on airflow, power, and fan efficacy.

Filter	System	Flow (cfm) [1]	Change in flow (%)	Power (W)	Change in Power (%)	Efficacy (cfm/W) [1]
MERV4	Ref, A, C, G	1200	-	660	-	1.82
ESP	B	1198	-0.2%	659	-0.2%	1.82
MERV16 (deep pleat) only	Not tested[2]	1168	-2.7%	647	-2.0%	1.81
MERV13 (2.5 cm)	E	1142	-4.9%	626	-5.1%	1.82
MERV16 (deep pleat) + PuraGrid	D	1052	-12.3%	605	-8.4%	1.74

[1] Flow and fan efficacy provided in units most commonly used for evaluation of home and HVAC energy efficiency.
[2] Flow and power for the MERV16 filter without PuraGrid provided as relevant to system configuration without VOC removal media; this study did not test that configuration independently of System D.

4 DISCUSSION

This section first presents a brief discussion of the key performance results for the primary study metrics of pollutant removal and energy use for the systems evaluated in this study. We then explore more broadly how the results of this research may inform the consideration of using filtration and air cleaning throughout the housing stock. The section continues with reflections on the strengths and limitations of the approach employed for this study, and concludes with recommendations for future research into the performance of residential ventilation and filtration for enhanced pollutant removal.

4.1 PERFORMANCE FOR POLLUTANT REMOVAL AND ENERGY

The first finding of note is that the Reference configuration, with the test house operating with windows closed and mechanical exhaust ventilation set to the rates required by Title 24, provided significant reductions in outdoor $PM_{2.5}$, UFP, BC and ozone. Time-averaged concentrations in the test house with the Reference system were lower than outdoors by 66–73% for $PM_{2.5}$, 84–87% for UFP, 48–58% for BC, and at least 97% for ozone. It was not possible to discern higher reductions for ozone because the indoor ozone levels were below the instrument quantitation limit. An important factor in the protection provided by the Reference configuration is the substantial removal rate of particles as ventilation air was pulled into the home through the relatively tight envelope. The windows-closed protectiveness for outdoor particles and ozone provided by newer, California homes with exhaust ventilation could be even higher than in the house used for this study since (a) deposition rates in the unfurnished test house were lower than those measured and expected in homes with residents, and (b) many newer homes have tighter envelopes than the test house, presumably translating to lower penetration factors.

An important caveat to the performance of the exhaust ventilation system is that it pulls air through envelope assemblies that can be a source of chemical air pollutants into the home. In a study of airtight, energy efficient test homes in Tennessee, Hun et al. (2013) found that indoor formaldehyde levels were much higher when outdoor air was provided by exhaust versus supply ventilation. In the current study, indoor formaldehyde was measured for only four systems (all during the summer period): Reference, C, D, and G. The highest indoor formaldehyde concentrations, of about 94 ppb, were measured for the Reference system with exhaust ventilation and no air cleaning. Systems D and G, with air cleaning on the recirculating central air handler and exhaust ventilation, had indoor formaldehyde of 88-89 ppb. System C, which featured air cleaning on supply ventilation and an insignificant amount of recirculation (for tempering only), and thus no substantial VOC removal for indoor air, had indoor formaldehyde levels of only 80 ppb. This result suggests that switching from exhaust to supply ventilation provided more formaldehyde reduction benefit than the air cleaning systems used in D and G. Since other research (Hult et al. 2015) has shown that constructing homes with low-emitting materials is an effective approach to reducing indoor formaldehyde, and significant reductions are expected to result from California's Air Toxic Control Measure that limits formaldehyde in composite wood products (http://www.arb.ca.gov/toxics/compwood/compwood.htm), further research is needed to assess the impact of exhaust versus supply ventilation on formaldehyde concentrations in new California homes. A currently ongoing research project funded by the California Energy Commission (CEC Contract PIR-14-007 with Lawrence Berkeley National Laboratory) is collecting data in new California homes that should help to answer this question.

The next key finding is that high quality filtration on a supply ventilation system can provide very high levels of protection against outdoor particles. When operated in the System C configuration, with MERV16 filtration on a blended supply ventilation system, indoor time-averaged concentrations in the test house were lower than those outdoors by 97–98% for $PM_{2.5}$, 97–99% for UFP, and at least 84–92% for BC and 97% for ozone. In this configuration, both ozone and BC inside the home reached levels below instrument quantitation limits. System C is projected to use approximately 0.7 kWh per day in extra site energy (compared to the Reference system); but that energy burden could be cut if the high quality filtration were applied only to the minimum required flow of outdoor air instead of a blend of roughly 40% outdoor to 60% indoor air. The performance of Systems A and B, with MERV13 filtration on supply ventilation, was somewhat worse than the Reference system. Since even worse performance and higher indoor concentrations of outdoor pollutants would result if there were even less effective supply ventilation, this result indicates the importance of providing high performance filtration when using supply ventilation.

An important corollary to the finding that high performance supply filtration can protect against outdoor particles is the fact that supply filtration does nothing to improve protection against indoor generated particles. The small amount of recirculation / blending flow of System C was not enough to meaningfully impact the calculated 1h time-integrated concentrations following cooking. The ESP on System B has benefits to indoor particles when it is used. It lowered the first hour time-integrated concentration of cooking particle $PM_{2.5}$ by almost 75%. Since this system was also observed to produce ozone, the particular equipment has to be considered unsuitable to meet the objective of this study. But the ESP could be easily replaced with a high performance (e.g. MERV13 or higher) filter in the same configuration.

The incorporation of MERV16 filtration into the home's recirculating forced air system with regular (intermittent) operation, as implemented with System D, produced protection levels for outdoor particles that rivaled those of the MERV16 supply filtration of System C while also reducing exposures to indoor-generated particles. With the test house in the System D configuration, indoor time-averaged concentrations were lower than corresponding outdoor levels by 97% for $PM_{2.5}$, 97–98% for UFP, and at least 93–96% for BC. Relative to the Reference, System D produced first hour time-integrated $PM_{2.5}$ reductions for cooking particles of roughly 13% when operated on a schedule that provided the least protection (system was off for first 40 min then on for 20 min). If System D were operated continuously for the hour, it is estimated to reduce first hour exposures by 75% relative to Reference. And the exposure reductions for indoor-generated particles increase as the evaluation duration increases.

Another important finding was that MERV13 filtration on the recirculating forced air systems provided protection levels that were just a bit below those of the MERV16 system. This is important because MERV13 filters can be found in one-inch depths without introducing excessive airflow resistance. This makes MERV13 filters easy to use both in new construction at filter grilles or furnace filter slots without changing system design or equipment selection and in retrofit situations where it would not be necessary to install a new filter mount. System F featured a deep pleat MERV13 filter on a mini-split fan-coil unit that ran continuously at a lower speed / flow and System E had a 1" MERV13 filter on the installed FAU running on a 20/60 cycle. System F provided indoor concentrations that were lower than corresponding outdoor levels by 95–96% for $PM_{2.5}$, 96% for UFP, and at least 86–92% for BC. System E provided indoor concentrations that were lower than corresponding outdoor levels by 88–91% for $PM_{2.5}$,

93% for UFP, and at least 80–84% for BC. As operated, System E showed a minimum protection benefit of 22% relative to Reference, for first-hour, time-integrated concentrations following cooking. And continuous operation over that hour would produce an exposure reduction benefit of 64%. System F, operated continuously by design, reduced first-hour, time-integrated $PM_{2.5}$ concentrations following cooking by 68%.

The demonstrated pollutant reduction benefits of all three of these central systems (D, E, F) must be considered against the substantial energy use requirements of any system that relies on the forced air heating and cooling system and ductwork. With a standard forced air system with PSC motor, Systems D and E are projected to use about 1450 more kWh/y than the Reference. The estimated energy costs of these systems drop dramatically – to roughly 600 kWh/y – if the FAU features an ECM motor that can be operated continuously in an efficient, low speed mode. The energy cost of having a mini-split run continuously for enhanced pollutant removal is estimated to be similar or lower. Advanced controls that operate these systems only when the home is occupied or about to be occupied could reduce energy costs for all systems that use filtration.

System B provides insight about the potential benefits of adding enhanced pollutant removal to the forced air system but not including a minimum (20/60) run time controller. Recognizing that the performance of the ESP, which was found to produce ozone and is therefore not recommended, could be accomplished with a media filter, we look to the summer monitoring period for System B to provide an estimate of non-timer controlled FAU filtration benefits. During this period, the FAU operated intensively for 4 of the afternoons, then progressively less intensively for the remaining 3 afternoons. The ratio of indoor to outdoor 24h concentrations of $PM_{2.5}$ was 19% for the week, meaning that indoor $PM_{2.5}$ was 81% lower than outdoors. The enhanced pollutant removal system thus was helpful, at least during the peak of the cooling season.

System G, which combined an HRV with a HEPA + activated carbon bypass, provided much less protection against outdoor particles than either the high performance supply filtration System C or the recirculating forced air Systems D, E, and F. And this relatively poor performance came with the highest energy burden of any of the systems tested. It is important to note that the bypass component of this system was sized for continuous rather than intermittent operation, but operating the system continuously would involve even greater energy costs. There is a 3x larger version of the bypass system that meets manufacturer guidance for capacity but uses 100W more power. That translates to an additional 321 kWh per year of energy, making this system even less workable from an energy standpoint.

Another important, if unsurprising, finding is that the level of protection that systems provide for short-term peaks (e.g. highest daily 1h concentration) generally exceeded the protection level for longer-term averages. This is a general feature of being indoors that is augmented by the benefits of a tight building shell, low air exchange rate, and high removal rate for air infiltrating through the building envelope.

Although they were not the focus of this study, the two portable units provided protection on par with System E at a small fraction of the energy use. The potential role of portable units is further discussed in the next sub-section.

4.2 COMPREHENSIVE ASSESSMENT OF PERFORMANCE AND SUITABILITY FOR CALIFORNIA

This sub-section considers the results of the extensive performance assessment of selected systems in the context of other criteria and constraints for enhanced pollutant removal systems to be incorporated into building codes, high performance home standards, and retrofit practices.

We note first the following considerations and constraints.

The Reference system architecture of a forced air heating and cooling system with baseline mechanical ventilation provided by a single exhaust fan in a home with a substantially airtight envelope is currently and will remain for some time the basis against which alternative systems will be considered. The Reference system provides no explicit filtration or air cleaning enhancements for protection against outdoor- or indoor-generated pollutants, but the building code requires on demand exhaust ventilation in kitchens and bathrooms. When used, these local exhaust fans remove pollutants, odors and excess moisture generated by sources in these rooms. While the temporary increase in ventilation rate can bring more outdoor pollutants into the home, the design intent is to efficiently exhaust air containing high concentrations of contaminants before they mix throughout the home.

The potentially large energy cost that results from extended operation of a conventional system with PSC motor can be greatly reduced with an efficient BPM motor that is operated continuously at low speed, and further reduced if operated only when occupied. While the energy costs of running the FAU for filtration may make that configuration an unsuitable option for green and high performance home standards, it may still be a good option for individuals who are particularly vulnerable to air pollution health effects.

Though limited in scope, the measurements and analysis of filter airflow indicated no substantial performance problems when deploying high performance filtration in the conventional FAU in the test house. Filters with higher resistance had lower airflow and correspondingly lower power consumption.

Another simple and relatively low cost upgrade is MERV16 filtration on the supply. This system is very effective at reducing exposure to outdoor particles for a relatively small energy cost. While the blended system has the advantage of being more protective of comfort, it may be sufficient to distribute the small flow of unconditioned air through a tie-in to the ductwork (as we did for System A). This could reduce energy cost from the already small 260 kWh to <60 kWh per year. The latter is calculated as the increment shown for System A + 40% of the filtration energy cost shown for System C. That system has the added benefit of requiring less ductwork than System C and it provides ventilation air throughout the home. One big downside to that approach – the lack of filtration for indoor generated particles – can be overcome by installing some recirculation filtration – either in the central air handler or portable air filtration units – that are operated as needed.

Though not evaluated quantitatively in this study, it is very important to recognize that supply ventilation without filtration is likely to produce higher indoor concentrations of outdoor pollutants, relative to the Reference system. In this study, the supply ventilation system *with MERV13 filtration* had overall higher indoor/outdoor ratios for outdoor $PM_{2.5}$, UFP and BC. Supply ventilation with lower quality or no particle filtration is expected to produce higher indoor concentrations of outdoor particles. If this finding is reinforced through further study, it could constitute an argument for a building code requirement that supply filtration systems

include filtration of at least MERV13 or equivalent quality. Even without further study, there may be sufficient basis to incorporate supply filtration into green / high performance home standards.

The results of this study leave open the question of the quality of filtration that is necessary or advisable for supply ventilation. Filtration on the supply air stream faces the challenge of being a single-pass system that has only one opportunity to clean the air that is mechanically moved through the system. By contrast, filtration on the FAU return will typically process 4 or more residence air volumes during each hour of operation, and at least 1 residence volume of air during a 20-min cycle of operation. This can be compared to supply ventilation airflow on the order of 0.25 air volumes (air changes) per hour or less. This contributes to the observed difference in MERV13 filter performance between Systems A and B, which had a MERV13 filter on the supply, and Systems E and F, which had MERV13 filters on a recirculation loop inside the home and performed much better.

It is also very important to recognize that the MERV rating system is not designed to provide consistent size-dependent performance curves over all particle sizes; as a result, filters with the same MERV rating can have very different performance. The three MERV13 filters used in this study appeared to have substantially varying single pass performance based the analysis presented in Section 3.6. The 10 cm (4") deep pleated MERV13 filter used in System F appeared to have substantially better single-pass capture than the 2.5 cm (1") deep MERV13 filter used in System E. The 5 cm (2") MERV13 filter used on the supply for Systems A and B had single-pass efficiencies that were somewhat lower than the System E filter for particles larger than 0.3 μm diameter but substantially higher than that filter for particles smaller than 0.3 μm diameter. There also appeared to be differences in the single-pass efficiency of the MERV16 filters in Systems C and D, with the filter in C having much higher removal efficiency for the smallest particles. Consistent with these performance measures, there were much larger differences in overall performance between MERV13 and MERV16 filters on the supply (A compared to C) than on the FAU (E and F compared to D).

Another issue to consider for new homes standards and options is the trend of increasing air tightness. A home that has less than 3 ACH50 compared to the 5 ACH50 of the test house is highly likely to have even higher removal rates for infiltrating air (Stephens and Siegel (2012)), leading to even lower indoor concentrations of outdoor particles. This could lead to even bigger differences between unfiltered supply and exhaust ventilation systems.

Changes to heating and cooling equipment as insulation and airtightness levels increase could also offer opportunities for both new homes and retrofits. An increase in the availability and use of multistage / variable output equipment that also has sophisticated controls could lead to more opportunities to modulate filtration airflow for lower energy operation.

Because systems using FAUs only operate when there is a call for heating or cooling, their operation will be increasingly more limited as homes become energy efficient. Central systems in very efficient homes will also have lower airflows providing less filtration for each increment of time that the system operates.

The VOC assessment was limited by low concentrations of outdoor VOCs. All three systems with VOC removal technology achieved modest improvements over the Reference system. Higher capacity VOC removing systems are likely to show significant improvements over the

performance achieved by the three tested systems. These had limited capacity, considering both the amount of sorbent/catalyst used and the airflow through the systems, even though these conditions are typically recommended for residential use.

4.3 STRENGTHS AND LIMITATIONS OF THIS STUDY

The design of this study – in which various systems for ventilation and enhanced pollutant removal were installed in the same, unoccupied test house – enabled assessment of relative system performance for similar mixes of outdoor particles, ozone and VOCs; for indoor VOCs emitted by the materials in the home; and for the same indoor particle source. This design had the great strength of avoiding confounding effects of varied occupancy-related sources and occupant activities that affect ventilation.

The design of conducting an evaluation in an unoccupied house also represents a noteworthy limitation since the exposure reduction performance of any system will be greatly impacted by occupant activities and occupancy patterns. Studying such effects requires data collection in a relatively large number of homes and can only be done for a limited collection of systems.

The sophisticated particle monitoring system used for this study – with identical suites of instruments intermittently switching between indoors and outdoors – enabled collection of a large quantity of robust, high quality data from the unoccupied test house. The system was expensive to set up and required extended periods of commitment for a large quantity of monitoring equipment. Yet it provided the valuable functional feature that valid data were obtained during periods when single instruments failed because the companion instrument (on the other switching manifold) continued to collect data from both indoors and outdoors at adequate resolution. This system necessarily relied on measurements at one central location inside the home. Several fans were placed throughout the living space and operated to promote mixing at all times, even when the forced air system was not running. While this configuration was expected to produce an effectively well-mixed house, we did not confirm the uniformity of pollutant concentrations at any time with measurements.

As with all experimental studies, results from this study are based on data obtained from a limited range of conditions. The physical structure of the house, its as-found mechanical system, and characteristics of the local outdoor air pollution are reasonably representative and relevant to many homes throughout California. And the analysis approach of considering indoor / outdoor ratios and relative reductions of indoor-generated particles provide results that are more relevant than absolute reductions or levels or pollutants achieved in the home. Monitoring during both fall/winter and summer provides results for the outdoor pollutant mixes with distinctly different characteristics and patterns. The study was limited in obtaining data for only a handful of days in each season for most of the systems. And there were variations in weather, outdoor particle concentrations and air exchange rates that may have impacted results for specific monitoring periods. The overall consistency of results when a system was run more than once in a season, and also between seasons supports the general robustness of the findings about relative system performance, at least for outdoor particles. The results for indoor particle performance are less robust in that each system (other than the Reference) was challenged with only a single indoor emission event, and only one type of indoor source.

There were some specific limitations to the suite of systems and conditions evaluated that should be noted. In retrospect, it would have been very valuable to include testing of supply

ventilation without any enhanced filtration (e.g. using a MERV4 filter); this would have provided a quantitative estimate of the increase in indoor concentrations of outdoor particles and ozone for such a system. The evaluation of VOC removal technology was limited by the low outdoor VOC concentrations at the site and the limited mix and low concentrations of indoor-emitted VOCs. Largely because the study was focused on using home systems to protect Californians from outdoor pollutants, system performance for indoor-generated particles was evaluated for only one indoor emission source and only one event for most systems. This represents a significant limitation since performance for indoor particles can be an important distinguishing feature of air cleaning systems and especially relevant to comparing air cleaning on supply ventilation versus recirculating systems.

5 SUMMARY AND CONCLUSIONS

This study measured the performance of seven mechanical systems featuring combinations of ventilation and enhanced pollutant removal components and controls as well as a Reference system that we understand to be the most common configuration of building code compliant mechanical ventilation and thermal conditioning systems in current and recent California residential construction. Enhanced pollutant removal systems included high performance particle filtration on the supply ventilation system, particle filtration on the return ductwork of the forced air heating and cooling system (FAU), and VOC removal technologies on the FAU. The systems were installed in a 2006-built house in Sacramento, California that represents typical, modern California home construction. Very limited testing was also conducted with two portable air filtration units added to the Reference system. The systems were installed with dampers to enable manual switching of the airflow pathways (and thus switching of the systems) in under an hour.

Two identical sets of air pollutant analyzers were installed in the house and configured to simultaneously and continuously measure indoor and outdoor air pollutant concentrations. Instruments for particulate matter were configured on manifolds that switched intermittently between indoors and outdoors to enable uninterrupted and accurate comparisons of indoor and outdoor conditions. Instruments measured particle number concentrations with some size resolution in the range of 6 nm to 2.5 μm (including ultrafine particles or "UFP" from 6–100 nm), black carbon (BC), and ozone. Fine particulate matter mass ($PM_{2.5}$) was estimated by a light scattering instrument and from the particle number concentration measurements. For systems with volatile organic compound (VOC) removal technology, performance was assessed by collecting 24h integrated samples indoors and outdoors during two or four days of the summer monitoring period; the samples were analyzed to determine concentrations of formaldehyde and a panel of common VOCs.

The ventilation and enhanced pollutant removal systems were operated to assess performance over multi-day periods during locally cool/cold conditions in fall/winter seasons and hot, summer conditions, and also for indoor generated particles produced from a carefully scripted cooking event.

Data from the two sets of instruments were combined to produce continuous time series of indoor and outdoor pollutant concentrations. Following an extensive quality assurance review, data were analyzed to calculate indoor and outdoor running 24h and 1h averages. These were in

turn used to calculate indoor / outdoor ratios for 24h running averages for the duration of each multi-day study period and the highest daily 1h outdoor and corresponding indoor concentrations for each diurnal cycle. These results provide estimates of the in-home protection that each system offers against outdoor air pollution. Estimates of the performance of test each system in reducing exposures to indoor-generated pollutants were determined by comparing the calculated 1h time integrated concentration for each system relative to the 1h time-integrated concentration for the Reference system following the scripted cooking event.

The Reference system provided substantial protection against outdoor pollutants in both fall/winter and summer, providing time-averaged concentrations in the test house that were lower than corresponding outdoor levels by 66–73% for $PM_{2.5}$, 84–87% for UFP, 48–58% for BC, and at least 97% for ozone. (The ranges reflect the results from the two seasons.) The efficacy of supply ventilation systems depended strongly on the filter used. A system (C) with MERV16 filtration on a supply system provided the greatest reductions in outdoor pollutant levels with indoor time-averaged concentrations that were lower than corresponding outdoor levels by 97–98% for $PM_{2.5}$, 97–99% for UFP, and at least 84–92% for BC and at least 97% for ozone. In contrast to these results, a system (A) with MERV13 filtration on supply ventilation actually performed worse than the Reference. A system that added an electrostatic precipitator (ESP) on the thermostatically controlled central forced air unit (FAU) only produced better results than the Reference during summer, when the ESP operated for several hours each day along with the FAU air conditioner. A system (D) that added MERV16 filtration to the central forced air system and added a controller to run the FAU air handler for at least 20 min of each hour provided time-averaged concentrations indoors that were lower than outdoors by 97% for $PM_{2.5}$, 97–98% for UFP, and at least 93–96% for BC and 97% for ozone. A system (E) with MERV13 filtration with the same time controller (E) provided protection levels that were substantially better than the Reference, though less than those provided by MERV16; for this system, indoor levels were lower than outdoors by 88–91% for $PM_{2.5}$, 93% for UFP, and at least 80–84% for BC. A system (F) that featured a mini-split thermal conditioning system operating with MERV13 filtration on continuous low speed airflow provided indoor concentrations that were lower than outdoors by 95–96% for $PM_{2.5}$, 96% for UFP, and at least 86–92% for BC. Ozone results were not obtained for the last two systems discussed. A system (G) with a HEPA filter + activated carbon bypass loop that was operated at lower air flow rates than recommended by the manufacturer (since it was sized for continuous operation but operated with the 20/60 controller) produced protection factors that were better than the Reference but not as good as the better systems described above (C, D, E, F). In limited testing, a set of two portable air filtration units provided protection factors on par with System E.

The VOC assessment was limited by low concentrations of outdoor VOCs. All three systems with VOC removal technology achieved modest improvements over the Reference system.

Results of the pollutant performance measurements and energy use analysis indicate that that high performance MERV16 filtration on a supply ventilation system provides the best protection against outdoor particles at lowest incremental energy cost. Two energy-efficient portable air filtration units provided substantial reductions in concentrations of particles from both outdoor and indoor sources at relatively low energy cost. Such equipment may be employed as desired by residents but the equipment is not suitable for specification in high performance home standards because they are not part of the infrastructure of the home. Using the central forced air system to provide enhanced filtration (MERV13 to MERV16) was found to carry a substantial energy cost

(almost 1500 kWh/yr) when added to a forced air system with a conventional permanent split capacitor motor. Upgrading the FAU (or moving to a mini-split) with an energy efficient brushless permanent magnet motor (also called an electronically commutated or ECM motor) and employing control strategies to maximize air movement efficiency and to provide filtration only when needed can make high performance filtration on central FA systems more viable from an energy perspective.

6 RECOMMENDATIONS

In this section we start with several recommendations for residential filtration and air cleaning systems that derive directly from the experimental results and analysis of this study. As warranted, we expand and relate the findings to situations and scenarios that were not directly studied or analyzed, but for which we feel the findings of this study provide relevant guidance. In particular, we present recommendations that are relevant to anticipated changes in the California housing stock. Anticipating that readers of this report will have varying backgrounds and familiarity with heating, ventilating and air conditioning (HVAC) systems, we also note some important considerations related to HVAC design and maintenance. We conclude this section with several recommendations related to research and analysis that could further inform the standards and the practice of providing filtration and air cleaning in low-energy homes.

6.1 RECOMMENDATIONS DERIVED FROM STUDY FINDINGS

The first recommendation is for the building industry and the general public to recognize the potential to use the home as protection against outdoor pollutants. Even without enhanced filtration, a modern California home with windows closed and mechanical exhaust ventilation provides substantial protection against outdoor particles and ozone. In a scenario of extreme outdoor pollution, such as a wildfire or an extreme episode of photochemical or inversion-caused air pollution, the protectiveness of a typical new home could be increased by temporarily turning off or turning down the exhaust ventilation system to reduce the rate of outdoor air entry to the home. When doing this, residents should take special care to minimize activities that create and emit pollutants into the home and use ventilation (including local exhaust as feasible) when generating pollutants with indoor activities.

The next recommendation, targeted at new home builders and buyers, as well as owners and residents of recently built homes in California, is to recognize that supply ventilation without filtration leads to higher indoor concentrations of outdoor pollutants compared to the more common (reference) configuration of exhaust ventilation. The limited data from this study suggest a minimum of MERV13 or equivalent for supply ventilation systems (or the supply portion of a balanced system such as an HRV or ERV); but further consideration may be warranted to determine what level of filtration is needed for equivalent performance to an exhaust ventilation system when envelopes are tighter (and thus provide better filtration) than the house used in this study. We also note that attention needs to be paid to supply air inlets and the required frequency and ease of filter replacement. Air inlets should be located in easy to access locations for periodic inspection and cleaning. For existing systems that are designed to use filters with relatively small surface area and/or have filter cabinets located in difficult to reach places, owners and residents should ensure that filters are changed or inspected on a regular basis. For new homes whose owners require or desire substantially greater protection against outdoor particles, we recommend going to MERV16 or equivalent on the supply ventilation and

note that the results of this study show that MERV16 provided such great reductions that there is likely to be little benefit of going to higher levels of filter performance. MERV16 filtration on a supply ventilation system can be provided with a relatively low incremental energy cost, and is thus very compatible with California's building energy efficiency targets.

There is not support, in our assessment, to recommend choosing supply ventilation over exhaust ventilation for the express purpose of controlling formaldehyde concentrations in new California homes. While available data suggest a benefit of supply ventilation at reducing formaldehyde, the relevance of this strategy to California homes that are built with materials that comply with the new ATCM for formaldehyde should be evaluated.

The pollutant monitoring results of this study suggest that using the central forced air system to provide filtration and air cleaning can be very effective in reducing in-home concentrations of both outdoor and indoor-generated air pollutants. However, the results of the energy analysis indicate that simple versions of using the air handler for air cleaning can cause significant increases in energy consumption. To provide effective year-round filtration the central system needs to be operated either on a minimum runtime or continuously at a low speed setting. To reduce the energy impact of this approach, we recommend selecting forced air systems that have energy-efficient, variable speed air handler motors along with controls that allow the air handlers to be operated continuously at a low and very efficient setting when the system is not heating or cooling. An existing system with an inefficient motor may be retrofit with a more efficient air handler motor; but that is typically not a low-cost solution for existing homes.

The robustness of using the air handler for filtration improves when the filter cabinet can accommodate a deep-pleat, low resistance filter that removes a high percentage of all size fractions of $PM_{2.5}$ (including ultrafine particles) and the cabinet features seals to reduce and ideally eliminate air movement around the filter (termed bypass). For conventional forced air systems that have substantial duct leakage, there is a benefit to having the filter cabinet close to the air handler as this position reduces the amount of unfiltered air entering through leaks downstream of the filter. This concern becomes less important as filter pressure drop and duct leakage are reduced. And having the filter at the return grille makes it much easier to replace.

Another approach to reducing the energy burden of central filtration is to install and use a smart or learning thermostat that has the capacity to independently operate the air handler (for filtration) on a programmable schedule or occupancy-based control algorithm. The schedule or occupancy algorithm ideally could be used to start the air handler just a bit (e.g. 1h) before arrival after a non-occupied period to reduce concentrations prior to occupancy. A potentially even better control sequence is to reduce outdoor air ventilation rates during the non-occupied periods. By lowering the rate at which outdoor pollutants (principally particles, ozone and nitrogen dioxide) are brought into the home, indoor concentrations will be reduced by deposition, reducing the need for advanced filtration to reduce concentrations prior to occupancy. There is a limit on lowering rates at unoccupied times because we need to avoid exposure to high pollutant levels upon reentry to the home and generally this limit is based on particle concentrations (Turner and Walker 2013).

The limited field evaluation of VOC air cleaning technologies did not provide clear enough distinction about relative performance for us to make a recommendation about which technology is best suited for the residential market. And while limited data on VOC concentrations in new California homes (e.g., Jenkins et al. 1999) indicates that some VOCs may be present at levels

that, taken in over time, would exceed guidelines for lifetime risk, there remain too many uncertainties to recommend widespread adoption of VOC air cleaning technologies at this time. The VOC that consistently appears at levels exceeding health guidelines is formaldehyde. The implementation by California of the air toxic control measure (ATCM) for formaldehyde in composite wood products (http://www.arb.ca.gov/toxics/compwood/compwood.htm) is expected to result in dramatically lower formaldehyde concentrations in any new construction and also reductions in existing homes as new products and furniture that contain manufactured wood components is brought into those homes. A recent study by LBNL (Hult et al., 2014) showed that new homes constructed with low emitting materials have substantially lower formaldehyde levels than comparable homes with conventional materials. For existing homes with high formaldehyde levels, we recommend increasing outdoor air ventilation rates as an effective mitigation (ibid).

For homeowners choosing to install a VOC air cleaning system, we recommend paying particular attention to the following factors: system sizing and operating requirements (i.e. the recycle ratio or air exchange rate through the system), capacity and recommended frequency of air cleaning material replacement, and cost and difficulty of replacing the air cleaning materials.

Related to green and high performance homes standards, we offer the following assessments and recommendations. It seems appropriate to the objective of protecting against disproportionate exposures to outdoor pollutants to require that supply ventilation systems include high performance filtration of appropriate design (capacity), size (filter availability) and location (maintenance). In this context, disproportionate is in comparison to the reductions in indoor concentrations of outdoor pollutants that we measured for the Reference system with exhaust ventilation. It is certainly appropriate for green and high performance home programs to give credits for well-sealed cabinets that accommodate deep-pleat filters, for smart or learning thermostats that enable independently scheduled control of the air handler, and for efficient, variable speed air handler motors. Energy efficient air movement on the forced air heating and cooling system should be a requirement of any green / high performance home standard. As a complement to equipment specification, we strongly recommend that standards consider credits for homeowner education and systems that are designed for easy maintenance. Credits should also be allocated for robust fault detection and communication, such as including, e.g. pressure sensors to alert homeowners when a filter should be changed.

6.2 Research Recommendations

While the results of this study and other studies cited throughout the report provide a strong basis for improving residential filtration standards and practice, we recommend the following research to address key issues that could not be answered within the scope of this project:

Field studies should be conducted to quantify the particle removal characteristics (e.g. in terms of penetration factors) for newer California homes that have envelopes which are significantly tighter than the 5 ACH50, 2006-built house that was used in this study.

Field studies should be conducted to quantify the performance of enhanced air cleaning systems in occupied homes. Such evaluations necessarily will be much more limited in scope than what was done in this study. But the evaluation should still assess indoor concentrations of outdoor particles and overall indoor/outdoor ratios. And while various experimental designs may be employed, we particularly recommend flip-flop approaches in which a single home is

monitored during periods in which it is operated with/out air cleaning systems. General considerations for conducting field studies of filtration effectiveness are discussed by Chan and Singer (2014).

Research should be conducted with physics-based simulation models to extend the study to other system variations; to examine the impacts for homes with alternative configurations of mechanical equipment; to estimate the exposure reduction benefits; and to calculate the impacts on energy and exposure of more sophisticated equipment schedules. The data and analysis from this study can provide component performance specifications and/or model validation data sets. The Population Impact Assessment Modeling Framework, described in a series of papers by Logue and co-authors (2012-2015), is a suitable tool for this purpose.

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8 LIST OF PUBLICATIONS PRODUCED

A manuscript presenting results for particle and ozone removal has been submitted to a peer reviewed archival journal; however, no decision or reviews have been received prior to the submission of this Final Report. The following two conference papers have been accepted:

Singer BC, Delp WW, Black DR, Walker IS. 2016. Measurement-based evaluation of ventilation and filtration systems for reducing outdoor $PM_{2.5}$ in a modern California detached house. *Indoor Air 2016: The 14th International Conference on Indoor Air Quality and Climate. Paper 1124.* Ghent, Belgium, Jul 3-8.

Singer BC, Delp WW, Black DR, Walker IS. 2016. Evaluation of the performance of VOC-removing air cleaning technologies operated in a modern California detached house. *Indoor Air 2016: The 14th International Conference on Indoor Air Quality and Climate. Paper 1122.* Ghent, Belgium, Jul 3-8.

9 GLOSSARY OF TERMS, ABBREVIATIONS AND SYMBOLS

$\mu g\ m^{-3}$	Microgram per cubic meter
μm	Micrometers
APS	Aerosol particle sizer
AC	Air-conditioning
AHU	Air handling unit
AER	Air exchange rate
ACH	Air exchange ratio
ALA	American Lung Association
ACM	Alternative Calculation Methods
ATCM	Air toxic control measure
ASHRAE	Professional society formerly known as the American Society of Heating, Refrigerating and Air-conditioning Engineers
BPHP	Balance Point Home Performance
BC	Black carbon
BPM	Brushless permanent magnet
CARB	California Air Resources Board
CEC	California Energy Commission
CFIS	Central Fan Integrated Supply
CFA	Central forced air
CPC	Condensation Particle Counter

DNPH	Dinitrophenylhydrazine
DIF	Dynamic infiltration factor
ECM	Electronically commutated motor
ESP	Electrostatic air cleaner
ESP	Electrostatic precipitator
EPA	Environmental Protection Agency
EPR	Enhanced pollutant removal
ERV	Energy recovery ventilators
F/W	Fall/winter
FAU	Forced air unit
GC	Gas chromatography
HRV	Heat recovery ventilators
HVAC	Heating, ventilating and air conditioning
HEPA	High-efficiency particulate arrestance
HVI	Home Ventilating Institute
HPLC	High performance liquid chromatograph
IO	Indoor/Outdoor
ID	Internal diameter
LBNL	Lawrence Berkeley National Laboratory
MERV	Minimum Efficiency Rating Value
MS	Mass spectrometry
$Na_2S_2O_3$	Sodium thiosulfate
nm	Nanometers
NO_x	Nitrogen oxides
O_3	Ozone
OPC	Optical particle counter
$PM_{2.5}$	Fine particulate matter, particles with aerodynamic diameters <2.5 μm
PN	Particle number concentration
PSC	Permanent Split Capacitor
QL	Quantitation limit
SMPS	Scanning mobility particle sizer
SEER	Seasonal energy efficiency rating

SF_6	Sulfur hexafluoride
SU	Summer
TD	Thermal desorption
TDS	Thermal Desorption System
UFP	Ultrafine particles (diameters < 100 nm)
UV	Ultraviolet
VOC	Volatile organic compound
WD	Wind direction
WS	Wind speed

10 LIST OF APPENDICES

10.1 SYSTEM PERFORMANCE FOR OUTDOOR POLLUTANTS IN FALL/WINTER - APPENDICES

Appendix FW-1-R. Results for Reference System, February 21–27, 2014

Appendix FW-2-C. Results for System C, February 27–March 6, 2014

Appendix FW-3-E. Results for System E, October 28–November 4, 2014

Appendix FW-4-F. Results for System F, November 4–10, 2014

Appendix FW-5-A. Results for System A, November 11–17, 2014

Appendix FW-6-B. Results for System B, November 18–25, 2014

Appendix FW-7-D. Results for System D, November 25–December 2, 2014

Appendix FW-8-G. Results for System G, December 2–8, 2014

Appendix FW-9-PA. Results for Portable Air Cleaners in Automatic Mode, December 8–12, 2014

Appendix FW-10-PM. Results for Portable Air Cleaners on Medium Speed, December 12–15, 2014

Appendix FW-11-EX. Results for System E (filter taped), December 16–19, 2014

Appendix FW-12-AX. Results for System A (filter taped), December 19–23, 2014

10.2 SYSTEM PERFORMANCE FOR OUTDOOR POLLUTANTS IN SUMMER - APPENDICES

Appendix SU-1-E. Results for System E, June 6–12, 2014

Appendix SU-2-A. Results for System A, June 12–17, 2014

Appendix SU-3-F. Results for System F, June 18–22, 2014

Appendix SU-4-G. Results for System G, June 25–July 2, 2014

Appendix SU-5-R. Results for Reference System, July 2–9, 2014

Appendix SU-6-D. Results for System D, July 9–16, 2014

Appendix SU-7-R. Results for Reference System, July 16–23, 2014.

Appendix SU-8-C. Results for System C, July 23–30, 2014

Appendix SU-9-B. Results for System B, July 30–August 6, 2014

Appendix SU-10-VOC. Results for VOC removal in Systems G, C, D, and Reference, June - July, 2014

10.3 Performance for Pollutants Generated Indoors by Cooking – Appendices

Appendix IN-1-E. System E Performance for Cooking–Related Pollutants, June 12, 2014

Appendix IN-2-A. System A Performance for Cooking–Related Pollutants, June 18, 2014

Appendix IN-3-F. System F Performance for Cooking–Related Pollutants Operated on June 23, 2014

Appendix IN-4-G. System G Performance for Cooking–Related Pollutants, July 2, 2014

Appendix IN-5-R. Reference System Performance for Cooking–Related Pollutants, July 9, 2014

Appendix IN-6-D. System D Performance for Cooking–Related Pollutants, July 16, 2014

Appendix IN-7-R. Reference System Performance for Cooking–Related Pollutants, July 23, 2014

Appendix IN-8-C. System C Performance for Cooking–Related Pollutants, July 30, 2014

Appendix IN-9-B. System B Performance for Cooking–Related Pollutants, August 6, 2014