MEASUREMENT STUDY TO EVALUATE CONTROLS FOR REDUCING IN-HOME POLLUTANT EXPOSURES AT HOMES NEAR HIGH TRAFFICKED ROADWAYS

POPULATION HEALTH DIVISION
SAN FRANCISCO DEPARTMENT OF PUBLIC HEALTH
ENVIRONMENTAL HEALTH

BAY AREA AIR QUALITY MANAGEMENT DISTRICT

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SEAL OF THE CITY AND COUNTY OF SAN FRANCISCO

ACKNOWLEDGMENTS

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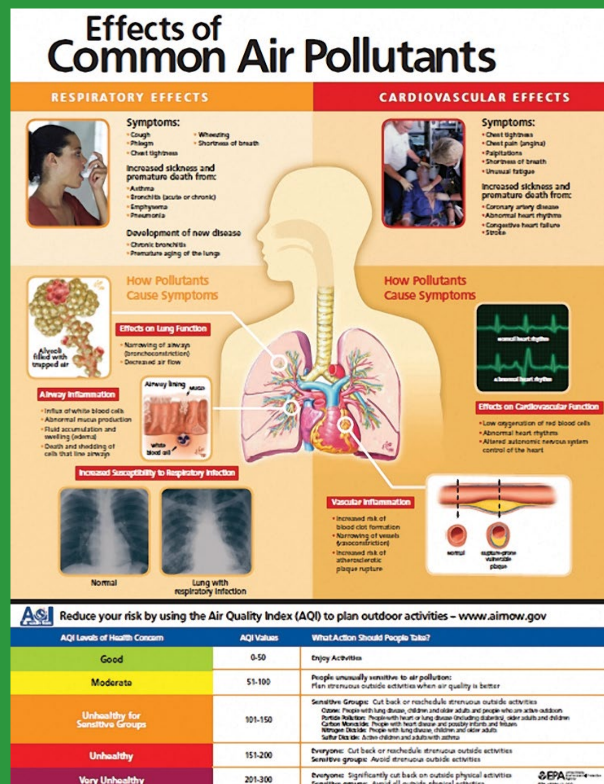
EXECUTIVE SUMMARY

Project Overview

The San Francisco Board of Supervisors passed Ordinance No. 217-11[1] on November 9, 2011 allocating Mirant Potrero L.L.C Settlement Funds for projects designed to improve the health and wellbeing of Potrero Hill (zip code 94107) and Bayview Hunters Point (zip code 94124) residents through physical activity, organic gardening, asthma management and education, and home indoor air quality interventions[2]. Six projects fulfilling the requirements of the Ordinance were recommended to the Board of Supervisors by the San Francisco Asthma Task Force and the San Francisco Power Plant Task Force.



Recognizing the health impacts to Potrero Hill and Bayview Hunters Point residents exposed to traffic pollution, the Board of Supervisors charged the San Francisco Department of Public Health (SFDPH) with implementing one of the recommended projects, that of investigating methods for improving indoor air quality in homes near freeway corridors and busy roadways. Many studies have demonstrated correlations between poor air quality near busy roadways and higher incidences of respiratory and cardiovascular health impacts among local residents[3]. Children are particularly vulnerable with documented health effects such as wheezing, reduced lung function, and asthma[4]. These heavily used roadways release a mixture of criteria pollutants such as nitrogen dioxide, fine particulate matter, and other toxic compounds. Fine particulate matter produced from vehicle exhaust is of particular concern as it penetrates to the lower airways of the lung and leads to increased cardiovascular and respiratory health effects across the population, including premature mortality.

In response, the SFDPH Environmental Health Branch, the Mayor's Office of Housing and Community Development (MOHCD), Lawrence Berkeley National Laboratory (LBNL) Environmental Energy Technologies Area and the Bay Area Air Quality Management District (Air District) collaborated on a two-phase measurement study, starting in 2013, to evaluate potential mitigation measures to reduce in-home pollutant concentrations for residences near high-trafficked roadways.

This report provides the project details including the methodology, measurement results, and conclusions following the two phase study. In Phase I, four single family homes in Bayview/Hunters Point area received modifications to their central heating system to accommodate high efficiency filters, home retrofits to improve air sealing around their home and upgrades to kitchen and bathroom ventilation, as needed, to minimize outdoor air infiltration. Phase II introduced standalone air filters into four condominium units as interventions for Potrero Hill residents.

Both phases involved a comprehensive monitoring program performed by Lawrence Berkeley National Laboratory (LBNL) to evaluate the effectiveness of the ventilation devices (central forced air and standalone units) at reducing indoor air filtration. Comparisons of the devices' effectiveness, ease of use, and their associated costs were factors considered when finalizing the recommendations in this report.

Background

San Francisco's residential population has been growing since 1980 and is projected to grow to over one million by 2040 according to Plan Bay Area[5]. Much of this projected growth is expected to occur in eastern San Francisco in close proximity to San Francisco's industrial and transportation corridors. These eastern corridor residents live in proximity to the city's most congested freeways, with higher air pollution conditions compared to its western counterparts. San Francisco is promoting a high-density, mixed-land use pattern to accommodate the growing housing demands and encouraging use of sustainable modes of transportation. This kind of development helps reduce per capita emissions of greenhouse gases and air pollution. However, residents living in these areas continue to have some of the region's highest air pollution and associated health risks.

One of the ways to reduce in-home exposures to fine particles from outdoor sources such as vehicle exhaust is to tighten building envelopes. Keeping windows and doors closed and well-sealed reduces the rate at which outdoor air particles enter the home. But when a building is well sealed, air movement is impeded and particles can build up from activities generated indoors. Many indoor sources of air pollution such as smoking, cooking, burning incense and candles, and wood fires can produce chemicals and particles harmful to health.

Filtration systems added to a forced air furnace or a portable air filter can effectively reduce indoor fine particle concentrations regardless of the source. As required by San Francisco Health Code Article 38, newly constructed sensitive use buildings in San Francisco's high pollution areas are required to install an air system capable of achieving protection from $PM_{2.5}$ at MERV 13 filtration equivalency (see Figure 1). To comply with this code, developers often choose to design their sensitive use buildings using a mechanical supply air system with enhanced filtration.

Most existing San Francisco homes have neither mechanical supply air systems with enhanced filtration nor airtight envelopes. For these homes, the main options for particle removal are to: 1) add enhanced filtration to the forced air heating system or 2) use a standalone air filtration unit with a high efficiency filter. Phase I of this study tested the forced air furnace system enhanced filtration approach, by installing enhanced filters with a minimum MERV 13 rating, expected to remove over 80% of all fine particles. MERV is an abbreviation for the Minimum Efficiency Reporting Value, a measurement scale designed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to rate the effectiveness of air filters (Figure 1).

Standard 52.5 Minimum Efficiency Reporting Value	Dust Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
20	n/a	n/a	< 0.30 pm particle size	Cleanrooms	≥99.999% eff. On .10-.20 pm Particles
19	n/a	n/a	Virus (unattached)	Radioactive Materials	Particles
18	n/a	n/a	Carbon Dust	Pharmaceutical Man.	Particulates
17	n/a	n/a	All Combustion smoke	Carcinogenetic Materials	≥99.97% eff. On .30 pm Particles
16	n/a	n/a	.30-1.0 pm Particle Size	General Surgery	**Bag Filter**- Nonsupported microfine fiberglass or synthetic media, 12-36 in. deep, 6-12 pockets
15	>95%	n/a	All Bacteria	Hospital Inpatient Care	
14	90-95%	>98%	Most Tobacco Smoke	Smoking Lounges	**Box Filter**- Rigid Style Cartridge Filters 6 to 12" deep m ay use lofted or paper media.
13	89-90%	>98%	Proplet Nuceli (Sneeze)	Superior Commercial Buildings	
12	70-75%	>95%	1.0-3.0 pm Particle Size Legionella	Superior Residential	**Bag Filter**- Nonsupported microfine fiberglass or synthetic media, 12-36 in. deep, 6-12 pockets
11	60-65%	>95%	Humidifier Dust Lead Dust	Better Commercial Buildings	**Box Filter**- Rigid Style Cartridge Filters 6 to 12" deep m ay use lofted or paper media.
10	50-55%	>95%	Milled Flour Auto Emissions	Hospital Laboratories	
9	40-45%	>90%	Welding Fumes		
8	30-35%	>90%	3.0-10.0 pm Particle Size Mold Spores	Commercial Buildings	**Pleated Filters**- Disposable, extended surface area, thick with cotton-polyester blend media, cardboard frame
7	25-30%	>90%	Hair Spray Fabric Protector	Better Residential	**Cartridge Filters**- Graded density viscous coated cube or pocket filters, synthetic media
6	<20%	85-90%	Dusting Aids Cement Dust	Industrial Workplace	**Throwaway**- Disposable synthetic panel filter.
5	<20%	80-85%	Pudding Mix	Paint Booth Inlet	
4	<20%	75-80%	>10.0 pm Particle Size Pollen	Minimal Filtration	**Throwaway**- Disposable fiberglass or synthetic panel filter.
3	<20%	70-75%	Dust Mites Sanding Dust	Residential	**Washable**- Aluminum Mesh
2	<20%	65-70%	Spray Paint Dust Textile Fibers	Window A/C Units	**Electrostatic**- Self charging woven panel filter.
1	<20%	<65%	Carpet Fibers		

FIGURE 1: MERV RATING SCALE

For forced air systems, an inline filter slot is located on the return side of the heating and/or cooling equipment (see bottom of Figure 2). Although originally used to protect the mechanical equipment from dust and large particles, an enhanced performance filter can be installed in this slot to effectively prevent fine particles from recirculating. For the filter to be effective, adequate seals are required around the filter cabinet to reduce air from moving around the filter. And if ongoing filtration is desired without heat, the thermostat must have a capability to operate the forced air system intermittently or continuously at low speed when the furnace is not operating. Since conventional furnace fans consume a lot of power, an efficient blower motor that can operate at variable speed is a valuable economic upgrade when selecting this option.

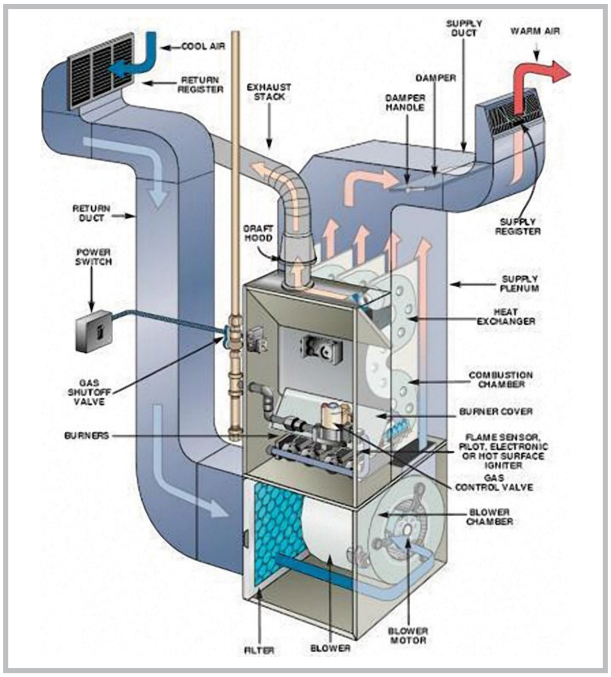


FIGURE 2: SCHEMATIC OF CENTRAL FORCED AIR FURNACE[6]

Phase II of this study tested an alternative approach, which is to operate one or more standalone air filtration units. These are small appliances that contain a fan and one or more filters to remove particles and sometimes odors. Compared to central forced air systems, they typically use much less energy per volume of filtered air since they don't have to move air through long stretches of ducting. Standalone filtration units vary in size from small models designed for 100-200 square foot rooms to devices that serve many hundreds of square feet. Basic models can be purchased for under $100; higher end units cost several hundred dollars and they may have the capacity to clean a larger size room. Higher end devices are typically quieter and may include a particle sensor that automatically modulates the fan speed and airflow through the filter in proportion to the particles detected. Though it is important to note that the low-cost sensors on these devices do not accurately detect some sources of particles, and thus may not always operate when needed. Replacement filters are an additional cost for both standalone units and for central forced air systems.

Researchers have investigated the exposure reduction benefits of filtration systems by conducting experiments under controlled conditions in test homes[7], monitoring particle concentrations in occupied homes provided with enhanced filtration[8], and with computer simulation models of home airflows[9]. These studies have reported substantial potential for exposure reduction and health benefits[10] when the filtration systems are installed and maintained properly, but effectiveness drastically declines when the systems are not used as intended.

Intent of Study

The purpose of this limited study was to investigate the effectiveness of providing air filtration equipment to reduce fine particulate in homes near US-101 and I-280 freeways and located in two districts of San Francisco, Bayview Hunters Point and Potrero Hill. To address impacts to existing residents, SFDPH —Population Health Division Environmental Health Branch, LBNL—Indoor Environmental Group, and the Air District collaborated on this two-phase pilot program and measurement study, providing air cleaning equipment in existing homes, starting in 2013 until its completion in 2016. MOHCD and Rebuilding Together SF (RTSF) also supported Phase I of the pilot program. The expectation was that the study would demonstrate whether air filtration systems were an effective and economic option available to current San Francisco residents to reduce their indoor air exposures given that enhanced filtration is currently required in newly built and rehabbed sensitive use building in poor air quality areas of San Francisco under Article 38.

The program was conducted in two phases: (1) Phase I involved adding enhanced filtration to central forced air furnaces in four single-family homes. To effectively use matching funds managed by the Mayor's Office of Housing and Community Development, homes selected for participation in the Phase I study required income-eligible residents, located near a busy roadway in zip code 94124. Phase I homes also received a new furnace replacement if needed to accommodate high-efficiency filters.

All Phase I homeowners received a new thermostat capable of operating the air distribution fan independent of heating demand for year-round filtration. (2) Phase II provided standalone air filtration units in four condominium units within a single multi-unit building. Each Phase II participant received a portable standalone air filtration unit. The study was designed to investigate conditions prior to installation and to quantify performance of the filtration system immediately following installation and operation as set up by the program.

FORCED AIR FURNACE WITH HIGH EFFICIENCY
FILTRATION (MERV 13 RATED)

STANDALONE AIR CLEANER WITH HIGH EFFICIENCY
FILTRATION (HEPA FILTER, MERV 16 RATED)

Mitigation Strategies

During Phase I, SFDPH worked with MOHCD to offer supplemental upgrades funded to improve energy use such that they would also improve indoor air quality as part of the central furnace replacement. Mitigation strategies to reduce in-home fine particulate concentrations included some combination of the following retrofits in each of the four homes:

- Upgraded filter cabinet and installed higher performance filter (with “MERV13” rating) to remove fine particulate matter using the central furnace air handler.
- Installed programmable thermostat and timer to enable intermittent operation of the air handler when heating is not required to reduce energy consumption and/or noise.
- Repaired or replaced central forced air furnace as needed to enable its use for enhanced filtration.
- Upgraded air handler with an energy efficient, variable speed motor (electronically commutated motor—ECM).

- Installed or serviced a venting kitchen range hood to remove particles and other pollutants, moisture and odors generated during cooking.
- Installed energy efficient bathroom fan to remove excess moisture and reduce the risk of mold growth.
- Provided portable air filtration unit (to the fourth home, as prelude to Phase II).

Phase II involved installing and operating a Rabbit Air MinusA2 standalone air filtration unit in each of the four condominium apartments. The Rabbit filters were selected based on their rated filtration performance, energy consumption, and sound level. Filtration devices from other manufacturers that provide similar airflow and have similar filter quality are expected to have similar filtration effectiveness as the Rabbit Air units. Each standalone filter was set to operate in "Auto" mode, which changes the filtration rate and fan speed depending on the detected level of particles in the environment. The auto mode was selected primarily because its light sensor defaults to the lowest and most quiet fan setting under low light conditions, i.e. overnight.

The program included discussions with occupants about the air quality improvement goals and a verbal agreement that the installed systems would be operated during the post-retrofit evaluation period. All participants were provided with a short demonstration of how to operate their filtration systems and invited to contact the contractor who performed the installation or the program staff if they had questions about the equipment.

Environmental Measurements

Monitoring equipment was installed to measure air pollutants and environmental parameters inside and outside of the homes to evaluate filtration performance. Fine particles measurements were collected to estimate the concentrations of particulate less than 2.5 microns in diameter ($PM_{2.5}$). Environmental measurements included temperature, humidity, and carbon dioxide. A complete set of devices was typically installed in a common room of the home (e.g., living room or dining room) and a limited set of monitors (e.g., for temperature, humidity and carbon dioxide) generally was installed in the master bedroom.

In Phase I, in-home measurements were collected 1-2 weeks pre-retrofit and 2-3 weeks post-retrofit with an attempt to collect both sets of measurements during the same season. $PM_{2.5}$ mass concentrations were estimated using either a light-scattering monitor or a particle counter with six size bins combined with assumptions about the particle density and distribution of particle sizes within each bin. Both furnace and air distribution fan operation were monitored. Fine particles were measured using a single set of instruments that intermittently sampled indoor air from a common room inside the home and outdoor air from an inlet mounted on the home's exterior. Identical lengths of tubing were used for both indoor and outdoor sampling lines.

In Phase II, measurements were recorded from the condominium units roughly over a three-week period with the filtration units operating for a portion of this period. Only the portable air filtration unit was monitored. The building did not have a central HVAC system to study. The aerosol photometer was used to estimate $PM_{2.5}$ mass concentration in the condominium apartments. Cross-calibrated particle monitors (i.e. calibrated to a common source) were placed on the roof and in each of the four apartments.

In both phases, an occupant at each participating home completed a short daily log of window opening and potential particle-generating activities that occurred that day, (Appendix A3 and A4). In Phase I, DPH staff called each occupant daily by telephone to log their activity. Phase II occupants self-completed the daily logs of behavior affecting indoor air quality, which were collected at the end of the study period.

The data were analyzed to identify times when indoor particle concentrations did not appear to be impacted by indoor sources, based on comparing the indoor and outdoor profiles. For each of these periods, the ratio of indoor to outdoor particle concentrations was calculated. The ratio is an indicator of how effectively the filtration system is at reducing in-home exposure to outdoor particles compared to exposures that occur outdoors. **If effective, the indoor-to-outdoor ratio should be dramatically lower post-retrofit compared to the pre-retrofit monitoring period.** Although filtration reduces particle concentrations emitted indoors, it was not possible to systematically evaluate this benefit during this study because of the various indoor emission events that occurred between pre- and post-retrofit.

Study Findings

Phase I Results

Each of the four homes included in Phase I presented special challenges in both the retrofit implementation and evaluation phases, providing important lessons for future program design. In three of the homes a new forced air system was installed (in the fourth, only the furnace motor was replaced). All four homes had enhanced filtration added, including a sealed filter compartment, a high efficiency filter, and a thermostat capable of operating the furnace fan on a schedule independent of the furnace. Unfortunately, the complexity of the thermostats in three of the homes contributed by the contractor's faulty programming led to discomfort and noise complaints from the residents. In two homes, the controller was reset to operate the fan only when heat was required due to residents' objections of the excessive noise created by the fan. In addition, a faulty fan motor installation at one of the homes led to degraded performance of the heating system, distribution of cool-feeling air by the forced air system, and discomfort for the elderly residents prior to diagnosing and fixing the problem. Conversely, the resident at another home was uncomfortable from the warm air distributed during filtration. The resident in the third home violated the research agreement and turned off the forced air system completely during post-retrofit sampling to avoid the electricity costs. As a result, the effectiveness of the system could not be evaluated. And in all of the homes, frequent window opening and/or indoor particle generating events (e.g., cooking, candle and incense burning) complicated the evaluation and made it difficult to determine the effectiveness of the filtration systems.

Even with these problems, the collected data indicated a significant reduction in fine particle concentrations when the forced air systems with enhanced filtration were operating. Before the retrofit, indoor concentrations were roughly 50–70% of outdoor levels, meaning that indoor levels were roughly 30–50% lower than outdoor levels, when there were no obvious indoor particle emissions. **When the forced air systems operated continuously with enhanced filtration (in two of the four homes), indoor particle levels were roughly 10-20% of outdoor levels, meaning they were 80-90% lower than outdoor levels. This finding reinforces the idea that filtration has the potential to achieve substantial reductions in exposure and health risk.**

The fourth home in Phase I was supplied with both a new furnace with enhanced filtration and a standalone air filtration unit. The post retrofit monitoring was completed in three weeks using a combination of the central forced air system and the standalone filter. The indoor concentration was roughly 40% lower than the outdoor levels when no filtration from either the standalone filter or furnace was used. **Operating both the central forced air filtration and the standalone unit together lowered indoor concentration by about 90% compared to outdoor levels.**

Phase II Results

Phase II of the program provided standalone air filtration units to four condominium apartments in the same building at roughly the same time. The condos are located over a busy grocery store with a delivery bay, and in close proximity to busy roadways. Two apartments were less than 1,000 square feet with two bedrooms each, and the other two apartments were less than 700 square feet with one bedroom each. In all four condominiums, the filtration unit was placed in the main bedroom and the air quality monitor was placed in the living room or second bedroom with the door to the living room open.

Each condominium was monitored over multiple days with the filtration turned on and off. One apartment already had an operating standalone air filter; for this apartment, the protocol was revised to include four periods: one period of operating just the existing filter; one period with both existing and DPH-provided filtration units operating together; one period with all filters turned off; and one period with just the DPH-provided filtration unit.

There were variations in occupancy schedule, window opening, and the apparent impact of indoor particle emission events across the apartments. These factors affected whether a benefit of filtration could be discerned. The analysis was additionally challenged by the very low outdoor particle concentrations that occurred during two of the four weeks in which the homes were monitored. Since the filtration units were set to "Auto" mode, they were not expected to operate at more than a minimal flow rate condition when particle concentrations were low. Rather than evaluating the indoor/outdoor concentration ratio, the analysis investigated the effectiveness of the filter to quickly decay particle concentrations following an indoor emission event. Based on the few meaningful comparisons that could be made, the data indicate modest to moderate benefits from operating the standalone filtration units. **When outdoor particulate concentrations were above 10 micrograms per cubic meter (μg/m^3), and during periods not impacted by indoor emissions, indoor to outdoor particle ratios were 10-30% lower with the standalone air cleaning device in Auto mode than without the device.**

Lessons Learned

Installing, operating, and maintaining a central forced air furnace with enhanced filtration has some drawbacks and challenges as outlined below.

1. **Equipment Cost.** Retrofitting an existing home with modern forced air furnace and ducting capable of providing high efficiency filtration can cost several thousands of dollars per home, and may require electrical upgrades, asbestos removal, and other rehabilitation.
2. **Energy Cost.** A central forced air system, even with an efficient air distribution fan and motor, requires a lot of energy to operate and may be unaffordable for low-income residents.
3. **Complexity.** The thermostats installed in the homes that separately controlled the distribution fan from the heating element were confusing to residents and difficult to program. Upgrading an existing system with a variable speed fan motor improves efficiency but may interfere with furnace operations if not done properly, leading to discomfort and inadequate heat for residents. It is recommended to work with a contractor who has experience doing this retrofit upgrade and ideally has done the upgrade on the brand and model of system installed in the home. It is important that the contractor ensures that installation of the new fan motor does not interfere with the operation of the furnace.
4. **Discomfort associated with recirculating unconditioned air.** Circulated air from a basement or crawlspace will be cool in the winter and feel cold to residents when it exits the supply register if the heating element is not turned on. Likewise, circulated air during the summer may feel uncomfortably warm to residents.
5. **User motivation.** Enhanced filtration works best if the central furnace fan is turned on and windows remain closed. Several residents turned off the systems due to noise or concern about higher electricity costs.

To avoid some of these downsides, a simpler alternative may be to provide standalone air filtration systems in households. Moderate reductions in indoor particle concentrations and indoor particle removal rates were observed when standalone air filtration units were operated in four condominium apartments and one single family house. There were no major implementation challenges or performance issues, and costs were less than $700 per condominium for the air cleaner, a set of replacement filters, and low electricity usage. One important caveat is that a single standalone air filtration unit is designed to clean the air in a single room or a few connected rooms (e.g. an apartment or small flat), but may not be effective for a moderate to larger single family home or a multistoried dwelling. The homeowner or program subsidizing the purchase would have to weigh the cost of central furnace upgrade versus the purchase of multiple standalone units to be located in each bedroom and common area.

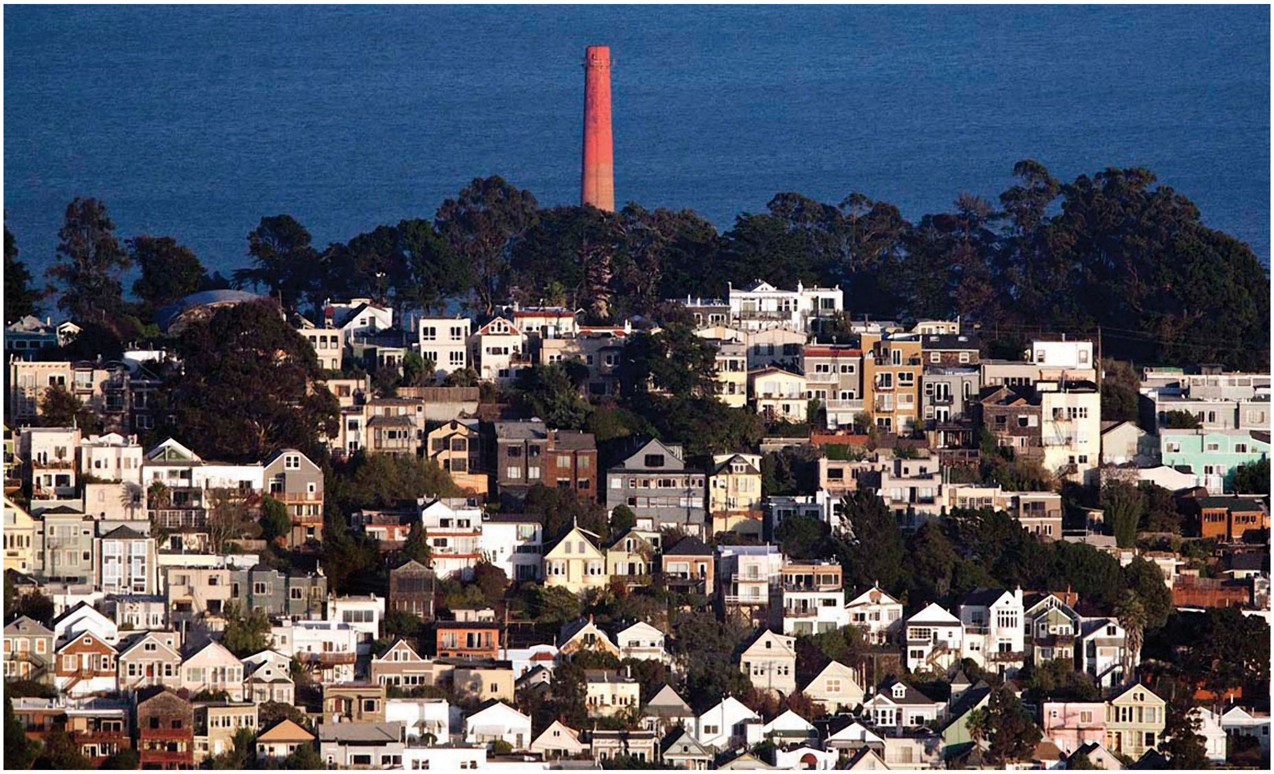
Conclusion and Recommendations

Overall, the central forced air furnace with enhanced filtration and the standalone filters each provided moderate to significant reductions in indoor particle concentrations compared to outdoor levels, when they were operated and maintained, as desired.

During periods when central forced air filtration systems operated with windows closed and no indoor particle emissions, indoor particle concentrations were 80-90% lower than those outdoors. In contrast, under similar conditions with no filtration, indoor concentrations were 30-50% lower than outdoors.

The following recommendations were derived based on the pilot study investigation.

1. **Tighten building envelopes.** Building envelope energy efficiency standards have been established by the California Energy Upgrade program, and are implemented via third party-certified building performance contractors. Those contractors use a variety of air sealing, insulation and weatherization techniques to tighten building envelopes. The building envelope can also be maintained by minimizing the number of times the windows and doors are opened to reduce fine particles from entering from outside. All of these steps can improve the performance of the supply air enhanced filtration system or standalone air cleaning device. Note that San Francisco has its own Green Building code[11], and other jurisdictions do as well.
2. **Reduce indoor emission events.** Residents are encouraged to reduce indoor emissions events such as smoking, candle and incense burning that generate fine particle matter and cumulatively add to the in-home particle concentrations. In smaller homes or homes with more activities—including cooking, cleaning, etc.—indoor sources can account for the majority of fine particles in the air. Both cooking and cleaning can also result in the release of irritating chemicals. In addition, many installed kitchen range hoods are not ducted to the outdoors, but capture cooking grease mist and particles onto a washable filter. These kitchens, particularly those with gas stovetops, should have range hoods vented to the outdoors and occupants should receive education of the health benefits of using the available exhaust system.
3. **Educate residents.** Any filtration system or standalone filter is only effective if used properly and consistently. Turning off the forced air furnace system as many of the residents did in this study negates any health benefit from installing these systems. Education, training and informational resources should be provided to recipients to include training on equipment use, guides on sizing to ensure that correctly sized units are obtained, and information on where to purchase replacement filters. Programming thermostats to operate the central forced air system intermittently was challenging even for the HVAC contractors, and may be particularly challenging for older residents with limited vision or experience with the devices.



FORMER MIRANT POWER PLANT ADJACENT TO POTRERO HILL, SAN FRANCISCO

4. **Consider using standalone air cleaning devices.** Standalone air filters have lower capital cost compared to central furnace upgrade, are simpler to deploy and are easy to use. Residents deciding between standalone air filters and a furnace upgrade should compare the initial cost, annual cost for filter replacement, energy performance as it impacts annual electricity cost, ease of use, and third-party validated performance (known as the Clean Air Delivery Rate). Educational information should also be provided to assist residents in making these comparisons.

5. **Upgrades to central forced air system.** For existing homes, upgrading the central furnace may be the more cost-effective solution compared to installing numerous standalone units. Residents should consider upgrading their central furnace if multiple rooms are frequently occupied or the house has multiple floors. Critical to upgrading the furnace is the selection of an easy to use thermostat/controller able to operate the air handler independent from the furnace and a low air flow option for nighttime to reduce noise from the fan motor. Additionally, the new furnace and ducting should be installed in the energy-efficient manner now available through the California Energy Upgrade program and its referrals to third-party certified building performance contractors.

6. **Focus on vulnerable subpopulations.** To maximize health benefits, the program could focus outreach and/or preferentially provide filtration units to residents who are most vulnerable to the effects of air pollution, i.e. premature infants, people with asthma or chronic obstructive pulmonary disease (COPD), elderly, and those with chronic respiratory and cardiovascular health conditions. People who are more vulnerable to the effects of air pollution may have greater incentive to use control equipment that is provided in such a program.

MAIN REPORT

Project Overview

The San Francisco Board of Supervisors passed Ordinance No. 217-11[12] on November 9, 2011 allocating Mirant Potrero L.L.C Settlement Funds for projects designed to improve the health and wellbeing of Potrero Hill (zip code 94107) and Bayview Hunters Point (zip code 94124) residents through physical activity, organic gardening, asthma management and education, and home indoor air quality interventions[13]. The six projects fulfilling the requirements of the Ordinance were recommended to the Board of Supervisors by the San Francisco Asthma Task Force and the San Francisco Power Plant Task Force.

Recognizing the health impacts to Potrero Hill and Bayview Hunters Point residents exposed to traffic pollution, the Board of Supervisors charged the San Francisco Department of Public Health (SFDPH) with implementing one of the recommended projects, that of investigating methods for improving indoor air quality in homes near freeways and busy roadways. Many studies have demonstrated correlations between poor air quality near busy roadways and higher incidences of respiratory and cardiovascular health impacts among local residents[14]. These heavily used roadways release a mixture of criteria pollutants such as nitrogen dioxide, fine particulate matter, and other toxic compounds. Fine particulate matter produced from vehicle exhaust is of particular concern as it penetrates to the lower airways of the lung and leads to increased cardiovascular and respiratory health effects across the population, including premature mortality.

In response, the SFDPH - Environmental Health Branch, the Mayor's Office of Housing and Community Development (MOHCD), Lawrence Berkeley National Laboratory (LBNL) Environmental Energy Technologies Division and the Bay Area Air Quality Management

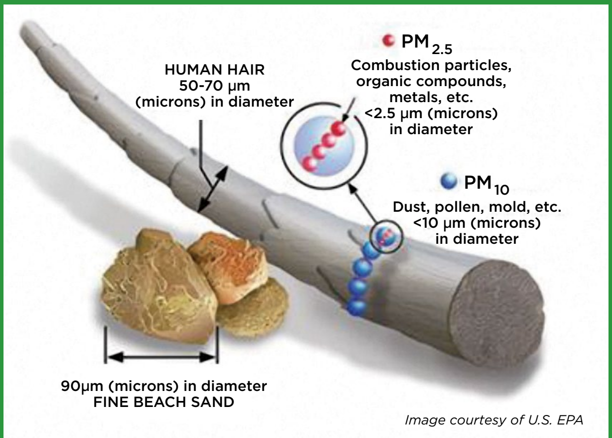


Image courtesy of U.S. EPA

District (Air District) collaborated on a two-phase measurement study, starting in 2013, to evaluate potential mitigation measures to reduce in-home pollutant concentrations for residences near high-trafficked roadways.

One of the ways to reduce in-home exposures to fine particles from outdoor sources such as vehicle exhaust is to tighten building envelopes or installed mechanical supply air systems. These options are effective, but due to their high costs, are only selectively implemented with new residential developments. For existing homes, the less expensive alternatives are to add enhanced infiltration to forced air heating systems or use standalone air filtration units with high efficiency filters. Both systems are the less costly alternatives, capable of effectively removing fine particles in existing homes if installed and maintained properly. Each alternative was investigated in the field as part of this study. In Phase I, four single family homes in Bayview/Hunters Point area received modifications to their central heating system to accommodate high efficiency filters, home retrofits to improve air sealing around their home and upgrades to kitchen and bathroom ventilation, as needed, to minimize outdoor air infiltration. Of the over 40 homeowners that were initially interested, four single family homes in Bayview/Hunters Point were selected to participate in this study. Phase II introduced standalone air filters into four condominium units as interventions for Potrero Hill residents.

In addition to home improvements, both phases involved a comprehensive monitoring program performed by Lawrence Berkeley National Laboratory (LBNL) to evaluate the effectiveness of the ventilation devices (central forced air and standalone units) at reducing indoor air filtration by collecting before and after indoor and outdoor air measurements during each home renovation. The study was also an opportunity for SFDPH to partner with Air District to assess whether the control technology is an effective mitigation that can be applied to existing homes for reducing the harmful impacts of outdoor air infiltration. This report documents the project details including the methodology, measurement results, and conclusions following the two phase study. Comparisons of the devices' effectiveness, ease of use, and their associated costs were factors considered when finalizing the recommendations in this report.

Background

Trafficked Related Air Pollution and Adoption of Senate Bill 375

San Francisco's residential population has been growing since 1980 and is projected to grow to 1,085,700 by 2040 according to Plan Bay Area[15]. Much of this projected growth has already occurred and will continue to occur in eastern San Francisco, in close proximity to the City's industrial and transportation corridors and its most congested freeways, California State Highways 101 and 280. The higher prevalence of industrial businesses and proximity to local freeways results in higher air pollution conditions in eastern San Francisco compared to its western counterparts. Air pollution produced from these sources can infiltrate the indoor air environment through openings, joints, cracks, open windows and doors, and as makeup air from mechanical ventilation systems. People exposed to poor air quality from roadway-generated pollution have increased incidences of severe health problems including higher rates of asthma onset and aggravation, cardiovascular disease, impaired lung development in children, pre-term and low-birthweight infants, childhood leukemia, and premature death[16].

Year	Population	10-Year Percent Increase
1970	715,674	---
1980	678,974	-5.1%
1990	723,959	6.6%
2000	776,733	7.3%
2010	805,235	3.7%
2020	890,400	10.6% *projected*
2030	981,800	10.3% *projected*
2040	1,085,700	10.6% *projected*
Sources: U.S. Census, 2015 (1970-2010); ABAG, Projections 2013 (2020-2040)		

TABLE 1: CITY AND COUNTY OF SAN FRANCISCO POPULATION GROWTH TRENDS

The source of the health impact is fine particulate matter, called PM, consisting of a complex mixture of solids and liquids found in exhaust from all fuel-combustion equipment. Research has proven that inhalation of fine particulate matter or $PM_{2.5}$, meaning particles less than 2.5 micrometers in diameter, is of great concern. This is because these fine particles are so small that once inhaled, penetrate into the deeper parts of the lungs and then circulated in the blood stream. Elderly and chronically ill who spend most of their time indoor are particularly susceptible due to the long durations spent indoors. Higher indoor air pollution and longer exposures can lead to significant health problems such as increased illness and premature death from asthma, bronchitis, emphysema, pneumonia, coronary heart disease, abnormal heart rhythms, congestive heart failure and stroke.

The California Senate took a hard look at the evidence and found that to accommodate the growing population in California combined with projected growth in number of vehicles and air pollution, they would need to adopt legislature lessening people's reliance on cars. In 2008, the California Senate with support from regional planning agencies, air management districts, and health departments, passed the Sustainable Communities and Climate Protection Act (California Senate Bill 375) which looks at reducing greenhouse gas emissions from vehicle travel by encouraging denser residential developments served by public transit so that people could live, work, and attend school without the need for personal cars. While these growth areas include a mix of land uses and access to sustainable modes of transportation, which can reduce global and regional air pollution, individuals living in these areas may have increased exposure to air pollutants and their associated health risks. Recent health and roadway impact studies have demonstrated correlations between poor air quality near busy roadways and higher incidences of respiratory and cardiovascular health impacts among local residents[17]. Children are particularly vulnerable with documented health effects such as wheezing, reduced lung function, and asthma that may be compounded by their attendance at local schools or child care sites near busy roadways[18]. Nearly 17,000 schools across the United States are located near heavily traveled roads.

Community Air Risk Evaluation Program (CARE)

The Air District's CARE Program, initiated in 2004, works extensively with local governments, communities, and businesses to reduce air pollution and adverse health outcomes in disproportionately impacted areas within the Bay Area. Periodically, the CARE program identifies impacted areas by overlaying maps that combine emissions, estimated cancer risks, predicted $PM_{2.5}$ concentrations, and health outcome data. The most recent mapping in 2013 identified the eastern portion of San Francisco as one of the cumulative impact areas in the Bay Area. The designation of a CARE area allows the Air District to then preferentially award mobile source grants to vendors operating in these disproportionately impacted areas[19]. The mobile source grants have proven to be an effective mitigation at reducing vehicle emissions, mainly from trucks, along transportation corridors and freeways.

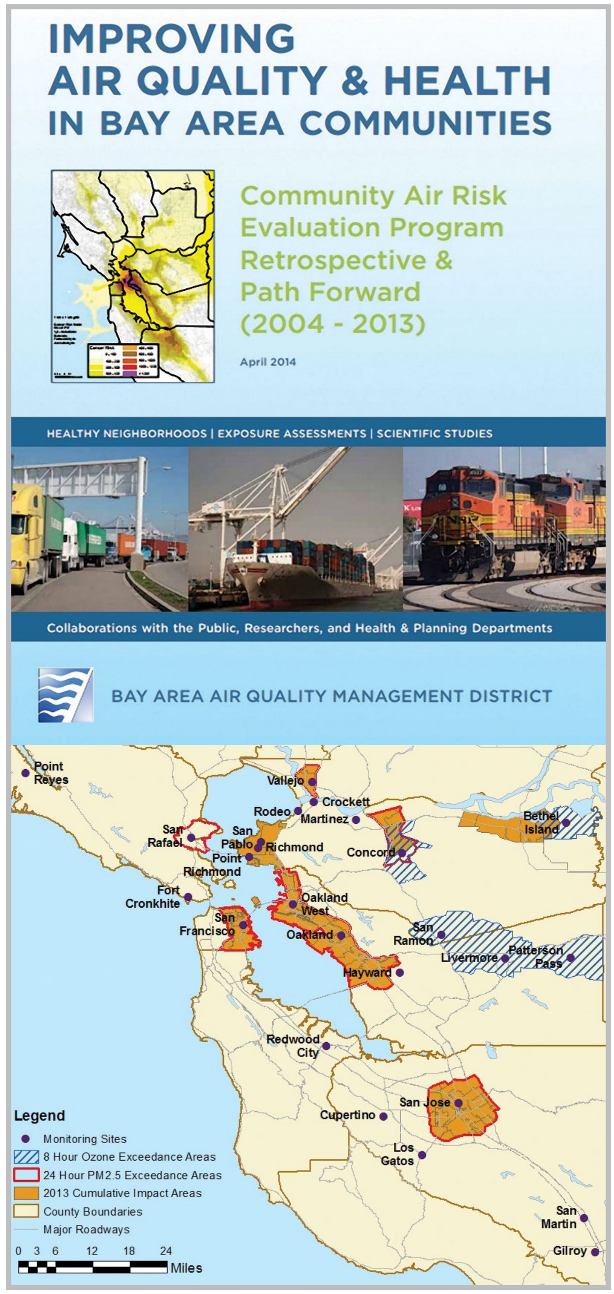


FIGURE 3: CUMULATIVE IMPACT AREAS IDENTIFIED BY AIR DISTRICT CARE PROGRAM (2013)

SF Health Code Article 38 and Air District CEQA Guidelines

San Francisco addressed the potential health impacts associated with the high density development by adopting Health Code Article 38[20] *Enhanced Ventilation for Urban Infill Development* in 2008 which requires new residential and sensitive use developments near high trafficked roadways to install an air system capable of achieving protection from PM2.5 at MERV 13 filtration equivalency for the protection of residents' health. To comply with this code, developers often choose to design these buildings using a mechanical supply air system with enhanced filtration. Researchers have found that the harmful effects created from traffic-related air pollution can be mitigated by use of high efficiency filters that remove fine particulates from the air. The greatest relief occurs when such high efficiency filtration is installed in homes. The National Human Activity Pattern Survey (NHAPS)[21], sponsored by US EPA, found that Americans spend approximately 69% of their time in their home, 11% at other indoor locations such as a school, 7.6% outdoors, 5.5% in a vehicle, 5.4% at an office or factory, and 1.8% in a restaurant. The preponderance of time spent at home, school, and at work means that most of one's exposure to air contaminants occurs indoors. Maps supporting the analysis and identification of areas subject to the regulation were based on modeled mobile source emissions along major roadways in San Francisco. Although the regulation has been in effect for several years, evaluation of the cost associated with post-entitlement construction was delayed due to the 2008 economic downturn.

Concurrent with the development of the CARE maps, the Air District began revision of its California Environmental Quality Act (CEQA) Guidelines by proposing updated thresholds of significance and recommending a broader approach for assessing cumulative impacts. Considering the updated CEQA guidelines and complexities of conducting cumulative analysis for individual projects, SFDPH and SF Planning Department opportunistically decided to expand its original mapping in Article 38 of only mobile sources to include all sources of air pollution in support of a single CEQA document for streamlining environmental reviews and allowing city departments to work collaboratively toward reducing health disparities. The single CEQA document, called a Community Risk Reduction Plan[22], was pioneered by the Air District in its updated CEQA guidelines[23] to improve consistency between projects.

The City and County of San Francisco Air Quality Cumulative Risk Reduction Plan (CRRP) is a comprehensive citywide plan being developed to protect human health from the negative effects of air pollution within San Francisco[24]. The CRRP will define the City's air pollution goals and reduction strategy. One advantage of a plan-based CRRP approach compared to the project-by-project assessments is that the CRRP will identify finer-scale air pollution sources for the entire city and facilitate consideration of comprehensive measures that benefit existing and new residents. In addition, projects that comply with an approved CRRP can potentially streamline environmental review. Pursuant to CEQA and San Francisco Administrative Code Chapter 31, San Francisco, as a lead agency, must analyze whether a proposed project would expose sensitive land uses to substantial air pollutant concentrations. Individual projects that comply with the goals, actions, and implementation strategies set forth in San Francisco's CRRP will be able to avoid and potentially lessen any cumulative impacts in support of the city's air quality goals.

The Air District working with SFPHD and SF Planning Department developed a San Francisco-specific emission inventory of mobile and stationary sources used to model exposure point concentrations and risk estimates for the CRRP. The mapped results were then used to identify areas, called Air Pollution Exposure Zones where $PM_{2.5}$ concentrations and cancer risks were above health protective levels. Residential projects that fall in these zones are required to install filtration-enhanced ventilation under Article 38. San Francisco adopted the revised Health Code Article 38 with updated Air Pollutant Exposure Zone map (see Figure 44) in December 2014. Article 38 was further amended to require SFDPH and SFPD to provide revised Air Pollutant Exposure Zone every five years to determine which property parcels are subject to the Article's required filtration-enhanced ventilation. While Article 38 requirements protect new residents, SFDPH existing health concerns for residents already living near busy roadways. SFDPH implemented this limited pilot study to investigate the effectiveness of the enhanced filtration equipment in existing homes close to the US-101 and I-280 freeways. The study idea first came about to explore a mitigation strategy that could potentially be incorporated into the San Francisco CRRP. The desired

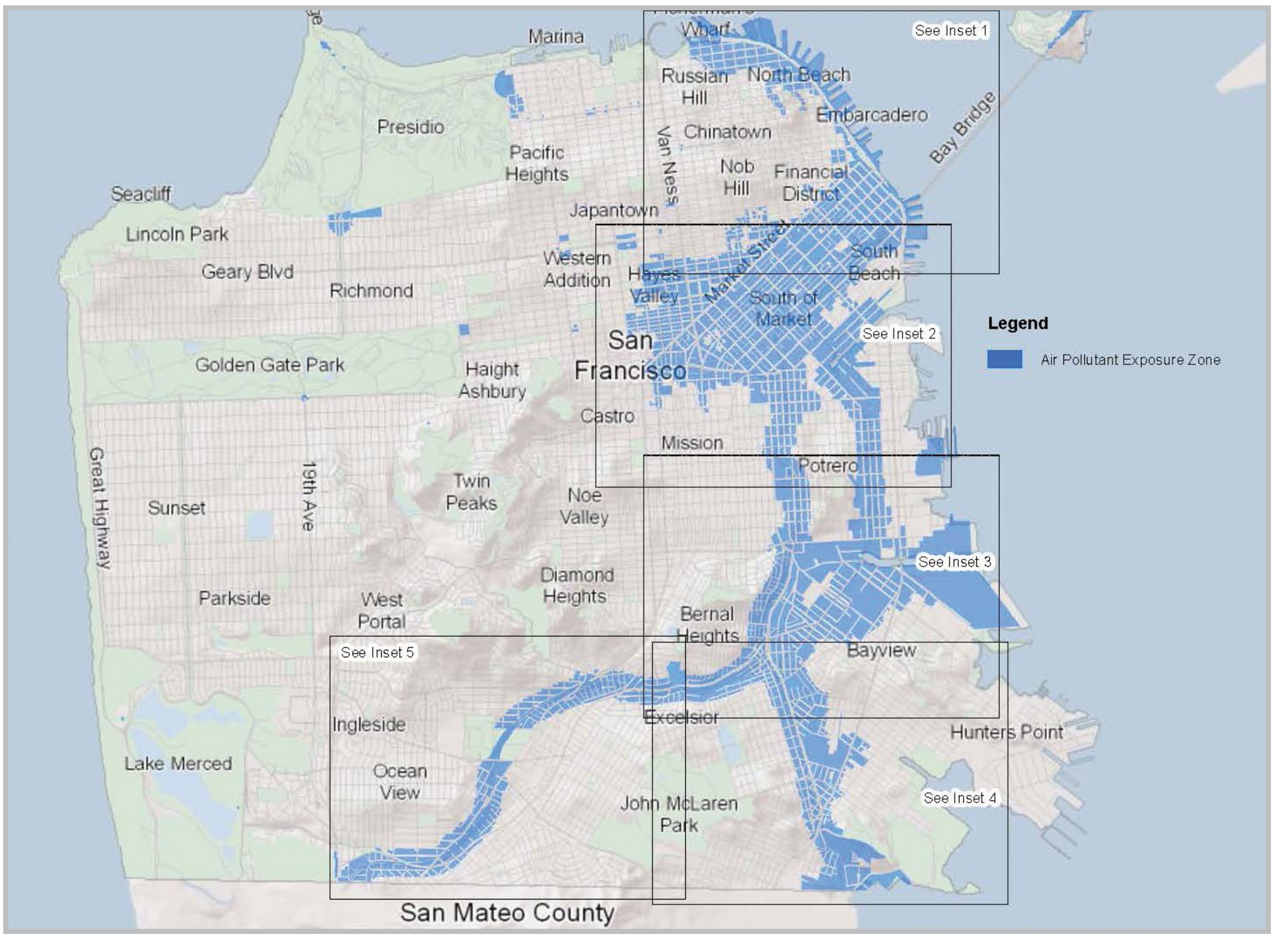


FIGURE 4: SAN FRANCISCO AIR POLLUTANT EXPOSURE ZONE (MAP REQUIRED BY SF HEALTH CODE ARTICLE 38, 2014)

wanted to pursue whether this control would benefit existing homes near high trafficked roadways which lead to the implementation and completion of this study.

Intent for Study

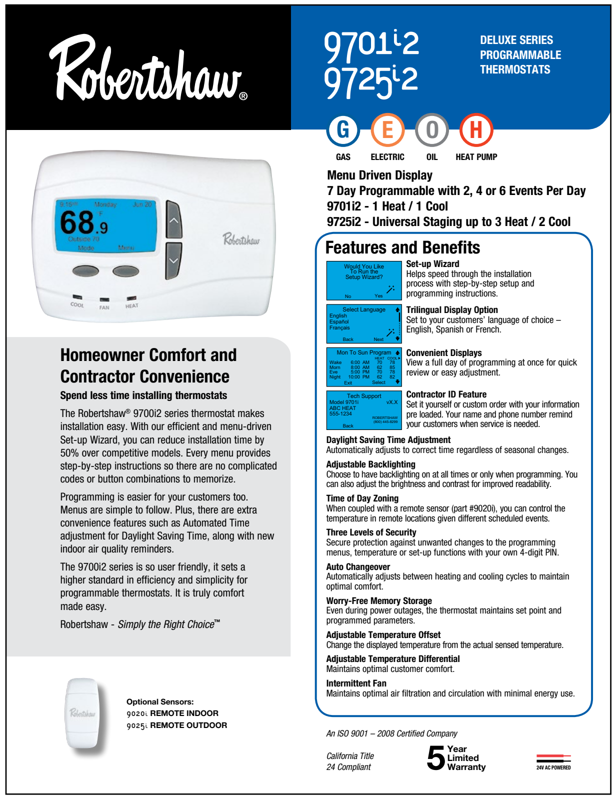
Although these required controls are effective for new residential construction, few studies have looked at adopting measures to address objectives at that time were to determine if a replicable intervention improving indoor air quality in homes near busy roadways could be substantiated and to evaluate the effectiveness of specific enhanced filtration systems in reducing residential exposures to fine particulate. Filtration systems added to a forced air furnace or a portable air filtration system can effectively reduce indoor fine particle concentrations. Unfortunately, existing homes in San Francisco have neither mechanical supply air systems with enhanced filtration nor airtight envelopes. For existing homes, the main options for particle removal are to: 1) add enhanced filtration to the forced air heating system or 2) use a standalone air filtration unit with a high efficiency filter. This study tested both options to determine optimum conditions for each type air cleaning system, the conditions where each system would be preferred; and the feasibility and cost of such retrofits. Lastly, it was important to learn and document the challenges of these mitigation strategies.

The expectation was that the pilot study would demonstrate whether air filtration systems were an effective and economic option for existing San Francisco residents to address indoor air pollution in their homes. This report present results of the limited measurement-based evaluation of program performance and some of the issues that arose during the study.

Program Design

Study Description

The study involved two air filtration mitigation strategies, conducted in two phases. Each phase studied the improvement of installing enhanced filtration in a central furnace system versus using standalone air filter devices. Phase I of the program focused on retrofitting central forced air furnaces with a high-efficiency filter (rated MERV 13) to provide improved particulate filtration. Phase I homes received a new furnace replacement if needed to accommodate high-efficiency filters and thermostat controls to increase the capture of fine particulate matter. Four detached single-family homes in Bayview/Hunters Point were selected for the study from 2013 through 2016. All homeowners received a new thermostat capable of operating the air distribution fan independent of heating demand for year-round filtration. The program used grants from MOHCD to expand the improvements to include upgrades to bathroom and kitchen exhaust fans, abatement of lead-based paints,



installation of electrical wiring, and sealing the building envelope wherever needed or feasible.

Phase II involved installing and operating a Rabbit Air MinusA2 standalone portable air filtration unit in four condominium apartments. Pre- and post-retrofit measurements were made at each home after the retrofits and repairs were completed by the contractors. The study did not evaluate how individually each repair/retrofit changed the indoor air envelope and its impact on the outdoor air infiltration. Although daily activity logs were completed by each of the home owners, the study did not quantify how residents' behavior and activity can contribute to poor indoor air quality at home. Some of the occupants in Phase II already owned and used air filtration devices. This phase of the study examined the air quality within the homes with and without the use of the air filtration devices. Phase II limitations and confounders included the location of each condo relative to street level, the existence of air cleaning devices already owned and operated by the occupants, and the deliveries and pick up operations occurring at nearby grocery store.

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Study Partners and Roles

The SFDPH Children's Environmental Health Promotion Program, within the Population Health Division Environmental Health Branch, managed the coordination between all participating agencies.

Phase I

SFDPH established a work order with MOHCD to lead the scoping process, contractor and homeowner interactions. SFDPH worked with the MOHCD to evaluate each home for the potential scope of work to be funded, and as necessary, install furnace retrofits, improve air sealing of building envelopes and add kitchen and bathroom ventilation, to minimize the intrusion of polluted outdoor air from entering indoor living spaces. Scoping included installing a high efficiency particulate matter filter (rated as MERV 13) in the recirculating forced air furnace, local exhaust fans at stoves to control water vapor and combustion products from cooking, and bathroom fans as needed to manage moisture. MOHCD developed the scope of work for each home, the "Grant Agreement with Owner Regarding Indoor Air Quality Improvements" entitling home owners to receive services, and selected qualified contractors in their City-approved vendor pool to do the retrofits and provided oversight to their completion within the scope of work. For all repairs, SFDPH and MOHCD worked with contractors that are licensed as Building Analysts by the Building Performance Institute (BPI). Because the Mirant Funds are allocated only for air quality improvements, MOHCD used additional healthy housing and lead abatement funding sources to have contractors do other rehab steps required such as electrical upgrades, mold remediation and asbestos and lead hazard abatement.

SFDPH contracted with Rebuilding Together San Francisco (RTSF), a non-profit agency that mobilizes teams of volunteers to revitalize neighborhoods by repairing homes and renovating non-profit facilities and schools. RTSF assisted with community outreach, by conducting a door hanger outreach campaign to advertise the project along the Highway 101 corridor in Bayview/Hunters Point. RTSF also surveyed their existing and prospective clients who were homeowners living in the same zone of concern. After RTSF conducted the initial phone or office screen with interested parties; homeowners that matched the geographical constraints and indoor air quality parameters of the Mirant Funds were then referred to MOHCD's application and contracting process.

The Air District became involved with the project through contacts with the SFDPH. The SFDPH was interested in quantifying the effectiveness of the ventilation systems as a viable mitigation for existing homeowners impacted from roadway exhaust. The Air District funded the measurement portion of the study, working with SFDPH to contract with the LBNL to design and conduct limited monitoring in each study home to determine the effects of air filtration. LBNL obtained the

DOOR HANGER USED FOR COMMUNITY OUTREACH

Human Subjects Research approval through their agency's Institutional Review Board (IRB). The Air District participated in discussions with SFDPH and LBNL on outreach materials, air monitoring issues, and analysis of measurement results.

LBNL was the lead for the in-home measurement study including collection of indoor and outdoor measurements at each home prior to and after the installation of the enhanced filtration systems. LBNL's role was technical assistance with measurement-based evaluation of performance. LBNL responded to any questions or concerns regarding the study and scheduled appointments for installing the equipment, changing the filters, and maintaining the instrumentation. LBNL made recommendations about retrofit elements such as type of thermostat to use (some of which could not be implemented as recommended), collected measurements of air pollutants including fine particles and other parameters, and tracked equipment use in an attempt to evaluate the impact of each home renovation. In some cases, LBNL worked with the contractors to overcome challenges related to thermostat programming including identifying an easier to use thermostat in the 3rd and 4th homes of the Phase I pilot.

SFDPH interacted by phone daily with home occupants when logging their responses to a short survey, the *Daily Indoor Air Quality (IAQ) Satisfaction and Activity Survey for Mirant Home Participants*, designed to capture any individual behaviors that would influence indoor air quality measurements (Appendix A3). SFDPH staff also responded to homeowner's concerns and questions, and changed filters in the measurement instruments as necessary. Upon completion of each research agreement, SFDPH, via the San Francisco Public Health Foundation, paid each occupant a $200 stipend for their participation and associated energy costs.

Phase II

In Phase I, SFDPH had conducted outreach by mail to property owners living in a modeled zone of high particulate emissions adjacent to Highways 101 and 280 in the Bayview Hunters Point and Potrero Hill districts. From this mailing, the condo property on Mariposa and Kansas Street was identified as an ideal location to assess the provision of standalone air filtration devices. SFDPH contracted the Air District to subcontract and provide oversight of LBNL. SFDPH arranged the monitoring visits with homeowners. LBNL measured fine particle pollutant concentrations and other parameters indoors and outdoors during consecutive periods with and without the standalone air filtration devices operating. Outdoor air measurements were taken from the roof of the condominium building, rather than at each condo unit.

Study Methodology

Both phases were completed from 2013 to 2016 and overall, the results from pre- and post-retrofit measurements from each location showed marked improvements in indoor air quality. However, numerous challenges arose during the study, as well as limitations in matching the technology with the needs and capabilities of the homeowners. These barriers are further discussed in the following sections.

Site Selection

As a condition of the Mirant Settlement award, homes eligible to participate in the pilot program and evaluate study had to be located in Bayview/Hunters Point (zip code 94124) or Potrero Hill (zip code 94107) districts. DPH initially partnered with RTSF to assist with outreach and survey homeowners along Highway 101 corridors. RTSF conducted phone screening and were able to refer eight homeowners matching the demographic (low-income occupants of single family homes) and the forced air furnace required parameters of the Settlement Funds to DPH. Four of those homes were selected to receive retrofits in Phase I.

SFDPH later expanded outreach to homeowners within 900 feet of freeways 101 or 280, where the modeled annual average particulate matter concentrations from the CRRP mapping were greater than nine micrograms per cubic meter (9 µg/m^3), as shown below in Figure 5. Forty homeowners responded to the mailer requesting participation in the air filtration study. This mailing allowed SFDPH to identify a worthwhile study site for Phase II, a condominium building in Potrero Hill district located near a large retail grocery store and in close proximity to a freeway. The building management was supportive of the study by allowing temporary installation of rooftop monitoring equipment and recruiting additional participants when others dropped out of the study. Four condominium occupants at this site participated in the Phase II research.

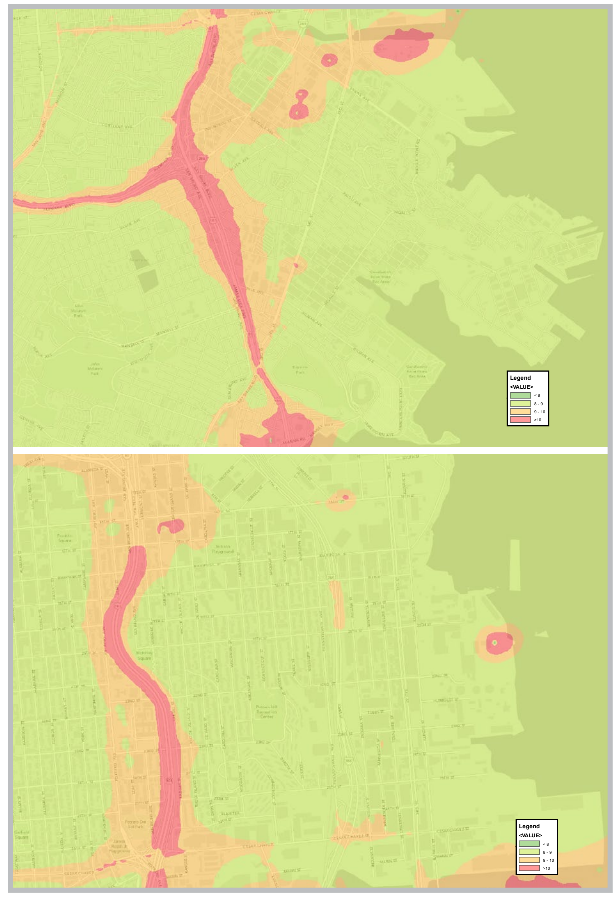


FIGURE 5: ANNUAL AVERAGE $PM_{2.5}$ CONCENTRATION IN POTRERO HILL (TOP) AND BAYVIEW HUNTERS POINT (BOTTOM) DISTRICTS

Study Design

The centerpiece of the Phase I pilot program was to reduce in-home pollutant exposures by retrofitting low-income homes with improved filtration for fine particulate matter and in some cases improving ventilation by replacing or upgrading range hoods and bathroom exhaust fans. For each home participating in Phase I of the study, some combination of the following retrofits were performed:

- Upgraded filter cabinet and installed higher performance filter to remove fine particulate matter using the central furnace air handler.
- Installed specialized programmable thermostat to enable intermittent operation of the air handler when heating is not required.

- Repaired or replaced central forced air furnace as needed to enable its use for enhanced filtration.
- Upgraded air handler with an energy efficient, variable speed motor (electronically commutated motor—ECM).
- Installed energy efficient, venting range hood with capacity to capture a high percentage of pollutants and moisture from cooking, or service existing range hood to improve performance.
- Installed energy efficient bathroom fan if none exists.
- Air-sealed building envelope to reduce uncontrolled outdoor air infiltration.

Forced air systems have traditionally included a filter to protect the fan, motor, and furnace heat exchanger from dust and large particles that can degrade performance. A higher performance filter to enhance filtration can be installed, but requires an adequately sealed filter and an advanced programmable thermostat to control the air handler when heating is not required.

There are benefits and limitations to installing a central air handler for reducing in-home exposures of $PM_{2.5}$. The main benefit is that enhanced filtration occurs as a co-benefit whenever the central furnace (or air conditioner) operates. The key limitation of simply installing a better filter and cabinet without also adding advanced controls is that filtration will then only occur when the furnace is being used for heat or when the fan is manually set to operate. There are thermostats that have an "air circulation" (or similarly named) setting to operate the air handler for a preset or programmable fraction of time (e.g. for 20 minutes or each hour) when heat is not required. A thermostat may allow this setting to be used during any programming interval, e.g., overnight ("sleep"), during the morning "wake" period, or during any other period. A programmable thermostat with fan timer ensures that filtration occurs routinely during any desired periods of the day. While this solves the problem of efficacy, it creates a problem of higher energy costs because most central air handlers currently in homes, and even new units being sold today, have inefficient air handlers that require 700-1000 watts or more to operate. While lower speed operation is possible in some units, such "multistage" operation is still not very common in base model units. There are efficient brushed permanent magnet (BPM) motors (including electronically commutated motors or ECMs) for air handlers that have much better modulation capabilities and that use a fraction of the power to move the same net amount of air when they operate continuously at lower speeds as opposed to a conventional permanent split capacitor (PSC) motor operating intermittently at a higher speed. In consideration of these challenges and opportunities, the program was designed to consider the suitability of a fan motor upgrade (if installing a new furnace) or replacement to reduce the energy costs of enhanced filtration.

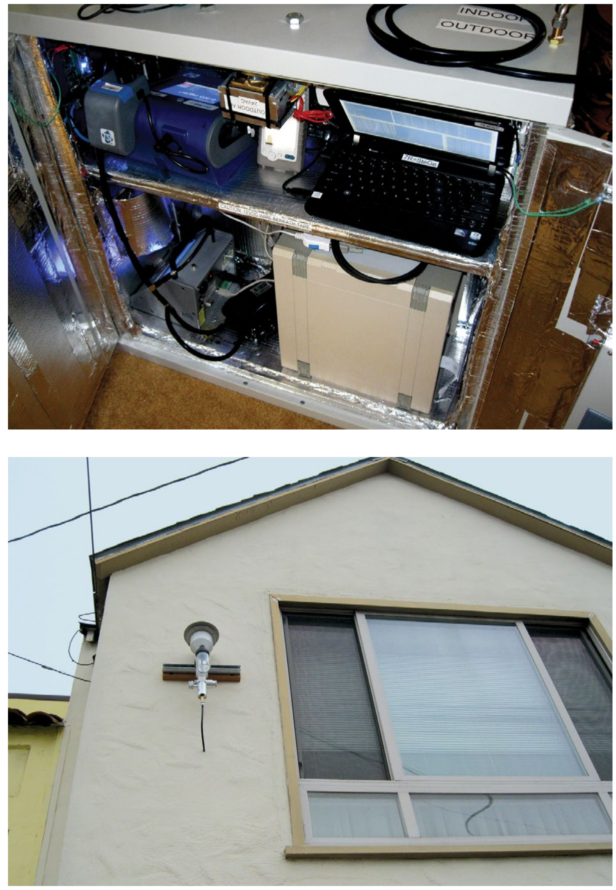
Phase II of the study focused on standalone air cleaners, which were installed in four condominium apartments in the same building. Standalone air cleaners are designed for single room application and are ideally suited for smaller homes or where there is no existing central air system. Some of the advantages of using standalone air cleaners are portability, simplified controls, and much lower power consumption relative to a central forced air system. However, standalone cleaners move less air (expressed as cubic feet per minute) through the filter compared to a central forced air furnace; this translates to lower overall capacity to remove fine particles from the indoor environment. At each condominium, an air cleaner was installed in the bedroom where it was expected that the occupants would spend most of their time and would receive the greatest benefit. Two of the air cleaners were relocated to the living room when researchers discovered that the occupants were already operating an air cleaner in their bedroom.

LBNL designed and led the measurement-based evaluation for both phases of the study.

For each phase, measurements of air quality and environmental conditions were made inside and outside of every participating home for one or two weeks pre-intervention (or without the standalone filtration unit operating in Phase II) and two or three weeks post-intervention (or with filtration unit operating in Phase II). Since Phase I involved retrofits, these periods are described either as being pre- and post-retrofit or pre- and post-intervention. Every attempt was made to conduct the pre- and post-intervention monitoring within the same season. However, scheduling and other issues resulted in post-intervention monitoring being performed several months or longer after the pre-intervention monitoring in several homes. In Houses H01–H03, there were two weeks each of pre- and post-retrofit monitoring. For House H04, there was one week of pre- and three weeks of post-intervention monitoring because the intervention involved both a furnace retrofit and provision of a standalone air cleaner. The post-intervention monitoring at H04 included four different operational configurations: (1) central air handler with filtration operated on a timer, (2) standalone filtration device operated without the central air handler, (3) central air handler on timer and standalone filtration device operated together, and (4) reference condition with no filtration.

Equipment and Measurement Methods

Data were collected with three types of environmental samplers or monitors: (1) devices that measured carbon dioxide (CO_2) and characteristics of fine particulate matter with time resolution on the scale of one to two minutes; (see Tables 2 and 4) (2) air samplers that were analyzed in the laboratory and provided a single measure of the integrated pollutant concentration over the time that they were deployed, (see Table 3) and (3) devices that measured environmental parameters and equipment operation including temperature, humidity, and exhaust fan use (see Table 4); these generally recorded data at one minute time resolution.



INDOOR AND OUTDOOR AIR SAMPLING EQUIPMENT

In Phase I, time-resolved measurements of fine particulate matter were made with a set of instruments connected to a manifold and sample line that alternately drew air from a central location indoors and from an outdoor sampling inlet. Small, passive monitors were used to measure carbon dioxide (CO_2), temperature (T), and relative humidity (RH) in several locations throughout each home and sensors were placed on a heating supply register and on the range hood to record operation of these pieces of equipment. CO_2 was monitored to identify when there were substantial cooking events, as the use of gas burners releases a large amount of CO_2 in a short amount of time, causing a spike in concentrations. CO_2 is also a rough indicator of occupancy and it can, under some circumstances, be used to estimate outdoor air exchange rates.

Particulate Matter Measurement	Instrument Units	Monitoring Device	Data Resolution and Notes
Particle number concentration in bins defined by minimum particle diameters (µm) of 0.3, 0.5, 0.7, 1.0, 2.0, and >5.0	# L^{-1}	MetOne BT-637S Optical Particle Counter (metone.com)	Manufacturer specified accuracy of ±10% to calibration aerosol. Range of 0-105,900 particles/L.
Mass concentration estimated by light scattering (nephelometry)	mg m^{-3}	TSI DustTrak II 8530 (tsi.com)	Instrument output multiplied by factor of 0.38 to estimate $PM_{2.5}$ mass.[26]

TABLE 2: DEVICES USED TO MEASURE FINE PARTICULATE MATTER INSIDE AND OUTSIDE OF STUDY HOMES IN PHASE I

Parameters	Units	Locations	Device	Specifications & Notes
Formaldehyde, Acetaldehyde	ppb	Outdoors; Kitchen; Bedroom; Duplicate in 1 location; Blank	Waters Sep-Pak XPoSure	Used passive sampling rates from Mullen et al. 2013[27]
NOX, NO2	ppb	Outdoors; Kitchen; Bedroom; Duplicate in 1 location; Blank	Ogawa NO_X/NO_2	Validation reported in Singer et al. 2001[28]

TABLE 3: MEASUREMENTS OF AIR POLLUTANTS OVER 1-WEEK INTEGRATED PERIODS IN PHASE I

Parameters	Units	Locations	Device	Notes
Temperature (T) and relative humidity (RH)	°F, %	Typically in common area and bedroom(s)	HOBO U10 (Onset)	Checked calibration against suite of similar sensors
Outdoor T, RH	°F, %	Outdoors on premises	HOBO U23 Pro v.2	Checked calibration against suite of similar sensors
Indoor carbon dioxide (CO_2)	ppm	Varied by house	Extech SD800	Calibrated prior to deployment at H01.
Furnace burner operation indicated by air T	°C	Furnace air supply register	HOBO U12-014 w/ thermocouple	Threshold to ID on/off varies by home.
Furnace burner and air handler operation	volts	Relay / signal from thermostat	HOBO with voltage divider to convert 24VAC to <2.5 VDC	Convert to on/off by comparing to threshold. Need to determine threshold from data.
Bath fan operation;	amp	Electrical current to fan	Current transducer (CT)	Threshold to ID on/off varies by home.
Range hood; operation	Pa or m/s	Pressure or air velocity at inlet	Differential pressure sensor or anemometer	Threshold to ID on/off varies by home. Not used in H01, H03.

TABLE 4: DESCRIPTIONS OF ENVIRONMENTAL AND EQUIPMENT OPERATION MEASUREMENTS IN PHASE I

Measurements of fine particulate matter included the number concentration of particles in six different size bins from >0.3 µm (microns) to >5 µm (10^{-6} meter) diameters and an estimate of mass concentration based on total light scattering. The light scattering instrument had a nominal lower size limit of particles of 0.1 µm diameter and was fitted with a 2.5 µm inlet to exclude particles larger than that limit. The instruments used to measure these parameters are described in Table 2. An instrument was also deployed to measure "black carbon", a characteristic of the fine PM that is related to diesel particulate matter; however, only limited valid data were obtained with that instrument and those data have not been analyzed and are not presented in this report. Measurements from the indoor DustTrak instruments were multiplied by 0.38 for all Phase I homes to estimate $PM_{2.5}$ mass concentrations; this adjustment factor is based on prior studies that have compared DustTrak data to coincident gravimetric measurements.[25]

In Phase I, air samplers were deployed to determine concentrations of volatile aldehydes (formaldehyde and acetaldehyde) and nitrogen oxides (including total nitrogen oxides and specifically nitrogen dioxide) over weeklong periods outdoors and in one or more indoor locations, such as the kitchen, living room and bedroom (Table 3). These measurements were not made in Phase II. Various environmental and equipment operation parameters were monitored at one minute or greater resolution using sensors that were placed in the relevant environmental locations or on the equipment. Instruments used to monitor these parameters are listed in the Device column of each Table.

The outdoor samples collected in Phase I were pulled through an assembly (BGI, Inc.) comprised of a PM_{10} inlet (to exclude all particles with aerodynamic diameters larger than 10 microns) with rain shield followed by a sharp-cut cyclone that excluded particles larger than 2.5 μm in diameter. This assembly was mounted as high as possible on an exterior wall, with a spacer to offset the inlet away from the plane of the wall. An eight-meter long section of conductive tubing (used to reduce particle losses in the sample line) connected the outdoor inlet to a switching valve. An identical length of tubing was used for the indoor sample, but no size-selective inlet was required because the mass concentration instrument, DustTrak, has its own 2.5 μm inlet and the particle counter reports results by particle size.

In Phase II, concentrations of fine particulate matter inside the homes were measured with DustTrak II 8530 monitors outfitted with inlets to restrict entry of particles larger than 2.5 μm diameter. The instruments were placed in each of the condominium units and outdoor measurements were made with instruments placed on the roof of the building. Outdoor $PM_{2.5}$ was measured with a Thermo Scientific pDR-1500 monitor placed into a large plastic bin with a rain covering over a gap of eight centimeters to allow airflow into the bin. The pDR-1500 works on the same basic measurement principle (light scattering) as the DustTrak. A DustTrak was co-located with the pDR-1500 on the roof for 11 days and both instruments were compared to data reported at the nearby Air District air monitoring station on Arkansas Street, which uses a MetOne Beta Attenuation Monitor (BAM) to measure $PM_{2.5}$ on an hourly basis. Multiplying the pDR-1500 by 0.938 and the DustTrak by 0.396 brought the instruments into alignment with the nearby BAM monitoring unit.

The Phase II study also included monitoring of the following parameters: CO_2 in the living room and bedroom using Vaisala GMW115 sensors connected to HOBO UX120-006M data loggers; T and RH in the living room and bedroom using HOBO U10-003 loggers; range hood use using Digisense 20250-22 anemometer/logger; and standalone air filter use using HOBO UX120-018 plug load monitor.

CO_2 instruments were calibrated before deployment; but the length of time varied from calibration to deployment varied. Each MetOne optical particle counter, DustTrak, and pDR-1500 used in the study was calibrated by the manufacturer prior to the start of each project phase in which it was used. Instruments measuring CO_2, temperature and relative humidity were calibrated to a gas standard or the mean value of a suite of co-located similar instruments.

In both phases of the study, participants were asked to provide information about activities in the home that can affect indoor air quality and the outdoor air exchange rate. In Phase I, the log included questions about perceived air quality, window use, smoking, candle or incense use, and cooking with cooktop or oven during the following time intervals: 11 pm to 6 am (i.e. overnight), 6–11 am (morning), 11 am to 4 pm (mid-day) and 4–11 pm (afternoon/evening). The log was completed during a daily telephone call from a DPH researcher to the participant. In Phase II, the participants were provided with paper forms that they were asked to complete on their own – one for each day of measurements in the home. The Phase II log asked about any occupancy, window use, cooktop or oven use, range hood use, electric grill or toaster use, smoking, candles or incense, and odors from outside. The time periods were adjusted slightly to perfectly align the logs with calendar days; intervals were midnight to 6 am, 6–10 am, 10 am to 4 pm, and 4 pm to midnight.

Analysis Techniques

Results are presented in plots showing measured parameters as a function of time during pre- and post-retrofit. Data are displayed for indoor and outdoor temperatures, CO_2, operation of the central forced air heating system, estimates of fine particulate matter concentrations indoors and outdoors and the ratio of indoor-to-outdoor concentrations of fine PM. The data displayed in figures are further described in "Study Findings by Site" and in the figure captions.

Data shown for fine particulate matter mass concentrations are taken either from the DustTrak monitor (with the adjustment multiplier as noted in Table 2 on page 25) or by calculating an estimated mass using the size-resolved particle number concentrations from the optical particle counter. The calculation assumes that all particles are spherical, that all particles within a size bin have the median diameter of the bin, and that all particles have a density of 1.65 grams per cubic centimeter.

For particles, the ratio of indoor to outdoor concentrations is presented as a summary indicator of filtration benefits because the absolute levels of indoor particulate matter will vary with outdoor PM and indoor sources. If there are no indoor PM emissions, indoor concentrations will be lower than outdoors because sealed windows/doors and walls delay and block particles from entering the home. With indoor emissions, concentrations indoors can be higher than outdoors. Fully quantifying the benefits of filtration to reduce concentrations resulting from indoor emissions requires advanced analysis techniques to quantify the impact of indoor particle emission events and incorporate these into the analysis; these techniques were beyond the scope of this study. Instead, the analysis for this evaluation focused on periods when there were no apparent impacts from indoor sources and looked at the indoor-to-outdoor ratios during times when the only source of indoor particles was from outdoors.

CO_2 concentrations are rough indicators of occupancy because people exhale CO_2; for a fixed space, higher CO_2 generally means more occupancy. But CO_2 levels also depend on the amount of outdoor air ventilation and spikes in CO_2 may indicate times where the occupants are cooking on natural gas burners in the home.

Study Findings by Site

Results for the Phase I single family homes are summarized in Table 5 and Table 7 contains a summary of the results from Phase II condominiums.

Phase I Study: Single Family Homes

This section presents a narrative description of the evaluation of retrofits implemented through Phase I of this study. For each home, the following are provided: a description of the home and implemented retrofits, challenges that were encountered, selected pre- and post-retrofit monitoring results with commentary, and lessons learned.

H01 – Scotia Street and Quint Street

Description of home

This is an attached house built in the 1930s. The main living space is on the second floor, above a garage and basement. Public records indicate two bedrooms, one bath, and just under 1500 square feet (sf) of living space. The house had a gravity furnace in the basement that was operable but the ductwork lacked integrity in places. There was no mechanical exhaust ventilation in the bathroom or kitchen, but the kitchen range was located beneath an elevated ceiling and skylight with operable window that effectively functioned as a passive stack vent.

Retrofits

The following retrofits were implemented in home H01 to achieve the study objectives:

- Installed new 80% efficiency forced air furnace (York Model #YPLC060A12MP12) with ECM motor and MERV13 filter with special low-pressure drop filter cabinet. The York furnace was installed in the same location as the gravity vent furnace, which was removed.

- Installed acoustically lined cold air return plenum, supply plenum with collars and lock-type air balancing dampers, galvanized duct from existing cold air return location to furnace, and galvanized duct from furnace to existing supply registers.
- Installed Honeywell VisionPro 8000 programmable thermostat; and
- Installed Energy Star™ certified exhaust fan in bathroom.

The intent was to install a furnace and thermostat control that would allow intermittent operation at medium speed to provide filtration when heat was not required. The thermostat was selected because it featured a "Circulate" setting that operates the air handler for approximately 35% of every hour when not used for heating.

Results

Pre-retrofit monitoring occurred from August 16 to 30, 2013 with passive, time-integrated sampling from August 16 to 23 and August 23 to 30. Post-retrofit monitoring occurred from September 25 to October 9, 2013 with a change of one-week integrated samples on October 2, 2013. The particle monitors were installed and sampled in the living room in the front of the house. Monitoring of other parameters occurred in the kitchen, in the middle of the house, and in the basement, which was downstairs from the kitchen.

The plan to have the air handler with high performance filtration operate intermittently was not successfully implemented because the contractor did not correctly program the thermostat. As a result, the air handler operated continuously for the first eight days of post-retrofit monitoring. The constant noise of the air handler—which was noticeably louder than the silent gravity furnace that was in the home before the retrofit—was objectionable to the homeowner. On the eighth day (October 3), the homeowner reset the thermostat control to "Auto", a setting in which the air handler operated only when heating was needed. For the remainder of the post-retrofit monitoring period, the air handler operated only when there was a call for heat; this happened several hours each morning and once overnight, on October 9, 2013.

Results for the periods of pre- and post-intervention monitoring in H01 are presented in Figure 6 and Figure 7. Diurnal outdoor temperature variations were much greater during the post-retrofit period in late September and early October than during the pre-retrofit monitoring in late August and early September. During the pre-retrofit period, outdoor temperatures ranged from around 60 degrees Fahrenheit (oF) overnight to 70-75 °F in the early afternoon. Post-retrofit, daily lows were in the low to mid-50s °F on many nights (early mornings) while the daily highs varied from the low 70s to above 80 °F. Indoor temperature patterns and ranges were broadly similar during pre- and post-retrofit periods, peaking in the low to mid-80s °F in the evenings and daily minima mostly in the low- to mid-70s oF occurring in the late morning. The relatively high indoor temperatures were desired and considered comfortable by the resident.

The consistency of occupancy and activities that can affect indoor particle emissions between pre- and post-retrofit periods is not clear from the available information. CO_2 concentrations were higher during post-occupancy than during pre-occupancy. This could have resulted from more occupancy, lower outdoor air ventilation, or some combination of the two. The daily activity log indicated that most window opening and most cooking occurred between the hours of 11 am and 4 pm. During this daily time interval, the participant reported that windows were opened every day during both pre- and post-retrofit monitoring, and for similar amounts of time: averages were 53 minutes per day pre-retrofit and 50 minutes per day post-retrofit. As another indicator of the consistency of household activities, the amount of cooking reported by the participant was also similar during pre- and post-retrofit periods. Pre-retrofit cooktop used during the 11 am to 4 pm interval occurred on 10 of 13 days with completed logs; the average cooktop use was 24 minutes per day, including days with no cooking. Post-retrofit, the cooktop was used during the 11 am to 4 pm interval on nine of the 14 days for an average of 21.5 minutes per day, including days with no cooking. Similar types of cooking were reported pre- and post-retrofit. During the 4–11 pm interval, cooking occurred on four days pre-retrofit and five days post-retrofit. Spikes in the CO_2 concentrations measured from the monitoring equipment are consistent with the reported use of gas cooktop burners, which emit CO_2.

The furnace was used for heating on eight of the 14 days pre-retrofit (though only very briefly on one of the days), suggesting the potential for incidental filtration benefit even during the summer in San Francisco; but this effect may only be relevant for homes in which residents prefer very high indoor temperatures. The furnace was used for heating on all of the post-retrofit days—which were in September and October; this indicates the potential to reduce in-home particle exposures through improved filtration in the air handler.

Estimated fine particulate matter mass concentrations during pre- and post-retrofit monitoring periods are also presented in Figure 6 and Figure 7; panel (d) shows 1-minute resolved and 8-hour running average concentrations indoors and outdoors and panel (e) shows the ratio of indoor-to-outdoor (I/O) 8-hour averages. The thickness of the gray band in (d), which expands with the difference between indoor and outdoor concentrations, is a quick visual indictor of the filtration benefit of reducing in-home exposure to outdoor particles. To enable this visual guide, the PM results are presented on a logarithmic scale, with equal spacing for every 10x increase or decrease in concentrations.

Broadly, the data show that high performance filtration in the air handler substantially reduced the indoor to outdoor ratio of fine particles and reduced in-home particle exposures compared to what they would have been without filtration. Pre-retrofit, the I/O ratio had a low value of roughly 0.5 during times when indoor sources were inconsequential; this means that indoor concentrations were 50% lower than outdoors. The ratio increased following sharp spikes in the indoor CO_2, an indicator of cooking. During the first eight days of the post-retrofit period, when the air handler with filtration operated continuously, the indoor-to-outdoor PM ratio was approximately 0.1 during times with no prominent indoor sources (e.g., September 28 to October 2); concentrations were thus reduced by 90% indoors relative to outdoors. During the final six days post-retrofit, the gray band expanded and the I/O ratio dropped each time the furnace operated. When there were no prominent indoor sources during this interval—e.g. on October 5 and 6—I/O ratios varied from about 0.5 when the furnace and air handler with filtration were off for an extended period down to <0.2 when the furnace and air handler with filtration operated each day. Overall I/O ratios were impacted by substantial cooking-related emissions on October 3, 4 and 7; these are indicated by sharp increases in indoor PM and also CO_2 spikes.

Summary of Pollutant Control Results

When the air handler with enhanced filtration operated in this home, the indoor particle concentrations were reduced by 50 to 90% relative to outdoors during periods without indoor source events.

Lessons Learned

Thermostat complexity is an important issue and challenge when trying to reduce air pollutant exposure using a central air handler with enhanced filtration. In this home, even the contractor did not correctly set the desired fan control on the thermostat. While training of program participants is possible, many will have difficulty implementing the series of steps required to program the thermostat to achieve intermittent operation on a desirable schedule. Those lacking technical sophistication will be particularly challenged. Setting a system to operate intermittently at all times is marginally easier, but it translates to large energy consumption. Standalone air filters, which typically have fewer and less complicated controls (because they are controlling only filtration and not the furnace), may be advantageous in addressing the challenge of technical complexity.

Energy costs associated with operating the air handler for many more hours than are needed for heating can be problematic for low-income households. These incremental costs will be lower for homes that already use the furnace throughout the year and in homes that choose —and manage to set the thermostat—to operate the air handler with filtration only some of the time, e.g. during evenings when people are home and awake. The resident of H01 desired a high indoor temperature for comfort and thus used the central furnace on many days, even during summer. The incremental costs of operating the central air handler filtration for this resident would not be as high as in a home where the furnace was used only during winter.

Noise is also an important consideration. In H01, a gravity furnace—which distributed heat through buoyancy and thus did not use a fan—was replaced by a forced air system in which a fan moves air through the ductwork. The resident of H01 found the noise to be objectionable, and turned off the air handler during the second week of post-retrofit monitoring. There are approaches to reducing noise in forced air systems. One approach is to reduce noise by lowering fan speed and operating the blower for longer periods of time at lower flow.

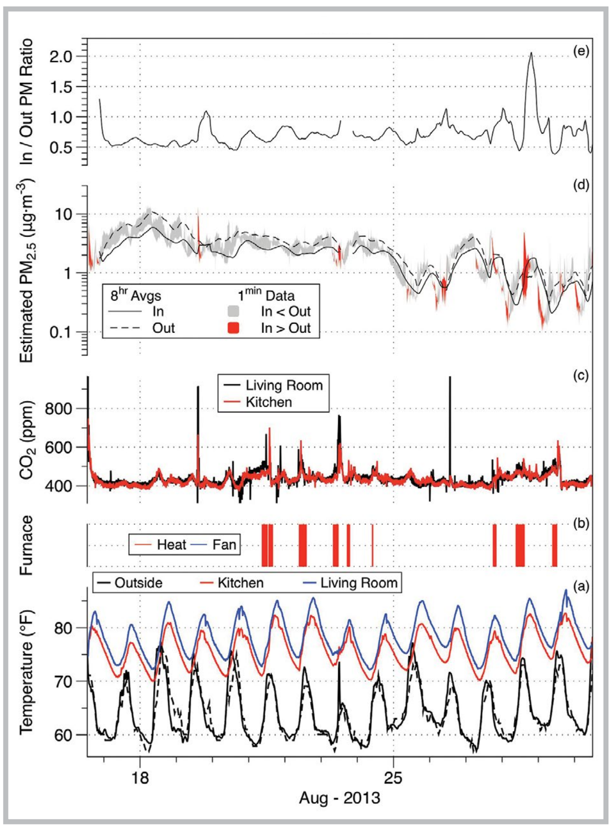


FIGURE 6: RESULTS FROM PRE-INTERVENTION MONITORING OF H01

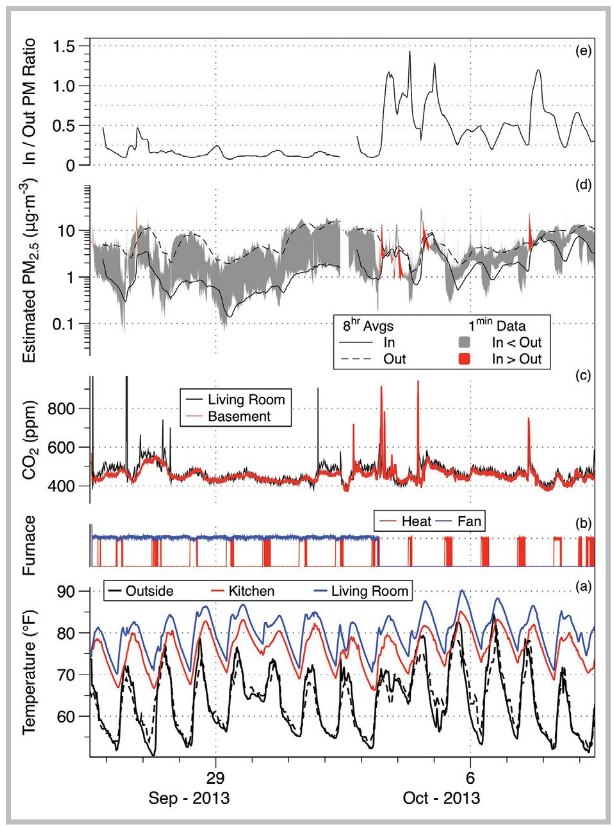


FIGURE 7: RESULTS FROM POST-INTERVENTION MONITORING OF H01

(a) Indoor and outdoor temperatures; hatched line is data from San Francisco airport. (b) Operation of central furnace indicated by temperature sensor at supply register. (c) Carbon dioxide (CO_2): concentrations near 400 ppm (outdoor levels) suggest light occupancy or high ventilation rates; sharp spikes indicate cooking with gas. (d) Estimated fine particulate matter ($PM_{2.5}$) calculated from size-resolved particle measurements; red indicates periods when indoors was higher than outdoors. (e) Ratio of indoor to outdoor 8-h running average $PM_{2.5}$. Break is when researchers visited to download data.

H02 – Ceres Street and Williams Avenue

Description of home

This attached house, built in the 1920s, has the main living space on the second floor, above a garage and basement. Public records show three bedrooms, one bath, and a little less than 1400 square feet of living space. The home had a relatively modern, central gas furnace and air handler that was installed through a subsidized retrofit program. The furnace was in an unconditioned, but enclosed basement area at ground level. The kitchen range hood was not vented. The home was occupied continuously, as one of the two residents was in ill health and could not easily leave the home.

Retrofits

The following retrofits were installed in home H02 to achieve the study objectives:

- Replaced blower motor with energy efficient ECM.
- Removed and replace cold air return duct and plenum.
- Installed acoustically lined cold air return plenum and flex duct to furnace.
- Installed new control wire from existing thermostat to furnace to allow fan-only function.
- Installed Honeywell VisionPro 8000 programmable thermostat.
- Set thermostat to operate central blower with filtration at least 20 min each hour.
- Installed MERV13 filter and new filter cabinet in central blower return.
- Removed old terra cotta flue to accommodate duct for range hood.
- Provided new electrical circuit for range hood.
- Installed new range hood (Broan Allure III QS3 Series QS336WW) and ducting to outside.

As with H01, the intent was to install a thermostat/controller that would operate the furnace air handler with filtration continuously at low speed or intermittently at medium speed when not needed for heating. The thermostat installed at H02 was the same model as used in H01; it was selected because it had a “Circulate” option allowing the air handler to operate for 35% of the time when not used for heating. This option could be used for any or all of the four daily program settings (i.e., wake, leave, return, and sleep). There was concern about the complexity of the thermostat based on the experience at H01; but the contractor could not find an available alternative with the same functionality. The blower motor was replaced with an energy efficient motor to reduce energy consumption when the air handler operated for filtration.

Results

Pre-retrofit monitoring occurred October 16–30, 2013, with time-integrated aldehyde and nitrogen oxides samples collected October 16–23 and 23–30. 2013. Environmental parameters were monitored in the living room at the front of the house, in the master bedroom at the back of the house, and a computer room that was between the kitchen, which was in the middle of the house, and the master bedroom. Post-retrofit monitoring occurred December 6–19, 2013, with samples changed during a December 12 visit. Environmental parameters were monitored in the living room, second bedroom (also in the middle of the house), and the computer room. A monitor was not placed in the master bedroom during the second week of post-retrofit because the room was inaccessible at the time of our visit. Indoor particles were measured in the kitchen, but several meters away from the stove. The instrument cabinet was placed in the basement and the sample line was fed up through the floor to the kitchen.

Several times during the post-retrofit monitoring period, the residents reported discomfort from cold air blowing from the heating supply registers; presumably this occurred when the air handler operated for filtration without the furnace operating for heat. They also reported that temperatures in the home were too low in general, creating additional discomfort. The circulating cold air problem was mitigated, though not fully solved, by closing the supply register in the living room. The generally low temperature issue was not diagnosed and resolved by the HVAC contractor until January 2014. Prior to the HVAC contractor fixing the problem, on several occasions the homeowners used the gas stove to heat the kitchen. The problem, diagnosed in January, was that the high temperature safety switch of the thermostat was being activated. It was initially thought that this occurred every time the heat turned off because the new ECM motor was not properly connected to the furnace control unit. The furnace is designed to have the air handler fan continue to operate for a short period of time after the furnace stops to ensure that the furnace heat exchanger is not damaged from heat stress. The diagnosis was that the air handler would shut off at the same time as the furnace without transferring the residual heat, leading to the heat exchanger exceeding the thermal cut-off threshold. When this threshold was exceeded, the furnace would initiate a three-hour safety shutdown during which combustion (heat generation) could not occur. In January 2014, the HVAC contractor made repairs to the system; these included checking the fan flow settings and properly connecting the fan motor to the furnace control. The program participants reported that these repairs resolved the problem.

Based on a subsequent, careful consideration of the data, it appears that the problem was not that the air handler fan was turning off; rather, it was not moving enough air to remove heat from the heat exchanger. This hypothesis is based on the observed particle concentrations, which indicate high levels of particle removal consistent with filtration. If the fan had been off, there would have been a gap in the filtration; but such a gap does not appear to be present in the data. This is further discussed below.

The results for pre- and post-retrofit monitoring are presented in Figure 8 and Figure 9, respectively. Outdoor temperatures were lower and heating demand was greater during post-retrofit than during pre-retrofit monitoring. During pre-retrofit monitoring in October, outdoor temperatures reached overnight lows of about 50 °F on most days and high temperatures ranged from >90 °F on October 16 to 60 °F on October 27. Outdoor temperatures during post-retrofit monitoring in December had overnight lows of 35-45 °F and daily highs of 50 °F to >65 °F. Pre-retrofit indoor temperatures drifted down to 70 °F in the morning and hovered on either side of 80 °F through the day and evening as the furnace operated. During the post-retrofit monitoring, temperatures drifted to 65 °F or below during the first 5 days and down to only 70 °F during the remaining days. Indoor high temperatures were mostly below 80 °F. These data are consistent with resident complaints that the house was colder after the retrofits. The furnace plot in panel 4b shows that there were some intervals with a nearly constant call for heat, e.g. December 9-10 and December 13-15. During these periods, the furnace burner operated intermittently as indicated by a temperature sensor at a furnace supply register. The very low I/O ratios from the particle measurements suggest that the furnace fan with filtration operated continuously throughout these periods. The sections of this plot that show bands of blue are periods when the fan was operating intermittently because there was no need for heat.

During the pre-retrofit period, master bedroom CO_2 concentrations rose each day in the late evening, consistent with the door being closed overnight. In the morning, bedroom CO_2 dropped as CO_2 in the other rooms increased indicating mixing of overnight CO_2 from the bedroom. Daily high CO_2 in the living room was often above 1000 ppm. Post-retrofit CO_2 concentrations were much lower than pre-retrofit concentrations except for the five large CO_2 spikes on December 7, 9, 10, 16, and 19. The lower CO_2 levels post-retrofit suggest much higher outdoor air exchange (ventilation) rates than pre-retrofit. Since the residents did not report opening windows much during the post-retrofit monitoring (and they would not likely have done so since it was winter and they

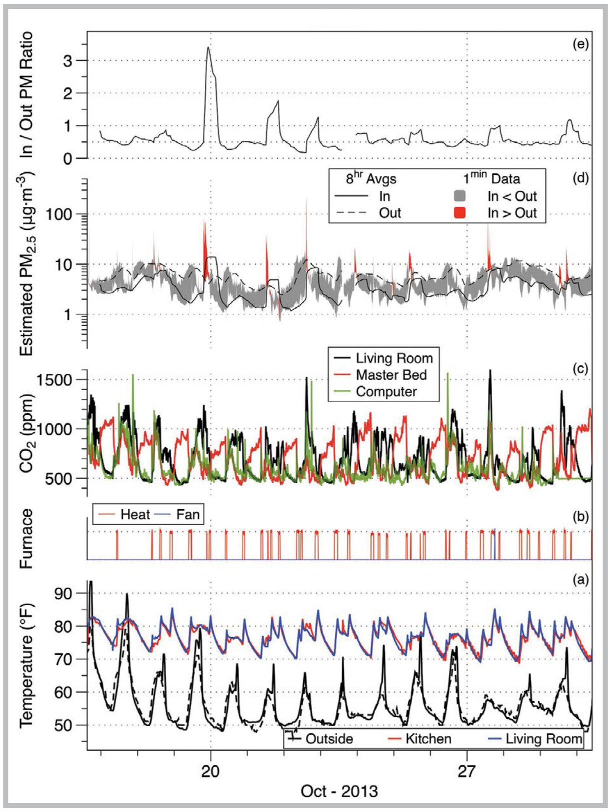


FIGURE 8: RESULTS FROM PRE-INTERVENTION MONITORING OF H02

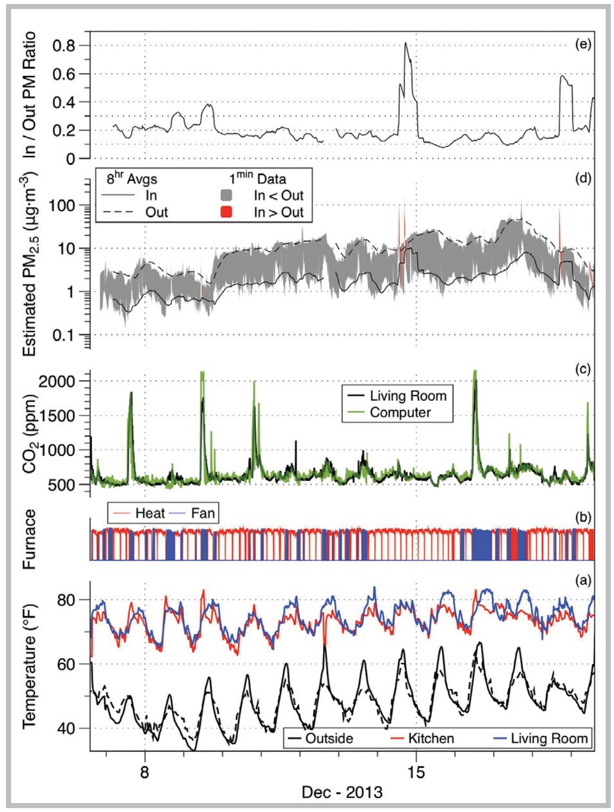


FIGURE 9: RESULTS FROM POST-INTERVENTION MONITORING OF H02

(a) Indoor and outdoor temperatures; hatched line is data from San Francisco airport. (b) Operation of central furnace indicated by temperature sensor at supply register. (c) Carbon dioxide (CO_2): concentrations near 400 ppm (outdoor levels) suggest light occupancy or high ventilation rates; sharp spikes indicate cooking with gas. (d) Estimated fine particulate matter ($PM_{2.5}$) calculated from size-resolved particle measurements; red indicates periods when indoors was higher than outdoors. (e) Ratio of indoor to outdoor 8-h running average $PM_{2.5}$. Break is when researchers visited to download data.

were feeling cold), the higher air exchange is presumed to have resulted from air leaking into or out of the HVAC ducts as the air handler was operating to provide filtration. With the exception of the event on December 16, all of the other CO_2 spikes correspond to cooking on natural gas burners as reported by the residents in their daily logs.

Interpretation of the particle data is complicated by indoor concentration spikes (in red, Figure 8d) that suggest many indoor emission events. During the pre-retrofit period, the residents reported cooking on 10 of the 14 days. Most of the cooking events were short in duration (<15 minutes) and involved boiling or heating liquids on the cooktop. There were fewer cooking events post-retrofit, but several involved use of the oven over periods of 30 minutes or more.

Nevertheless, the indoor/outdoor ratios in the pre-retrofit period (Figure 8e) settled around 0.5 when not directly impacted by indoor sources. Post-retrofit, the I/O ratio was in the range of 0.1–0.2 during periods not impacted by indoor emissions.

Nitrogen oxides (NOx) measurements were much higher both indoors and outdoors during post-retrofit weeks compared to pre-retrofit weeks. These data were analyzed to estimate the amount of indoor NOX that was generated by indoor sources, and the results suggest a negative IAQ impact of using the stove for heat. During two weeks of pre-retrofit monitoring, the indoor NOX estimated to come from indoor sources was 24-28 parts per billion (ppb) in bedrooms and 34-40 ppb in the kitchen. During the first week of post-retrofit monitoring at

H02—when the occupants reported using the gas stove to heat the kitchen on several occasions and there were very large spikes in CO_2 concentrations indicating gas burner use—the indoor NOX estimated to come from indoor sources was 58-63 ppb in bedrooms and 93 ppb in the kitchen. During the second week of post-retrofit monitoring, indoor-attributed NOX was 22 ppb and 42 ppb in the two bedrooms and 54 ppb in the kitchen.

Summary of Pollutant Control Results

During periods when there were no obvious indoor sources of particle emissions, the ratio of indoor to outdoor particle concentrations was reduced from roughly 50% when there was no filtration to 10-20% (80% to 90% lower indoor concentration than outdoor) when the air handler operated with enhanced filtration.

Lessons Learned

The experience at H02 highlights the risks of retrofitting an existing, well-functioning heating system. The retrofit led to more than a month of intermittent discomfort and hassle for the occupants as it took several visits for the HVAC contractor to diagnose and fix the problem that was created by the retrofit.

The discomfort felt by the H02 occupants from circulating/blowing cool air post-retrofit is another important issue to consider when considering filtration options. When the air handler operates for filtration, it moves air through ductwork located in the cooler basement area. The air exiting from the furnace supply register is cooler than the room temperature air in the living space and thus, may be uncomfortable for the occupants. However, if the air handler operated continuously at a lower flow setting, air would exit from the supply registers at a lower velocity and thus impact a smaller area within the living space, but again, the air from the register would still be cooler than the room temperature. Similar to H01, the complexity of operating the thermostat was an issue for the occupants.

H03 – Carr Street and Paul Avenue

Description of home

This is a small house with two bedrooms and one bath above a garage and basement area that are not accessible from the living space. The house is less than 1000 square feet. Part of the ground floor had been converted to an unregistered rental unit that was not connected to the main unit and not included in any part of the evaluation. As found, the house had no working central furnace. There was a non-operational electric heater mounted on the wall of the second (unoccupied) bedroom.

Retrofits

The retrofits were completed under two scopes of work. Mirant funds were used to fund the following work, all in the main (legal) living space:

- Installation of new furnace and ductworks.
- Installation of MERV13 filter and new filter cabinet in central blower return.
- Installation of programmable thermostat, Robert Shaw Model 9725i2.
- Installation of range hood.
- Installation of bath fan.

An SF MOH Healthy Home Grant was used to fund the following improvements:

- Installation of new roof.
- Upgrades to the kitchen and bath (in legal living space).
- Other health and safety updates.

As with the first two Mirant Project homes, the intent was to use the thermostat to operate the central air handler intermittently for filtration when the furnace was not operating for heat.

Results

The retrofits were normally conducted in two stages with the Mirant work completed first, followed by post-retrofit monitoring, and then Healthy Home repairs. The pre-retrofit monitoring occurred over two one-week periods from May 9 through 16, 2014 and May 16 through 23, 2014 with monitors in the living room, kitchen, and master bedroom. The cabinet of particulate matter sampling devices was placed in the second bedroom with the air inlet drawing from the living room.

Post-retrofit monitoring was delayed as the Mirant retrofit work extended into September. Just before monitoring was set to start in early October, there was a break in the street's water main that flooded the garage and downstairs unit. Monitoring was pushed back out of concern that conditions during the cleanup would be unusual and also because the homeowner was occupied dealing with the cleanup. One week of post-retrofit monitoring occurred November 11-17, 2014. This was in a different season than the pre-retrofit monitoring; but it was deemed a necessary compromise and potentially the only opportunity available to collect the post monitoring data. In fact, this week of monitoring produced almost no useful data on filtration because the homeowner turned the thermostat off (to avoid using the heat). During this first week of monitoring, the homeowner informed the research team that she planned to travel abroad the following week. The team decided to proceed with the Healthy Home scope of work and try again to conduct post-retrofit monitoring afterwards.

Two additional weeks of post-retrofit monitoring occurred March 23 to 30 and March 30 to April 6, 2015. Monitors were placed in the living room, kitchen, and master bedroom. Prior to the second round of post-retrofit monitoring, the project team explicitly discussed with the homeowner the importance of allowing the thermostat program to operate the air handler following a set schedule in order to evaluate the system performance. Despite this discussion and also the stipulation in the contract signed by the homeowner, the homeowner once again turned off the fan timer for most of the post-retrofit monitoring period. As a result, there were just a few, very brief periods during the post-retrofit monitoring during which the air handler with filter operated.

The furnace was installed in the attic where access is through a pull-down stairway. As an example of the types of problems that can be created during real-world installations, ducting was installed into the front of the cabinet that makes opening the cabinet door to change the filter extremely difficult.

For post retrofit monitoring, a Robert Shaw Model 9725i2 thermostat was installed. This thermostat was thought to be easier and simpler to navigate, based on its performance in a two-home demonstration project on indoor air quality management that LBNL had conducted in Sacramento. The Shaw thermostat was installed for the limited purpose of ensuring that the homeowner could manage the system if needed during post-retrofit monitoring. However, since the homeowner preferred the Shaw model over the programmable thermostat originally installed by the HVAC contractor, this thermostat was left in the home.

Results from the two weeks of pre-retrofit monitoring in May 2014 are provided in Figure 10. Results from the two weeks of post-retrofit monitoring in March-April 2015 are presented in Figure 11. Data from the November 2014 post-retrofit monitoring period are not presented because they provide no added value to the results presented in Figure 11 as discussed above.

During pre-retrofit monitoring, outdoor temperatures varied from daily lows of mid- to high-50s oF to daily highs that ranged from <80 to >90 oF, based on temperature data from San Francisco International Airport. (Higher temperatures recorded by the sensor placed outside the house suggest that it may have been placed in a location that was impacted by direct sun heating the building.) Outdoor temperatures were a bit cooler in the post-retrofit period, with daily lows mostly between 50 and 55 oF and daily highs mostly between 70 and 80 oF. Indoor temperatures varied diurnally over narrower ranges, but with day to day trends that reflected the outdoor conditions (i.e. hotter outdoor temperatures produced hotter indoor temperatures). During both pre- and post-retrofit monitoring, CO_2

increased and decreased each day much more steeply in this home than in other study homes. The sharp decrease each morning is consistent with a high ventilation rate clearing CO_2 after the home is vacated. The participant reported in the daily log that windows were open almost all the time from morning through the late evening. The pre-retrofit data indicate very high CO_2 concentration in the bedroom each night, with lower CO_2 in other rooms. This is consistent with a closed bedroom door overnight. During this pre-retrofit period, the participant reported windows being open overnight on May 20, 21, and 23; but the location of the open window was not specified. There was no furnace operation pre-retrofit because there was no furnace. And post-retrofit there was only a few hours of furnace fan operation on March 30.

A distinguishing feature of this home was the daily use of candles by the homeowner. During the pre-retrofit period, candle use was reported during 12 of 14 overnight periods, for durations of three to six hours each night. Candles were also used during 10 of the 14 morning periods (6–11 am) during pre-retrofit monitoring. During the post-retrofit monitoring, candles were burned during every overnight period and all but one morning period. Candles can emit substantial quantities of fine particles resulting in high monitored concentrations due to the small size of the home. However, on most days, the trend is for the I/O ratio to decrease overnight, when windows were usually closed, down towards about 0.5, and to increase towards 1.0 during the day, when open windows caused indoor conditions to look like outdoors. There were two prominent spikes in the I/O ratio during the pre-retrofit period; but in both cases they had more to do with rapidly dropping and/or low outdoor concentrations than with high indoor concentrations. The one large spike in I/O during the post-retrofit period resulted from a modest increase in indoor concentrations (to about 10 micrograms per cubic meter) when outdoor particles were low.

There are three possible explanations for the "missing" signal of particles from candle use. The first is that the particles emitted by the candles were invisible to the primary instrument that was used to quantify fine particulate matter. Particles emitted by candles are formed from "nucleation" processes in which gases condense into very small particles that start at a few nanometers (nm) in diameter or smaller (there are 1000 nm in a micrometer). Under typical indoor conditions, these particles rapidly grow in size from coagulation (combining with other small particles) and condensation of organic gases and water from the air. The optical particle counter that produced the data shown in Figure 10 and Figure 11 are not designed to measure particles smaller than about 300 nm (0.3 micrometers). If very few of the particles grew to that size, the candle emissions would not be substantial or obvious. Another possibility is that the candles were only used in the bedroom with a closed door and the airflow patterns in the house were such that air moved from the house to the bedroom to outdoors. (Though it seems unlikely that such an airflow pattern would occur every night). A third possibility is that the resident used candles that emitted only small quantities of fine PM mass.[30] Combinations of these explanations are also possible. For example, particle growth could be slowed by dilution with outdoor air ventilation.

It is also important to note even if the candles did not emit much fine particulate matter mass, they almost certainly emitted a large number of "ultrafine" particles.[31] These are particles that are smaller than 100 nm and are thought to be particularly hazardous because they can diffuse through barriers in the body that block larger particles. The evidence of harm by ultrafine particles is not as certain as it is for $PM_{2.5}$ or PM_{10}, but the expert consensus is that these particles are likely harmful to humans.[32]

Notwithstanding the uncertainties around the "missing" signal of particles from candle use, there are two important results from this home. First is that the installed filtration system was not used, even when the participant was reminded that the evaluation period was a condition of program participation. The second finding is that the participant seemed to routinely use candles for extended periods,

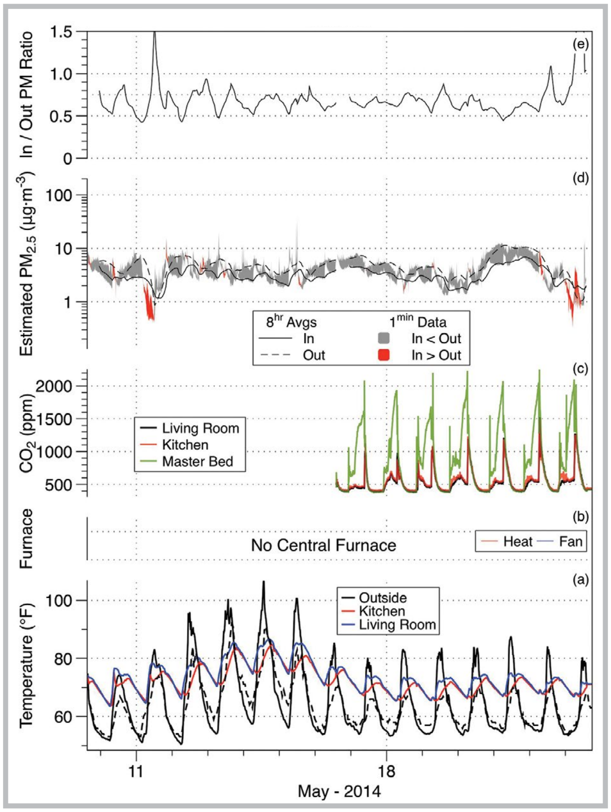


FIGURE 10: RESULTS FROM PRE-INTERVENTION MONITORING OF H03

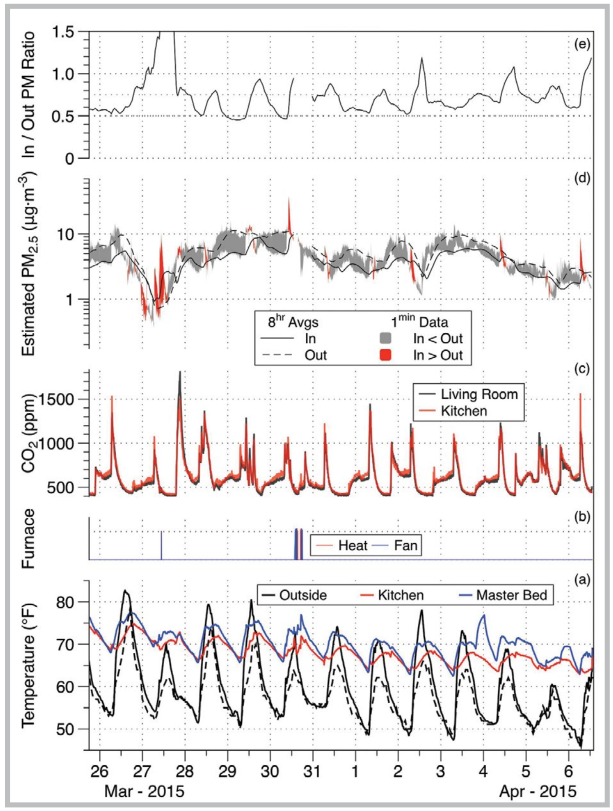


FIGURE 11: RESULTS FROM POST-INTERVENTION MONITORING OF H03

(a) Indoor and outdoor temperatures; hatched line is data from San Francisco airport. (b) Operation of central furnace indicated by temperature sensor at supply register. (c) Carbon dioxide (CO_2): concentrations near 400 ppm (outdoor levels) suggest light occupancy or high ventilation rates; sharp spikes indicate cooking with gas. (d) Estimated fine particulate matter ($PM_{2.5}$) calculated from size-resolved particle measurements; red indicates periods when indoors was higher than outdoors. (e) Ratio of indoor to outdoor 8-h running average $PM_{2.5}$. Break is when researchers visited to download data.

presumably in a small room (the bedroom), and without ventilation. Even if these were "low emission" candles, it must still be presumed that the participant was exposed to very high levels of ultrafine particles and chemical pollutants each night. While the specific mix of chemical and their magnitude is unknown, it is probable that the exposure to candle-related pollutants was much larger than exposures to outdoor pollutants that were the focus of the Mirant mitigation efforts.

Summary of Pollutant Control Results

Since the installed filtration system was turned off by the homeowner for almost the entire post-retrofit monitoring period, it's potential effectiveness when operating could not be evaluated.

Lessons Learned

The most important lesson from this home is that the participant showed no interest in using the installed filtration system to reduce his/her exposure to fine particulate matter from outdoor or indoor sources. There is no reason to doubt that this decision resulted from the participant's expressed concern about energy costs. But the study did not attempt to formally probe the participants' decisions. Despite the explicit and explained focus of the program (on air pollutant exposure reduction) and stated expectation that the system would be operated during the evaluation period, the air handler and filtration system were not used even during post-retrofit monitoring. The incentive of a new furnace, or even an upgrade to an existing furnace—e.g. the installation of an energy efficient blower motor to support longer run times for filtration—may entice homeowners to participate in the program for free home upgrades but not to use the equipment to reduce their exposure to pollutants. No usable data was collected from this home.

H04 – Bancroft Avenue and Quint Street

Description of home

The home is just under 1200 square feet with four bedrooms and one bathroom. The main living area is on the second floor and features a living room, dining room, kitchen, two bedrooms and bathroom. The ground floor featured a garage/basement and two additional bedrooms. The house was attached on one side to the neighboring house. The home had a marginally functioning central gravity furnace.

Retrofits

The retrofit package included the following:

- Installation of new single, stage forced air furnace (Tempstar Model #F8MXL0451408A) with efficient ECM fan motor.
- Installation of MERV13 high efficiency filter in the furnace air handler.
- Installation of programmable thermostat, Honeywell Vision Pro 8000.
- Cleaning and maintenance of microwave exhaust fan over the range hood.
- Installation of efficient bath fan (Panasonic 11VQL5) with timer switch.

The project team requested from the contractor to install the Shaw thermostat that was used in H03, but the product was not available through the supplier used by the HVAC contractor. Instead, the contractor installed an updated Honeywell thermostat that he claimed featured improvements over the model used in H01 and H02.

SFDPH also provided the homeowner with a standalone air filtration device, a Whirlpool AP51030K, as part of the retrofit mitigation package. The intent was to compare the effectiveness of the standalone device to filtration in the central furnace air handler.

Results

Pre-retrofit monitoring started on April 29 and finished on May 7, 2015. The evaluation plan for this home was to collect one week of pre-retrofit measurements and three weeks of post-retrofit measurements under the following conditions (less than one week each):

(a) Furnace fan running intermittently (e.g. for 35% of each hour) for filtration.

(b) Standalone air cleaner operating continuously for filtration.

(c) Both furnace fan and standalone unit operating.

(d) No filtration or standalone cleaner operating (repeat of control condition).

Additionally, the plan included setting the thermostat to exclude intermittent furnace fan operation for filtration at night, to avoid the potential for noise problems that occurred in H01.

Environmental monitoring instruments were placed in the kitchen in the back of the house, in the living room in the front of the house, and in the second bedroom, which was also in the back of the house, next to the kitchen. Particle measurements occurred in the dining room in the middle of the house.

The first period of post-retrofit monitoring occurred August 13 through 20, 2015. During this monitoring period, three malfunctions resulted in loss of particle data. First, the sampling equipment that intermittently drew air from outdoor and indoor locations clearly stopped functioning during the early morning of August 17, 2015. As a result, no useful indoor/outdoor particle data were collected August 17–20; and data leading up to this malfunction are of uncertain validity. The second issue was that the data-logging computer did not record data from the MetOne optical particle counter. After the instrument internal memory limit was reached at about 5.5 days, the instrument started overwriting data; particle counts are thus unavailable from August 13 to 14, 2015. To address this issue – which persisted through the remainder of post-retrofit monitoring, the data presentation for H04 relies on the DustTrak measurements. The third problem was that the anemometer/logger installed to monitor air handler use did not record data during the first week post-intervention.

The intent during the first post-retrofit period was to evaluate the effects of the forced air system with filtration during waking hours and have the system turn off at night for the comfort of the occupants. The thermostat was initially set to have the fan operate in Circulate mode during waking hours and Auto mode overnight (to enable the heater to operate if needed). Unfortunately, the thermostat was again set incorrectly, and the fan operated intermittently (approximately 12 minutes on, 18 minutes off) day and night from August 13 to 27, 2015.

Operation of the furnace fan at night again was bothersome to the occupants. As with H01, this was due in part to the switch from a silent gravity furnace to an audible forced air system. The distribution of unconditioned air was another source of complaint. Whereas in H02 the complaint was about "cold" air blowing from the central system supply registers (during winter), in this case of summer monitoring, the distributed air felt "heated" according to one occupant.

In the second post-retrofit monitoring from August 20 to 24, 2015, it was intended that the standalone filter would operate alone; but as noted above, the furnace fan continued to operate through August 27, 2015. The standalone air filter was placed in the dining room (in the middle of the 2nd floor) and set to operate on MEDIUM speed. The results from this evaluation period include both the standalone air filter and central furnace fan filtration. The third post-retrofit evaluation period was from August 24 to 27, 2015 and involved intermittent operation of the forced air fan with MERV13 filter with the standalone filter was turned off. The fourth post-retrofit evaluation period, from August 27 to 31, 2015, repeated the reference condition of no filtration or standalone filter. LBNL solved the programming error and changed the thermostat setting from Circulate to Auto in order to turn off the enhanced filtration systems. In the fifth and final post-retrofit evaluation, from August 31 to September 3, 2015, the standalone air filter was operated on MEDIUM speed, with no filtration provided by the central furnace fan.

Monitoring results for this home are provided in Figure 12 for the pre-intervention week and in Figure 13 for the second and third weeks of post-intervention monitoring. The first week of post-intervention data is not shown because of the data losses and questions about the timing and progression of the indoor/outdoor switching failure, and also because the condition of air handler with filtration operating intermittently was measured again during August 24-27.

Outdoor temperatures were cooler during the pre-intervention period, with overnight lows mostly in the low to mid-50s oF. There were periods of intermittent furnace use in the early morning hours of April 30 and May 6. It was considerably warmer during the three weeks of post-retrofit monitoring and there was no call for heat during this period.

The fine particle concentrations recorded during the pre-retrofit period indicate relatively low outdoor levels with both indoor concentrations and indoor/outdoor ratios greatly impacted by indoor emission events on May 1, 2, 4, 5, 6, and 7. Each of the peaks shown in Figure 12 correlates with a frying and/or toasting event recorded on the daily log. The logs also indicate that windows were open during most of the pre-retrofit monitoring period. The 8-hour running average indoor/outdoor ratio decreased and reached a level of approximately 0.5 during periods not impacted by indoor emissions; but the repeated occurrence of the indoors sources leaves ambiguity about the steady ratio with no indoor sources.

Figure 13 shows that the combination of central air handler with filtration operating intermittently and the standalone air cleaner on medium (August 20-24) substantially reduced particle concentrations, pushing the indoor/outdoor ratio to 0.1 (and potentially lower) during the times not impacted by indoor emissions. The daily log indicates that windows were open throughout this period; so the 90% (or greater) reduction in exposure relative to being outdoors is impressive.

The indoor/outdoor ratio was higher after the standalone air cleaner was switched off on August 24 (until August 27) while the air handler with filtration continued to operate intermittently; this suggests that some of the benefit of the combined system resulted from the standalone device. The ratio trended downward when there were no indoor sources and reached levels of 0.5, 0.5 and 0.4 each day before it increased from indoor emissions. The logs indicate continuously open windows during this period.

August 27-30 is another reference period of the home operating without enhanced filtration. Windows remained opened throughout this period and indoor concentrations and indoor/outdoor ratios were greatly impacted by large indoor emission peaks on August 28 and 30. The indoor/outdoor ratio was also impacted by a dramatic dip in outdoor concentrations on August 28. It is difficult to say anything definitive about the indoor/outdoor ratio exclusive of these events; but the interval from the afternoon of August 29 through the early morning of August 30 suggests a ratio of roughly 0.6.

The last interval of post-intervention evaluation featured the standalone air cleaner operating without the central air handler, on August 31 through September 3. Windows remained open throughout this period. And there were increases in indoor $PM_{2.5}$ each morning that appear to be emission events. Indoor concentrations were so low that the instrument reported at its lower limit of 1 microgram per cubic meter limit and the indoor/outdoor ratios based on this number were below 0.1. A limited analysis of decay rates—i.e. how fast indoor concentrations decreased after an indoor emission event—suggests that the filtration systems accelerated removal of particles.

Summary of Pollutant Control Results

Analysis of the exposure reduction effectiveness of filtration in this home was complicated by daily indoor particle emissions and constantly open windows. The standalone air filtration unit substantially reduced indoor particle concentrations and indoor/outdoor ratios of fine particulate matter. Intermittently operating the central air handler with enhanced filtration did not produce clear exposure reduction benefits in this home.

Lessons Learned

Problems at H04 were similar to those encountered at H01-H03. Control complexity was again an issue as the HVAC contractor was not able to correctly set the thermostat to operate the air handler on the desired schedule of intermittent operation during the day and on-demand for heat at night. Noise was an important issue as the nearly silent gravity furnace was replaced with a forced air furnace that uses a fan to distribute conditioned and/or filtered air through ductwork extending around the house. The sound of the air handler operating at night was bothersome to the occupants. The distribution of unconditioned air —in this case feeling like heated air—produced another discomfort problem.

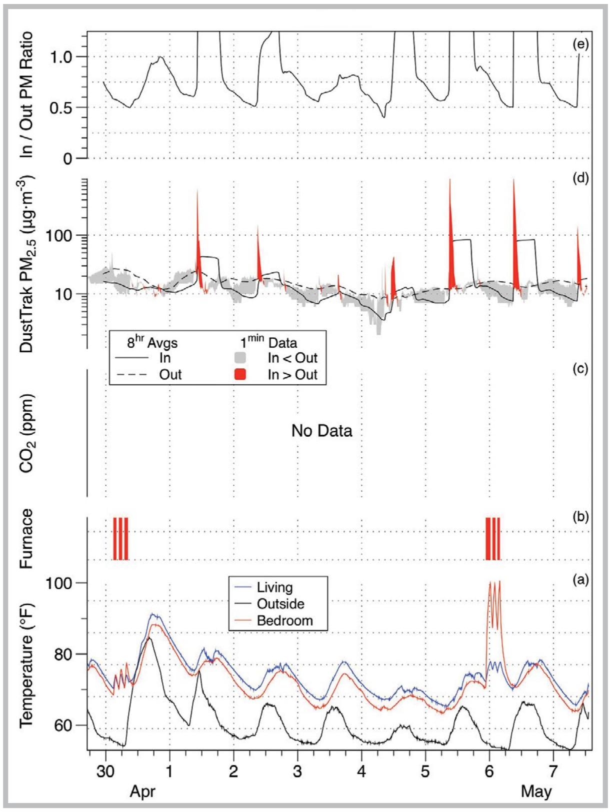


FIGURE 12: RESULTS FROM PRE-INTERVENTION MONITORING OF H04

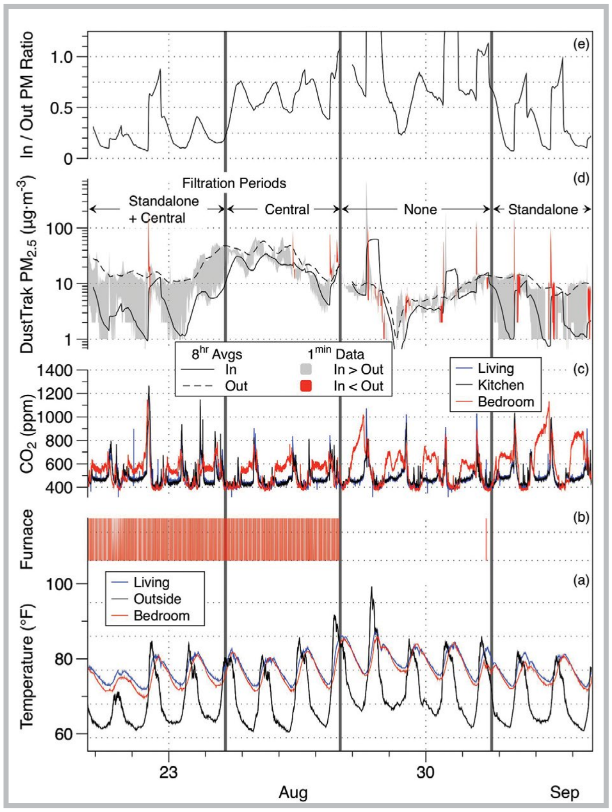


FIGURE 13: RESULTS FROM POST-INTERVENTION MONITORING OF H04

(a) Indoor and outdoor temperatures; hatched line is data from San Francisco airport. (b) Operation of central furnace indicated by temperature sensor at supply register. (c) Carbon dioxide (CO_2): concentrations near 400 ppm (outdoor levels) suggest light occupancy or high ventilation rates; sharp spikes indicate cooking with gas. (d) Estimated fine particulate matter ($PM_{2.5}$) calculated from size-resolved particle measurements; red indicates periods when indoors was higher than outdoors. (e) Ratio of indoor to outdoor 8-h running average $PM_{2.5}$. Break is when researchers visited to download data.

The results from House H04 indicate that a standalone air filtration unit provided substantial benefit without the operational challenges or high costs associated with furnace retrofits.

Home	Retrofits	Key Results
H01	• Installed new forced air furnace with efficient motor & ducting to replace gravity furnace. • Installed sealed filter cabinet with high efficiency filter. • Installed special thermostat to run furnace fan for filtration when not operating to provide heat. • Initially (incorrectly) set furnace fan to operate continuously.	• The continuous operation of furnace fan was objectionable (too loud) for the resident. • Before the new furnace was installed, the indoor level of fine particles from outdoors was 50% of coincident outdoor level. • When the furnace fan operated continuously, the indoor level of fine particles from outdoors was only 10% of coincident outdoor level (90% lower). • The resident did not want the system set to operate for filtration other than when heating.
H02	• Home had forced air furnace. • Replaced furnace fan motor with efficient, variable speed DC motor. • Installed sealed filter cabinet with high efficiency filter. • Installed special thermostat to run furnace fan for filtration when not operating to provide heat..	• Installation error led to furnace not reaching high indoor temperatures desired by occupants. • When operated for filtration, furnace fan circulated cool air, creating discomfort in late fall & winter. • Before intervention, the indoor level of fine particles from outdoors was 50% of outdoors. • When the furnace fan operated intermittently for filtration, the indoor level of fine particles from outdoors was only 10-20% of coincident outdoor level (80-90% lower). • Occupant chose to not operate furnace fan for filtration when heat was not needed.
H03	• Installed new forced air furnace with efficient motor & ducting; home had no central furnace. • Installed sealed filter cabinet with high efficiency filter. • Installed special thermostat to run furnace fan for filtration when not operating to provide heat. • Correctly set thermostat to operate furnace fan for 20 min per hour when no heat needed.	• Resident turned off operation of furnace fan for filtration (by manipulating thermostat) repeatedly, despite agreeing to allow the operation for 1-week evaluation. • Resident was concerned about cost of electricity to operate furnace fan intermittently even for 1 week. • Periods of furnace fan operation too short, and too many indoor particle sources to evaluate impact on outdoor fine particles.
H04	• Installed new forced air furnace with efficient motor & ducting to replace gravity furnace. • Installed sealed filter cabinet with high efficiency filter. • Installed special thermostat to run furnace fan for filtration when not operating to provide heat. • Provided standalone air filter unit. • Set thermostat to operate furnace fan for 20 min per hour when no heat needed (for evaluation period only).	• Nighttime operation of furnace fan for filtration was objectionable (too loud) to one resident. • Before intervention, the indoor level of fine particles from outdoors was 40% of outdoors. • When the furnace fan operated intermittently for filtration and the standalone filter operated together, the indoor level of fine particles from outdoors was only 10% of coincident outdoor level (90% lower). • Standalone air filter unit alone produced a clear but unquantifiable reduction in particles. • Benefit of operating the furnace filtration alone could not be evaluated because test period when only furnace was operating alone with no indoor events was too short. Therefore, the effectiveness of the furnace filtration could only be evaluated in combination with the standalone filter. This is because when both filters were operating, there was not a long enough period of no indoor particle source such that the in/out ratio could be determined.

TABLE 5: SUMMARY OF KEY RESULTS PER HOME IN PHASE I

Phase II Study – Potrero Hill Condominiums

The Phase II study involved installation and operation of standalone air filtration units in four condominium apartments in a single building in 2016. The units are identified as Condo 1 through Condo 4 through the remainder of this report. The RabbitAir filter units[33] (referred to as the DPH filter in this section) were set to operate in "Auto" mode, which includes a quiet setting when ambient light levels are very low (i.e., nighttime) and the particle sensor in the filter unit does not detect high levels of particles in the air that would require higher speed operation.

Monitoring occurred for approximately three weeks in each unit. The plan was to monitor each condominium for at least one week without enhanced filtration and one week with the standalone filter operating, and to use the third week to replicate one or both of the conditions. The plan was to place the DustTrak monitor in the living room and to place the DPH-provided standalone air filtration unit either in the bedroom—if the participant agreed to leave the bedroom door open or ajar overnight—or in the living room if the bedroom door was closed overnight.

All of the condo units had electric cooking ranges (cooktops and ovens); so cooking was not a major source of CO_2. But based on correlations between reported events on daily logs and the measured particle concentrations, cooking appears to have been a major source of particles in these homes.

See Table 6 for summary information.

Upon arriving at Condo 3 to set up monitoring equipment, the project team learned that the participant already was operating a standalone air cleaner in the main bedroom. The pre-existing air cleaner was a Dyson Tower model[34], henceforth described as Filter A. The monitoring plan for Condo 3 was revised to evaluate the following conditions: (1) Filter A only; (2) Filter A and DPH filter; (3) DPH filter only; (4) No filter. The DPH filter was also placed in the main bedroom. The participant from Condo 2 already had two air cleaners in the apartment; but the participant volunteered to not operate them to avoid complicating the study.

Condo	Size[1]	BR/BA	Notes
1	602	1/1	
2	932	2/2	Participant away on travel for much of second period of filtration unit operation.
3	972	2/2	Existing air cleaner operating in bedroom
4	692	1/1	

[1]Approximate square feet

TABLE 6: PHYSICAL DESCRIPTION OF EACH CONDOMINIUM UNIT THAT PARTICIPATED IN PHASE II

Condo 1

The DPH filter was placed in the main bedroom and the particle monitor was placed in the living room. The daily logs indicate no window opening throughout the monitoring period.

The monitoring results for this home are shown in Figure 14. The filter unit operated during the second week; there was no filtration during the first and third weeks. The third week was used for a second period of no filtration because the first week of no filtration featured very low outdoor concentrations and numerous indoor emission events during the first week confounded the I/O results.

There were relatively small variations in outdoor temperature patterns across the three weeks. The pattern of temperature in the living room and bedroom differed between the first week and the latter two weeks. In the first week, temperatures were consistently higher in the living room. In the latter two weeks, the living room had larger temperature swings but average temperatures in the two rooms were similar. The reason for this change was not determined. The consistency of carbon dioxide concentrations in the two rooms indicates good mixing. There was no consistent occupancy schedule, even during weekdays; but the period during which the home was least occupied was 10 am to 4 pm.

Outdoor particle levels were lower during the first two weeks compared with the third week. The very similar patterns of indoor/outdoor particle ratios during the second and third weeks suggest that the filter unit did not have a large impact on indoor exposure to outdoor particles during the period of evaluation. However, it is important to note that this was a period of generally low outdoor particle concentrations and even lower indoor particle concentrations causing the DPH filter to automatically operate on low-speed (low flow) for most of the week. The filter unit switched to a higher flow setting on August 30, August 31, and September 1, 2016 when the indoor concentrations spiked, presumably from indoor emission events, suggesting the "Auto" mode was at least partially effective. Faster decays (declines) in the indoor concentrations were also measured following these indoor emissions events indicating the device was effective at reducing the particle concentrations.

The limited operational monitoring data indicate that the Auto mode of the standalone filter unit was at least partially effective: it ran at low setting when indoor concentrations were low, but switched to a higher setting on three occasions when there were sharp increases in the indoor concentrations from presumed indoor emissions events. Other research by LBNL suggests that the sensor used to operate the Auto mode may not respond to all indoor particle emissions. To evaluate the effectiveness of this device at reducing exposure to outdoor particles would require additional testing during periods when outdoor particle concentrations are higher or operation at a fixed higher setting.

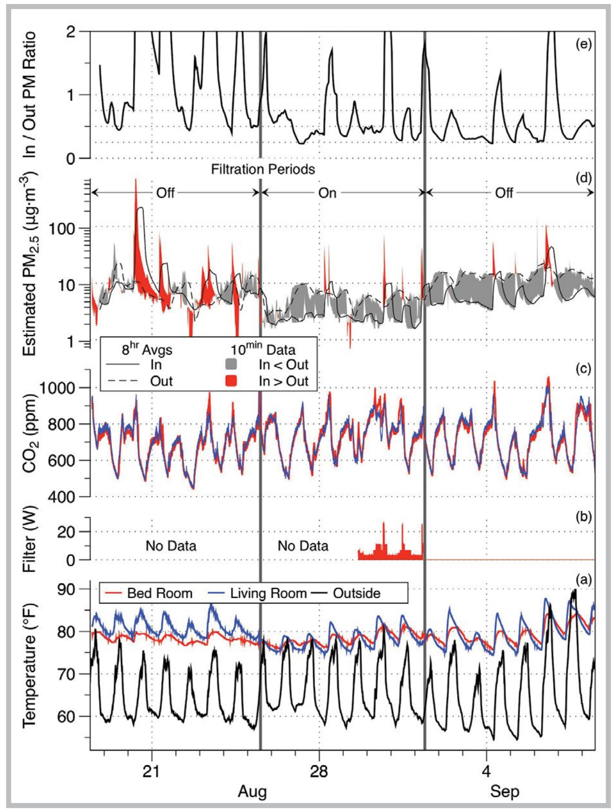


FIGURE 14: RESULTS FROM MONITORING OF CONDO 1

(a) Indoor and outdoor temperatures. (b) Operation of standalone filtration unit. (c) Carbon dioxide (CO_2): concentrations near 400 ppm (outdoor levels) suggest light occupancy or high ventilation rates. (d) Fine particulate matter ($PM_{2.5}$) concentrations estimated from DustTrak measurements; red indicates periods when indoor concentrations were higher than outdoors. (e) Ratio of indoor to outdoor 8-hour running average $PM_{2.5}$.

Condo 2

In this home, the DPH filter was placed in the main bedroom and the DustTrak monitor was placed in a second bedroom (being used as a music room) where the door between that room and the living room remained open throughout the monitoring. Data from the home is displayed in Figure 15. The DPH filter was operated for one week, turned off for one week, and operated for another 10 days during which the participant was away for six days. Windows were closed throughout the 6-day period when the participant was away and window use varied on other days. Windows were open some or most/all of the time on most days from 10 am to 4 pm, and tended to be closed more overnight. The daily log indicated that the participant was out of the unit for some or all of the 10 am to 4 pm period during most days of the study; the exceptions were the first and last days and the period when the participant was away September 4-10, 2016.

Outdoor temperatures were a bit warmer during the second week compared to the first, and there was a series of five days of warming while the resident was away during the last week. Overnight CO_2 levels were much higher in the bedroom than in the living room during all nights in which the home was occupied. The reason why temperature was higher in the bedroom during the first week, but lower in the bedroom during the second week is not known. Daily drops in CO_2 are consistent with the participant leaving for at least some time on each day, as indicated in the logs. The big difference in CO_2 between bedroom and living room each night suggests that the bedroom door was closed. Since the DPH filter was in the bedroom, this could impact the effect seen in the living room where the DustTrak monitor was located.

During the first week, there was one large peak indicating an indoor emission event on August 20, when a frying event was reported, and two other events in which outdoor concentrations dropped rapidly to cause the indoor/outdoor ratio to exceed 1.0. During the second week there were four peaks indicating indoor emissions. Peaks on August 31 and September 1 correlate with timing of reported frying events. There were "other" (not frying) cooking reported daily on August 24 through 27; but the events do not show large particle increases on all the days. The log notes that an automatic vacuum was used in the bedroom every Monday through Thursday between 10 am and 4 pm (August 22-25, August 29-September 1); this did not have an obvious impact on particle levels. The evaluation of filtration effectiveness is limited by the low outdoor particle concentrations during the first two weeks. The indoor/outdoor ratios during the first week, with the filter operating, dipped a bit lower (to 0.25–0.35) than they did during the second week (0.4–0.5), comparing times when there were no indoor sources. The ratios from the first week also were impacted by the two sharp declines of outdoor PM that temporarily pushed the indoor/outdoor ratio higher. The benefit of the DPH-supplied filter unit was clearer during the last week of monitoring, when there were few indoor sources and higher outdoor concentrations; during that week, indoor/outdoor ratios were around 0.2 when there were no indoor emissions events.

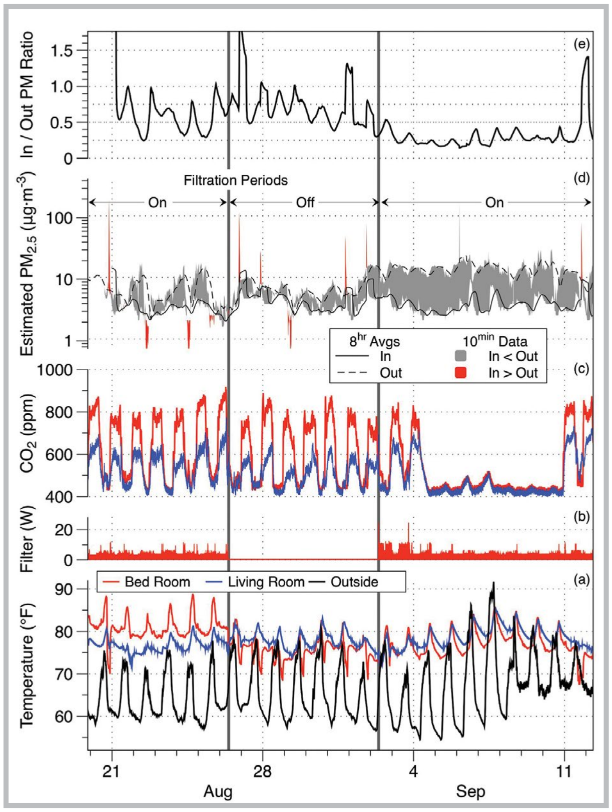


FIGURE 15: RESULTS FROM MONITORING OF CONDO 2

(a) Indoor and outdoor temperatures. (b) Operation of standalone filtration unit. (c) Carbon dioxide (CO_2): concentrations near 400 ppm (outdoor levels) suggest light occupancy or high ventilation rates. (d) Fine particulate matter ($PM_{2.5}$) concentrations estimated from DustTrak measurements; red indicates periods when indoor concentrations were higher than outdoors. (e) Ratio of indoor to outdoor 8-hour running average $PM_{2.5}$.

Condo 3

Upon arriving at the home to start the evaluation, the research team learned that there was already an air cleaner being used in the bedroom of this condominium. The evaluation plan was thus modified to have four conditions, as shown in Figure 16. The first involved the already present air cleaner, identified as “Filter A” operating as usual in this home (in the bedroom), reportedly from 9 pm to 7 am daily; this occurred August 20–26, 2016 The second period featured use of the DPH-provided filter and Filter A; this occurred from August 26 to September 2. The DPH supplied filter unit was used without Filter A from September 2 to 5. And no filters were used September 5 to 8. The DPH filter and the DustTrak monitor were placed at opposite ends of the living room.

The diurnal range of outdoor temperatures was similar for most days of the evaluation, with the exception that outdoor temperatures reached much higher daily highs on the last two days. On several days, temperatures were higher in the living room than the bedroom. The daily pattern and overall levels of CO_2 varied over the evaluation period. CO_2 was higher in the bedroom on many nights, indicating imperfect mixing. The very low CO_2 concentrations on August 28 through 30 are consistent with the home being unoccupied for these days, as indicated on the log. The logs indicate that windows were closed on these days but open throughout most of the other days of the evaluation. CO_2 concentrations were much higher on the first four days compared to all other days. The logs indicate that occupancy varied; but there were no patterns to explain the observed trend of higher CO_2 on the first few days. One possible explanation is that more windows were open during the days with lower CO_2. If this occurred, it would tend to push the ratio of indoor to outdoor particle concentrations higher.

Outdoor particle concentrations were much lower during the first two operating conditions (Filter A and Filter A + DPH filter) compared to the second two conditions (DPH filter and No filter). The evaluation of filter effectiveness is complicated by the low concentrations during these first two periods, which included several instances of outdoor concentrations dropping rapidly to produce indoor/outdoor ratios greater than 1. During the first two operating conditions, indoor/outdoor ratios dropped to about 0.5 during periods with no indoor sources. Starting on the evening of September 1 and continuing through four days of operation of the DPH-provided filter and roughly three days of no filter, outdoor concentrations were mostly above 10 micrograms per cubic meter (μg/m^3). On the first day of these higher outdoor concentrations, the combination of Filter A and the DPH-provided filter yielded indoor particle concentrations that were almost 70% lower than outdoors (i.e., 30% of

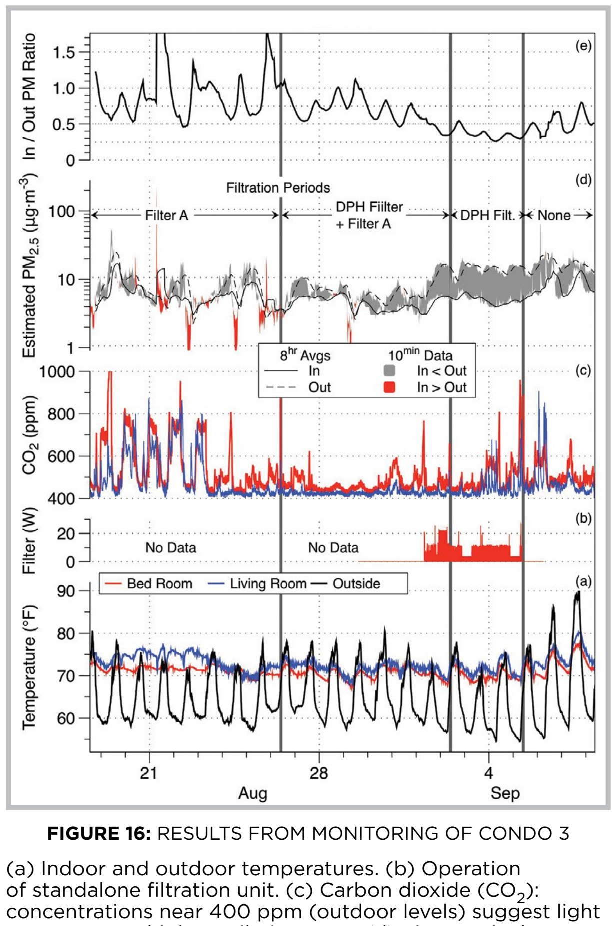


FIGURE 16: RESULTS FROM MONITORING OF CONDO 3

(a) Indoor and outdoor temperatures. (b) Operation of standalone filtration unit. (c) Carbon dioxide (CO_2): concentrations near 400 ppm (outdoor levels) suggest light occupancy or high ventilation rates. (d) Fine particulate matter ($PM_{2.5}$) concentrations estimated from DustTrak measurements; red indicates periods when indoor concentrations were higher than outdoors. (e) Ratio of indoor to outdoor 8-hour running average $PM_{2.5}$.

outdoor levels). Over the four days of DPH filter operating alone, indoor concentrations were between 25% and 50% of outdoors. In the few days without any filtration, the indoor/outdoor ratios swung from a low of 0.3 to a high of 0.8, i.e., from 30 to 80% of outdoors. Since the occupancy and window patterns indicated on daily logs and the similarity of measured CO_2 concentrations indicate similar conditions between the DPH filter and No filter periods, the consistently lower indoor/outdoor particle ratios during the period with DPH filter operation indicate some measure of effectiveness.

Condo 4

The evaluation period for this home started about two weeks later than the others. As a result, the moderate outdoor particle levels that occurred during the last week of monitoring at the other homes occurred during the first week of monitoring in Condo 4. Outdoor particle concentrations continued at these levels for several days into the second week of monitoring then dropped a bit, but did not fall to the very low levels that occurred during the first two weeks of monitoring in the other condo units. In Condo 4, the DPH-provided filter unit was operated during the middle week, and there was no filtration during the first and third weeks. The filter was placed in the bedroom and the DustTrak was placed in the living room of this one-bedroom unit.

Outdoor temperatures were similar during the second and third weeks, but overnight lows during these weeks were substantially higher than during the first week. There were at least two distinctly different indoor temperature patterns. During the first week, living room temperatures had sharp increases in the late morning and sharp decreases in the evenings whereas bedroom temperatures followed a more gradual diurnal trend. The cause of this difference is not known and it may or may not be relevant to the filtration evaluation. The similarity of CO_2 concentrations in the bedroom and living room indicate good mixing throughout the period. Importantly to the comparison of conditions during filter use and no filter use, the pattern of CO_2 concentrations was different during the second week than the other weeks. The very low concentrations on September 7 to 9, 2016 correspond to a period in which the participant reported that the windows were open all day. Since the participant also reported that the home was occupied during all periods other than during the 10 am to 4 pm interval on these days, it must be assumed that the low CO_2 resulted from high air exchange rates with the outdoors. The logs indicate that the home was also occupied most other days except for 10 am to 4 pm on weekdays. Windows were not opened at all on September 2 to 3 and September 11 through 18.

Figure 17 presents the monitoring results for Condo 4. The highest indoor particle concentrations occurred in the evenings of September 8 and 13 when frying events were noted on the daily logs. There were smaller but observable indoor peaks corresponding to frying events reported on September 4 and September 11.

The indoor/outdoor particle ratios suggest some benefit of the DPH-provided filtration unit. During the first week, with no filtration, indoor/outdoor ratios consistently dropped to about 0.2 during periods not impacted by indoor sources. During the second week, with the DPH-provided filter operating, the indoor/outdoor ratios dropped to about 0.1 during periods not impacted by indoor sources. With somewhat lower outdoor particle concentrations during the third week, in which there was no filtration, the indoor/outdoor ratios dropped to daily lows of about 0.25.

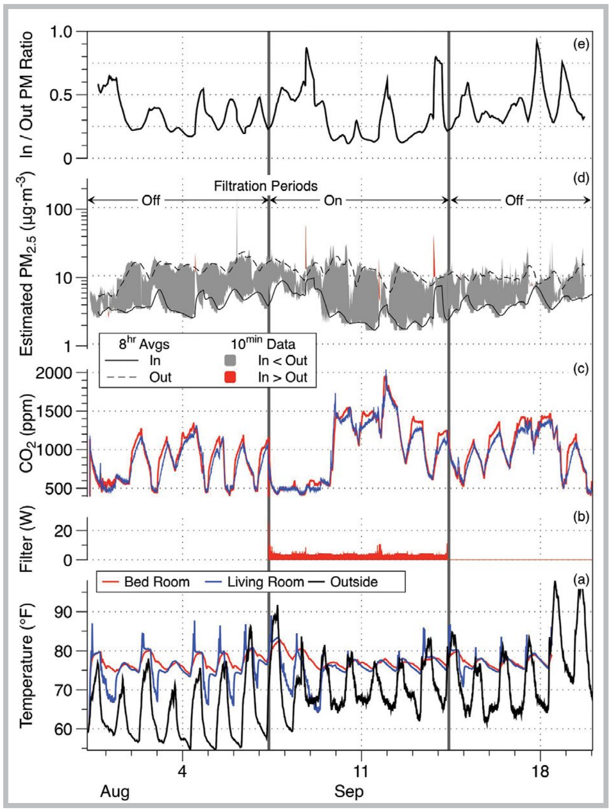


FIGURE 17: RESULTS FROM MONITORING OF CONDO 4

(a) Indoor and outdoor temperatures. (b) Operation of standalone filtration unit. (c) Carbon dioxide (CO_2): concentrations near 400 ppm (outdoor levels) suggest light occupancy or high ventilation rates. (d) Fine particulate matter ($PM_{2.5}$) concentrations estimated from DustTrak measurements; red indicates periods when indoor concentrations were higher than outdoors. (e) Ratio of indoor to outdoor 8-hour running average $PM_{2.5}$.

Summary of Results from Standalone Filtration Units in Condos

The evaluation of standalone filter performance was complicated by the low outdoor fine particle concentrations during the period of August 19 through September 1, which constituted the first two weeks of monitoring in Condos 1 through 3. Outdoor particle concentrations were higher during the first two weeks of the evaluation for Condo 4, providing a more meaningful outdoor source. However, the evaluation was also complicated by substantial variations in activity patterns including occupancy, window opening, internal mixing, and indoor sources that occurred in each of the four condos during the evaluation.

Based on the few meaningful comparisons that could be made, the data indicate modest to moderate benefits from operating the standalone filtration units. When outdoor concentrations were above 10 micrograms per cubic meter (µg/m^3) and during periods not impacted by indoor emissions, operation of the DPH-provided filter in Auto mode lowered indoor/outdoor PM ratios by an estimated 10-30% compared to the reference condition of no filter operating. Limited analysis of the decay rates of particles following indoor spikes indicates that the filtration units helped clear particles faster when there were indoor emission events. Since the standalone units were operated in Auto mode—a setting in which they are not supposed to operate at more than minimal airflow when filtration is not needed—these observed benefits are notable.

Summary and Lessons Learned

The study found that the use of “engineering” controls such as mechanical filtration to reduce in-home exposure to outdoor $PM_{2.5}$ is a potentially very effective approach for reducing pollutant-related health risk since most people spend more time in their homes than in any other single location. On average, Americans spend almost 90% of their time indoors and almost 70% at home.[35] In the Phase I study, four homes were retrofitted with enhanced filtration, including a sealed filter compartment, a high efficiency filter, and a thermostat capable of operating the furnace fan on a schedule independent of the furnace. The collected data indicated a significant reduction in fine particle concentrations when the forced air systems with enhanced filtration were operating. Before the retrofit, indoor concentrations were roughly 50–70% of outdoor levels, meaning that indoor levels were roughly 30–50% lower than outdoor levels, when there were no obvious indoor particle emissions. **When the forced air systems operated continuously with enhanced filtration (in two of the four homes), indoor particle levels were roughly 10-20% of outdoor levels, meaning they were 80-90% lower than outdoor levels. This finding reinforces the**

Condo	Testing Conditions	Key Results
1	• DPH filter installed in bedroom • Monitoring equipment installed in the living room • No window opening reported during testing period • Occupancy schedule was inconsistent • Numerous indoor emissions events recorded	• Low outdoor PM recorded during the testing period which reduced the frequency in which the filters automatically operated • Unclear how much filter operated on any setting higher than low; filter appears to have operated when there were large indoor sources • Large temperature swings recorded in the living room • Filter was effective at quickly reducing the indoor concentration after indoor event was detected
2	• Occupant owned two filters that voluntarily were turned off during the study • DPH filter installed in main bedroom • Monitoring equipment was placed in the second bedroom that was opened to the living room • Consistently unoccupied from 10 am to 4 pm • No occupant during the last week of testing • Windows were open for some or most days during testing, but closed overnight	• Suspected that the main bedroom door was closed at night • Consistently low outdoor PM count recorded during the testing period which reduced the frequency in which the filters automatically operated • Numerous indoor cooking events occurred in the evening • When filter operated, the indoor level of fine particles from outdoors was only 20% of coincident outdoor level (80% lower) when no indoor event occurred
3	• Occupant owned one filter A that was included in the study • DPH filter installed in main bedroom • Monitoring equipment was placed in the living room • Four testing conditions were tested: (1) Filter A only; (2) Filter A and DPH filter; (3) DPH filter only; (4) no filter • Imperfect mixing in the condo based on CO_2 measurements • Frequent window opening recorded	• Consistently low outdoor PM recorded during testing of Filter A only (condition 1) and Filter A and DPH working together (condition 3) • When Filter A and DPH were working simultaneously, the reduction in indoor levels was 70% compared to outdoor level • DPH filter working alone reduced the indoor concentration by 50% to 75% from outside levels • Without any filtration, the indoor/outdoor ratios swung from a low of 0.3 to a high of 0.8, i.e., from 30 to 80% of outdoors
4	• DPH filter installed in main bedroom • Monitoring equipment was placed in the living room • Frequent indoor events logged (cooking) • The unit was consistently occupied except between 10 am to 4 pm	• Occupant cooked every evening • Higher outdoor PM levels were recorded compared to previous testing during Condo 1 through 3 • With filtration, the indoor level of fine particles from outdoors was 90% reduced from outdoor levels • Without filtration, the indoor levels were reduced by 75 to 80% of outdoor levels

TABLE 7: SUMMARY OF KEY RESULTS PER CONDOMINIUM IN PHASE II

idea that filtration has the potential to achieve substantial reductions in exposure and health risk.

The fourth home in Phase I was supplied with both a new furnace with enhanced filtration and a standalone air filtration unit. The indoor concentration was roughly 40% lower than the outdoor levels when no filtration from either the standalone filter or furnace was used. **Operating both the central forced air filtration and the standalone unit together lowered indoor concentration by about 90% compared to outdoor levels.**

However, the study ran in to several problems that lead to the discomfort of the home occupants and confounded much of the collected air quality monitoring data. The complexity of the thermostats in three of the homes contributed by the contractor's faulty programming led to discomfort and noise complaints from the residents. In two homes, the controller was reset to operate the fan only when heat was required due to residents' objections of the excessive noise created by the fan. In addition, a faulty fan motor installation at one of the homes led to degraded performance of the heating system, distribution of cool-feeling air by the forced air system, and discomfort for the residents prior to diagnosing and fixing the problem. Conversely, the resident at another home was uncomfortable from the warm air distributed during filtration. The resident in the third home violated the research agreement and turned off the forced air system completely during post-retrofit sampling to avoid the electricity costs. As a result, the effectiveness of the system could not be evaluated. And in all of the homes, frequent window opening and/or indoor particle generating events (e.g., cooking, candle and incense burning) complicated the evaluation and made it difficult to determine the effectiveness of the filtration systems.

In Phase II where four condominiums were provided with standalone air filters, the researchers experienced similar confounding factors including variations in occupancy schedule and frequent windows opening and indoor emissions events which affected whether a benefit from the filtration could be discerned. The analysis was additionally challenged by the very low outdoor particle concentrations that occurred during two of the four weeks in which the homes were monitored. Since the filtration units were set to “Auto” mode, they were not expected to operate at more than a minimal flow rate condition when particle concentrations were low. Rather than evaluating the indoor/outdoor concentration ratio, the analysis investigated the effectiveness of the filter to quickly decay particle concentrations following an indoor emission event.

Unlike Phase I, Phase II did not experience any major implementation challenges or performance issues. Based on the few meaningful comparisons that could be made, the data indicate modest to moderate benefits from operating the standalone filtration units. **When outdoor concentrations were above 10 micrograms per cubic meter (μg/m^3), and during periods not impacted by indoor emissions, operation of the standalone air cleaning device in Auto mode lowered indoor to outdoor particle ratios by an estimated 10-30% more than those same reference conditions with no air cleaning device operating.**

Costs should be considered when selecting which control to install. The costs for the standalone units was roughly $700 per home for the air cleaner and a set of replacement filters. Energy efficient standalone units, like the ones used in this study, cost just a few tens of dollars to operate for all hours of the year. The cost is much lower if the unit is operated only when the home is occupied and even lower if the unit has an effective Auto mode to reduce fan speed when particle concentrations are low. One important caveat is that a single standalone air filtration unit is designed to clean the air in a single room or a few connected rooms (e.g. an apartment or small flat), but not a moderate to larger home or a multistoried dwelling. In such dwellings, retrofitting the central forced air system as was done in Phase I may be the more cost-effective option. A program built around retrofitting homes to use the central forced air system for filtration can yield substantial exposure reduction benefits for outdoor and indoor particulate matter; but the approach has many downsides and carries risks that can be avoided with the simpler alternative of providing standalone air filtration units to qualifying households.

Embarking on any research involving human subjects comes with its challenges. For the limited scope of this study, the researchers dealt with many unexpected issues that are documented below to assist other agencies when considering these engineering controls as a possible mitigation strategy for existing homes. The list is not exhaustive of all possible factors that may influence the outcome of using these interventions.

1. **Equipment Cost.** Retrofitting an existing home with modern forced air furnace and ducting capable of providing high efficiency filtration can cost several thousands of dollars per home, and may require electrical upgrades, asbestos removal, and other rehabilitation.
2. **Energy Cost.** A central forced air system, even with an efficient air distribution fan and motor, requires a lot of energy to operate and may be unaffordable for low-income residents. The electricity cost to operating the filter during occupied hours throughout the year may be hundreds to more than a thousand dollars.

3. **Complexity.** The thermostats installed in the homes that separately controlled the distribution fan from the heating element were confusing to residents and difficult to program. Upgrading an existing system with a variable speed fan motor improves efficiency but may interfere with furnace operations if not done properly, leading to discomfort and inadequate heat for residents. It is recommended to work with a contractor who has experience doing this retrofit upgrade and ideally has done the upgrade on the brand and model of system installed in the home. It is important that the contractor ensures that installation of the new fan motor does not interfere with the operation of the furnace.
4. **Discomfort associated with recirculating unconditioned air.** Circulated air from a basement or crawlspace will be cool in the winter and feel cold to residents when it exits the supply register if the heating element is not turned on. Likewise, circulated air during the summer may feel uncomfortably warm to residents.
5. **User motivation.** Enhanced filtration works best if the central furnace fan is turned on and windows remain closed. Several residents turned off the systems due to noise or concern about higher electricity costs. To avoid some of these downsides, a simpler alternative may be to provide standalone air filtration systems in households. Moderate reductions in indoor particle concentrations and indoor particle removal rates were observed when standalone air filtration units were operated in four condominium apartments and one single family house. There were no major implementation challenges or performance issues, and costs were less than $700 per condominium for the air cleaner, a set of replacement filters, and low electricity usage. One important caveat is that a single standalone air filtration unit is designed to clean the air in a single room or a few connected rooms (e.g. an apartment or small flat), but may not be effective for a moderate to larger single family home or a multistoried dwelling. The homeowner or program subsidizing the purchase would have to weigh the cost of central furnace upgrade versus the purchase of multiple standalone units to be located in each bedroom and common area.

Conclusions and Recommendations

Residents concerned about potential health impacts associated with poor indoor quality can take steps to reduce their exposures. Many indoor products and activities can generate harmful levels of air particles. Residents should avoid or reduce activities and use of consumer products indoors that results in air pollution emissions such as tobacco smoking, chemical solvents, incense or candle burning. Residents can also selectively choose consumer products with the lowest possible concentration of potentially harmful volatile organic compounds. Ensure that cooking appliances are properly ventilated to remove gas burning and cooking emissions at the source will also reduce indoor particle concentration. Installing a central forced air filtration system or standalone air cleaning device are more costly alternatives, but the study suggest that the controls are effective at decaying and removing indoor particle concentrations.

This limited evaluation study was designed to investigate whether the installed filtration systems provided discernible benefit immediately after they were installed and operating as set up by the program. The data collected in this study support the findings of prior studies that operating a central forced air system with enhanced filtration has the potential to substantially reduce indoor particle concentrations and exposures. During periods when a central filtration systems operated with windows closed and no indoor particle emissions, indoor particle concentrations were 80-90% lower than those outdoors. Under similar conditions with no filtration, indoor concentrations were 30-50% lower than outdoors. Sealing gaps and opening (i.e., improving the building envelope) can substantially lower indoor concentration by removing particles from air as it enters and resides inside a building.[36] The study found that when filtration was turned off the indoor particle concentrations were at least 30% lower than levels outside. The reason being that inside particles will deposit from air onto material surfaces inside a room, but deposition rates vary depending on particle size, air speed[37], and other factors. However, in all four homes in which the central forced air system was retrofitted to enable enhanced filtration, there were major implementation challenges and performance problems, and the costs were thousands of dollars per home.

The study also observed modest to moderate reductions in indoor particle concentrations and indoor particle removal rates when standalone air filtration units were operated in four condominium apartments in Phase II. Standalone filters were particularly effective at reducing indoor concentrations after an emission event was detected.

The following recommendations were derived based on the pilot study investigation.

1. **Tighten building envelopes.** Building envelope energy efficiency standards have been established by the California Energy Upgrade program, and are implemented via third party-certified building performance contractors. Those contractors use a variety of air sealing, insulation and weatherization techniques to tighten building envelopes. The building envelope can also be maintained by minimizing the number of times the windows and doors are opened to reduce concentration of fine particles entering from outside. Individuals can take steps to reduce the infiltration of outdoor air pollution indoors by improving the building envelop by sealing cracks and gaps around doorways, windows, and attic spaces. Slowing the infiltration rate of outdoor pollutants into the home, by installing rated windows and keeping windows and doors closed should also reduce indoor air pollution levels. All of these steps can improve the performance of the supply air enhanced filtration system or standalone air cleaning device.
2. **Reduce indoor emission events.** Residents are encouraged to reduce indoor emissions events such as smoking, candle and incense burning that generate fine particle matter and cumulatively add to the in-home particle concentration. In smaller homes or homes with more activities—including cooking, cleaning, etc.—indoor sources can account for the majority of fine particles in the air. Both cooking and cleaning can also result in the release of irritating chemicals. In addition, many installed kitchen range hoods are not ducted to the outdoors, but capture cooking grease mist and particles onto a washable filter. These kitchens, particularly those with gas stovetops, should have range hoods vented to the outdoors and occupants should receive education of the health benefits of using the available exhaust system.
3. **Educate residents.** Any filtration system or standalone filter is only effective if used properly and consistently. Turning off the forced air furnace system as many of the residents did in this study negates any health benefit from installing these systems. Education, training and informational resources should be provided to recipients to include training on equipment use, guides on sizing to ensure that correctly sized units are obtained, and information on where to purchase replacement filters. Programming and correct use of thermostats was particularly challenging, and also challenging for older residents with limited vision.
4. **Consider using standalone air cleaning devices.** Standalone air filters have lower capital cost compared to central furnace upgrade, are simpler to deploy and are easy to use. Residents deciding between standalone air filters and a furnace upgrade should compare the initial cost, annual cost for filter replacement, energy performance as it impacts annual electricity cost, ease of use, and third-party validated performance

(e.g. a Clean Air Delivery Rate). Educational information should also be provided to assist residents in making these comparisons.

5. **Upgrades to central forced air system.** For existing homes, upgrading the central furnace may be the more cost-effective solution compared to installing numerous standalone units. Residents should consider upgrading their central furnace in cases where many rooms in the home are occupied or frequently used or the house has multiple floors. Critical to upgrading the furnace is the selection of an easy to use thermostat/controller able to operate the air handler independent from the furnace and a low air flow option for nighttime to reduce noise from the fan motor. Additionally, the new furnace and ducting should be installed in the energy-efficient manner now available through the California Energy Upgrade program and its referrals to third-party certified building performance contractors.

6. **Focus on vulnerable subpopulations.** To maximize health benefits, the program could focus outreach and/or preferentially provide filtration units to residents who are most vulnerable to the effects of air pollution, i.e. premature infants, people with asthma or chronic obstructive pulmonary disease (COPD), elderly, and those with chronic respiratory and cardiovascular health conditions. People who are more vulnerable to the effects of air pollution may have greater incentive to use control equipment that is provided in such a program.

Additional Research Materials

The following list presents additional related background materials that may be of interest to the reader.

The potential benefits of installing higher performance filters in central forced air heating and cooling systems to reduce exposures to outdoor particles have been evaluated in the following studies, which applied simulation models across populations of homes:

- Zhao D, Azimi P, Stephens B. Evaluating the Long-Term Health and Economic Impacts of Central Residential Air Filtration for Reducing Premature Mortality Associated with Indoor Fine Particulate Matter ($PM_{2.5}$) of Outdoor Origin. *Int J Environ Res Public Health*. 2015; 12:8448-8479.
- MacIntosh DL, Minegishi T, Kaufman M, Baker BJ, Allen JG, Levy JI, Myatt TA. The benefits of whole-house in-duct air cleaning in reducing exposures to fine particulate matter of outdoor origin: A modeling analysis. *J Exposure Sci Environ Epidemiol.* 2010; 20:213-224.

The benefits of using in-duct or portable air filtration units to reducing exposures to all indoor particles, including tobacco smoke and particles of biological origin were investigated in the following simulation modeling studies.

- Fisk WJ, Faulkner D, Palonen J, Seppanen O. Performance and costs of particle air filtration technologies. *Indoor Air.* 2002; 12:223-234.
- Zuraimi MS, Nilsson GJ, Magee RJ. Removing indoor particles using portable air cleaners: Implications for residential infection transmission. *Build Environ.* 2011; 46:2512-2519.

Reductions in particle concentrations resulting from installing high performance particle filters in residential forced air systems or use of standalone air filtration units have been reported in several measurement-based studies, described below.

In a controlled study in a Sacramento test house, Singer et al.[38] found that enhanced filtration on a central air handler can reduce in-home exposure to outdoor particles by >90% relative to outdoors when operating intermittently at medium speed or continuously at low speed. Operation of two standalone air cleaners of the same make and model used by DPH also provided >90% reductions relative to outdoors. This study demonstrated that both approaches to air filtration can be very effective, when operated.

Both the potential effectiveness and the challenge of maintaining standalone air cleaner use was identified in a randomized control trial by Batterman et al.[39] That study evaluated the effectiveness of standalone air cleaners and window air conditioners at reducing particle exposures in the bedrooms of 126 low-income households with asthmatic children. When the filter was operated, $PM_{2.5}$ concentrations in the bedroom were reduced by 50%. Filter use varied across the participating homes and declined over time. During the month when particle concentrations were measured, the filters were used in the first season in 84±27% of the homes. In later seasons, this dropped to 63±33%. And during months with no monitoring, usage dropped to 34±30%.

The following study was a randomized trial of using portable air cleaners and coaching to reduce exposure to secondhand smoke:

- Butz AM, Matsui EC, Breysse P, Curtin-Brosnan J, Eggleston P, Diette G, Williams D, Yuan J, Bernert JT, Rand C. A Randomized Trial of Air Cleaners and a Health Coach to Improve Indoor Air Quality for Inner-City Children With Asthma and Secondhand Smoke Exposure. *Archives of Pediatrics & Adolescent Medicine.* 2011; 165:741-748.

The following study looked at the benefits of portable air filters to reduce exposures to smoke from forest fires and wood smoke:

- Barn P, Larson T, Noullett M, Kennedy S, Copes R, Brauer M. Infiltration of forest fire and residential wood smoke: an evaluation of air cleaner effectiveness. J Exposure Sci *Environ Epidemiol.* 2008; 18:503-511.

The following study looked at portable filtration system effectiveness in Danish homes:

- Spilak MP, Karottki GD, Kolarik B, Frederiksen M, Loft S, Gunnarsen L. Evaluation of building characteristics in 27 dwellings in Denmark and the effect of using particle filtration units on $PM_{2.5}$ concentrations. *Build Environ.* 2014; 73:55-63.

APPENDICES

A1. PHASE I DESCRIPTION OF SERVICES, MONITORING EQUIPMENT AND PROCEDURES FOR RESIDENTS

Introduction

You are signing an agreement with the San Francisco Mayor's Office of Housing to make upgrades to your home. These upgrades are designed to improve indoor air quality and lower your exposure to pollutants from the nearby freeway. It is important for the program to determine if the upgrades that are being made to your home actually improve your indoor air quality. To do this, we will make measurements of indoor air quality before and after the upgrades are installed in your home. Allowing us to make these measurements is required for you to participate in the program. The measurement plan was developed by Dr. Brett Singer of Lawrence Berkeley National Laboratory, which is also known as LBNL.

Several weeks before the upgrade work is started, researchers from LBNL and staff from the San Francisco Department of Public Health will come to your home to install measurement equipment and to make sure it is working properly. The measurements from your home will be studied by researchers from LBNL and by staff of the Bay Area Air Quality Management District. LBNL's involvement in this study is funded by the Bay Area Air Quality Management District and by the U.S. Department of Housing and Urban Development. The measurement plan has been reviewed and approved by LBNL's Human Subjects Committee.

Key Points Related to Indoor Air Quality Measurements

Indoor air quality monitoring will occur for two weeks before work is started on the upgrades and for another two weeks after the upgrade work is completed. It will take roughly 1 day to set up the equipment the first time and a few hours at the end of each sampling period to remove the equipment.

We will arrange with you the times that we come to your home to set up and remove equipment.

The sampling equipment needs to be plugged in. During the sampling period it is very important to not unplug the sampling equipment. If the equipment is unplugged or there is a power outage, we may need to arrange an extra visit to check the equipment.

If you have questions or concerns about the monitoring system for indoor air quality, please contact Dr. Brett Singer at (510) 486-4779 or bcsinger@lbl.gov.

What will we measure and how will we do it?

We will install devices that measure pollutant levels in the air inside and outside of your home. We will also install devices to monitor the use of fans and filters that can affect your indoor air quality. Measurements will be made for two weeks before and two weeks after the upgrades are made to your home.

Some of the air pollutant measurement devices have small pumps while others measure pollutants as air passes over the device. Some of the devices measure and record readings every minute. Other devices are samplers that collect air for a single measurement averaged over the entire time they are in the home. A small pump will pull air alternately from inside then outside of your home to allow the same set of devices to measure air pollutant levels both inside and outside. This pump and all the devices will be contained in or connected to a cabinet that will be firmly attached to the wall. The cabinet will have sound insulation to reduce any noise caused by the pump.

We will also install devices to record when the following appliances are used:

- The system that distributes air through your heating ducts;
- Your kitchen range hood or exhaust fan;
- Your water heater;

- Any portable air filters that are installed as part of this project.

We will place a device to measure and record temperature above your stove to record when the stove is used.

For devices that measure every minute, a telecommunications device inside the cabinet will send data using a cell phone network to LBNL's data network. This is a similar process to someone sending a message from a "smart" cell phone inside your home.

Several of the measurement devices and the pump require electricity. There will be a single power cord coming from the cabinet that will need to remain plugged into a power outlet while the devices are operating in your home. It is very important to not unplug this power cord while the devices are operating.

To measure air from outside, a small tube will be installed through your wall and a rainproof "air inlet" will be attached to the outside of your house. The tube is approximately the size of the cable used for cable television service. A licensed contractor will install the tube, the air inlet, and the cabinet on the wall. When the study is completed, the contractor will remove all of these and repair all holes made during installation.

When will the measurements happen?

Measurement devices need to be installed several weeks before the upgrades are made to your home. We will call you to schedule a time to come to your home to install the devices. It should take 4 hours or less to install the equipment and make sure it is working properly. We will then leave the equipment to measure air quality and appliance operation over the course of the next 2 weeks. If there are no major problems we will return at the end of the first week to collect some samples, place new samples and check equipment. This visit should take 1 hour or less. If there is an interruption of power to the cabinet during the week, a message will be sent to LBNL and the researchers will call to arrange to come to your home to check and restart the equipment.

At the end of the second week, we will visit your home again to remove monitors from appliances, turn off the air quality measurement devices and unplug the power cord. This should take 2 hours or less. The cabinet, tubing, and outdoor air inlet will remain in place during the retrofit work. Equipment will either be left in the home in the locked wall cabinet or removed while the retrofit work is conducted.

This series of steps will occur again after the upgrades have been completed. We will schedule visits in advance and we will be as flexible as possible to make them convenient for you.

It would be helpful to the study to have information about household activities that impact indoor air quality. We request but we do not require that you complete a short activity log during each day that we are measuring your indoor air quality. This will involve a short phone call each day from a project staff member who will ask about the following activities: cooking, use of candles or incense, vacuuming or dusting, smoking, and window opening.

Payment

You will receive $3 for each day that monitoring equipment is operating in your home and $2 for each day that you complete the activity log by telephone. You will receive an extra $50 when all of the required monitoring is completed. The total payment assuming 15 days of monitoring before retrofits and 15 days after retrofits will be $200. It may take up to 4 weeks following the completion of monitoring for you to receive this payment.

Questions or Concerns

If you have questions or concerns about the monitoring system, please contact:

Dr. Brett Singer at (510) 486-4779 or bcsinger@lbl.gov

If you have questions about your rights as a research subject, please contact:

Lawrence Berkeley Lab's Human Subjects Committee at (510) 486-5399.

A2. PHASE II DESCRIPTION OF SERVICES, MONITORING EQUIPMENT AND PROCEDURES FOR RESIDENTS

Introduction

As part of a trial program aiming to reduce exposures to air pollutants from freeways and other outdoor sources, the San Francisco Department of Public Health (DPH) is providing standalone air-cleaning devices, also known as air filters, to a small number of people living in your neighborhood. For you to participate in the program and receive the air filter, you must also participate in a study to assess the filter's effectiveness. The conditions of participation are described in an agreement that the DPH will ask you to sign. This document provides more information about the evaluation study.

The study was developed by Dr. Brett Singer of Lawrence Berkeley National Laboratory (LBNL). During the study, LBNL and DPH researchers will record information about your home and install devices to measure air quality in your home for a three-week period. Data will be analyzed by LBNL. Data and results will be made available to DPH and the Bay Area Air Quality Management District (AQMD). The AQMD is interested in how air filters can be used to reduce exposure to air pollution. The SF DPH is sponsoring this research. Study results also may be reported in scientific publications and presentations. Publications and presentations will not identify individual participants or apartments, but they may include information that would allow audience members to identify the building.

LBNL's Human Subjects Committee has approved the measurement plan.

What will we measure and how will we do it?

At the start of the study, LBNL and DPH researchers will visit your home at a time arranged with you. The researchers will install devices to measure temperature, relative humidity, carbon dioxide, and air pollutant levels at a central location and also on the roof of the building. Most of the devices are silent. A device that uses a pump will be placed inside a sound-muffling box to reduce its noise level, but it will not be silent. LBNL will work with you to find a location for the box that is acceptable to you.

Researchers will install devices to monitor the use of exhaust fans and other equipment that can affect indoor air quality. The following will be monitored:

- Operation of the standalone air filter.
- Operation of the central forced air heating system, if your apartment has one.
- Operation of your kitchen exhaust fan if you have one.
- Operation of cooking appliances.
- Opening of windows that are commonly used for ventilation.

Several of the measurement devices must be plugged in to operate. The researchers will show you which electrical outlets are being used. If needed, extension cords with multiple outlets will be provided to ensure that all the devices that you currently have plugged in can remain plugged in.

It is important to the study to have information about household activities that impact indoor air quality. You will be expected but not required to complete an activity log during each day of measurements in your home. LBNL will provide you with paper log sheets and you will receive compensation for each one that you complete. The log should take about 5 minutes to complete each day.

Order of Events

Measurement devices will be installed approximately 1 week before you receive the standalone air filter. The visit will be scheduled with you in advance. These visits typically occur on weekdays between 8 am and 4 pm; but other times may be arranged if necessary.

Equipment installation and set-up should take 2 hours or less.

After 1 week, an LBNL researcher will visit again to retrieve data from the instruments and to confirm that they are working properly. During this visit, you will receive the air filter and instructions on how to use it. This visit should take 2 hours or less.

Over the next two weeks you will be expected to leave the filter plugged in and operating. An LBNL researcher will arrange to meet you at your home briefly in the middle of this period to replace some samplers and to confirm the plan for the following week. After the three total weeks of monitoring have been completed, the researcher will arrange a time to remove the measurement devices and collect the daily activity logs. This will complete your participation in the evaluation study.

Payment

You will be allowed to keep the air filtration device and be given a set of replacement filters at the conclusion of the evaluation period. Additionally, you will receive $50 for each week of evaluation measurements, $1 for each completed daily activity log, and an additional $29 if you complete all 21 daily logs and all 3 weeks of monitoring. Your total payment for completing the entire evaluation will not exceed $200. This payment will compensate you for your time and for any expenses you incur (e.g. electricity costs) in participants. The payment will be provided by the SF Department of Public Health.

It may take up to 4 weeks following the completion of monitoring for you to receive this payment.

Can I withdraw from the study after I sign the agreement?

You may withdraw from the study at any time prior to the last visit when monitoring is completed. If you withdraw from the study you will not get to keep the air filter and you will not receive the replacement filters described above. You will receive $75 for allowing us to access your home to remove our monitoring equipment and the air filter if already in your home. It may take up to 4 weeks to receive this payment.

Can I see the results from my home?

If you request to see the results from your home, LBNL will provide an informal summary and explain the results to you. LBNL or SD DPH will also provide you with a copy of any formal reports or presentations of study results if you request them. There will not be a formal report for each individual home.

Questions or Concerns

If you have questions about the air filter that is being provided as part of the program, please **call Karen Cohn of the Department of Public Health at 415-252-3898 or Karen.cohn@sfdph.org.**

If you have questions about your payment, please **call Karen Cohn of the Department of Public Health at 415-252-3898 or Karen.cohn@sfdph.org.**

If you have questions about the evaluation study or the indoor air quality monitoring equipment, please **contact Dr. Brett Singer at (510) 486-4779 or bcsinger@lbl.gov or Tosh Hotchi at (510) 326-3729 or thotchi@lbl.gov.**

If you wish to stop participating after the indoor air quality evaluation has started in your home and before it is completed, please **contact Dr. Brett Singer at (510) 486-4779 or bcsinger@lbl.gov or Tosh Hotchi at (510) 326-3729 or thotchi@lbl.gov.**

If you have questions about your rights as a research subject, please **contact Lawrence Berkeley National Lab's Human Subjects Committee at (510) 486-5399 or harc@lbl.gov.**

A3. SAMPLE INDOOR AIR QUALITY SATISFACTION AND ACTIVITY SURVEY FOR MIRANT PHASE I HOME PARTICIPANTS

Home ID ______________________ **Date** ______________ **Day** ______________

This survey will be administered by telephone for each day that air quality monitoring is occurring in the home.

1. How would you rate the air quality in your home today?

- ❒ Very good
- ❒ Acceptable
- ❒ Barely acceptable
- ❒ Not acceptable

2. Please provide information about the following activities between **11 pm and 6 am:**

a. Amount of time door or windows open more than a crack: _________ minutes.
b. Number of any type of cigarettes or cigars smoked: _________.
c. Amount of time candles or incense burned: _________ minutes.
d. Amount of time cooktop used: _________ minutes.
e. Amount of time oven used: _________ minutes.
f. Note all types of cooking that occurred: frying – baking – boiling – toasting – other

3. Please provide information about the following activities between **6 am and 11 am:**

a. Amount of time door or windows open more than a crack: _________ minutes.
b. Number of any type of cigarettes or cigars smoked: _________.
c. Amount of time candles or incense burned: _________ minutes.
d. Amount of time cooktop used: _________ minutes.
e. Amount of time oven used: _________ minutes.
f. Note all types of cooking that occurred: frying – baking – boiling – toasting – other

4. Please provide information about the following activities between **11 am and 4 pm:**

a. Amount of time door or windows open more than a crack: _________ minutes.
b. Number of any type of cigarettes or cigars smoked: _________.
c. Amount of time candles or incense burned: _________ minutes.
d. Amount of time cooktop used: _________ minutes.
e. Amount of time oven used: _________ minutes.
f. Note all types of cooking that occurred: frying – baking – boiling – toasting – other

5. Please provide information about the following activities between **4 pm and 11 pm:**

a. Amount of time door or windows open more than a crack: _________ minutes.
b. Number of any type of cigarettes or cigars smoked: _________.
c. Amount of time candles or incense burned: _________ minutes.
d. Amount of time cooktop used: _________ minutes.
e. Amount of time oven used: _________ minutes.
f. Note all types of cooking that occurred: frying – baking – boiling – toasting – other

A4. EVALUATION STUDY FOR MIRANT PHASE II INDOOR AIR QUALITY IMPROVEMENT PROGRAM – Occupancy and Indoor Activities Data Log

Please mark an answer for each box. If you are unsure, make your best guess. If you have questions about this form, contact Dr. Brett Singer at 510-486-4779 or bcsinger@lbl.gov.

Home ID ___________ **Day of week** _________ **Date reported** __________ **Date completed** _________

	All Day	Midnight to 6am	6am to 10am	10am to 4pm	4pm to Midnight
Was home occupied?	__ Yes __ No	__ Mostly __ Sometimes __ Little/None	__ Mostly __ Sometimes __ Little/None	__ Mostly __ Sometimes __ Little/None	__ Mostly __ Sometimes __ Little/None
Were windows open?	__ Yes __ No	__ Mostly __ Sometimes __ Little/None	__ Mostly __ Sometimes __ Little/None	__ Mostly __ Sometimes __ Little/None	__ Mostly __ Sometimes __ Little/None
Any cooktop use?	__ Yes __ No	__ Frying __ Other __ None	__ Frying __ Other __ None	__ Frying __ Other __ None	__ Frying __ Other __ None
Any oven use?	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No
Any range hood use?	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No
Any toaster oven, or electric grill use?	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No
Any vacuuming?	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No
Any smoking?	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No
Any candles or incense?	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No
Any odors from outside apt?	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No	__ Yes __ No

Any events that could have impacted indoor air quality, such as burned food, nearby fires, party in the home, etc.? Please note the time it happened.

ENDNOTES

1. Enacted Ordinance Number 0217-11. Available at: www.sfbos.org/ordinances-2011
2. San Francisco Department of Public Health Population Health Division, 2014. April 2014 Mirant Settlement Progress Report: Potrero Hill Community Health. Available at: https://www.SFDPH.org/dph/files/reports/default.asp
3. Health Effects Institute (HEI), 2010. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects.
4. Gauderman, W.J., E. Avol, F. Lurmann, N. Kuenzli, F. Gilliland, J. Peters and R. McConnell. 2005. Childhood Asthma and Exposure to Traffic and Nitrogen Dioxide. Epidemiology 16(6): 737-743.
5. *Plan Bay Area* is San Francisco's Bay Area Region's Sustainable Communities Strategy, which is a state-mandated, integrated long-range transportation, land use, and housing plan.
6. Image from: https://www.bobvila.com/articles/furnace-filter/?bv=end1
7. E.g., Singer BC, Delp WW, Black DR, Walker IS. Measured performance of filtration and ventilation systems for fine and ultrafine particles and ozone in an unoccupied modern California house. Indoor Air. 2016; 27:780-90.
8. E.g., Batterman S, Du L, Mentz G, Mukherjee B, Parker E, Godwin C, et al. Particulate matter concentrations in residences: an intervention study evaluating stand-alone filters and air conditioners. Indoor Air. 2012; 22:235-52.
9. E.g., MacIntosh DL, Minegishi T, Kaufman M, Baker BJ, Allen JG, Levy JI, et al. The benefits of whole-house in-duct air cleaning in reducing exposures to fine particulate matter of outdoor origin: A modeling analysis. J Exposure Sci Environ Epidemiol. 2010; 20:213-24.
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13. San Francisco Department of Public Health Population Health Division, 2014. April 2014 Mirant Settlement Progress Report: Potrero Hill Community Health. Available at: https://www.SFDPH.org/dph/files/reports/default.asp
14. Health Effects Institute (HEI), 2010. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects.
15. *Plan Bay Area* is San Francisco's Bay Area Region's Sustainable Communities Strategy, which is a state-mandated, integrated long-range transportation, land use, and housing plan.
16. Reference from US EPA: https://www3.epa.gov/otaq/nearroadway.htm#content1
17. Health Effects Institute (HEI), 2010. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects.
18. Gauderman, W.J., E. Avol, F. Lurmann, N. Kuenzli, F. Gilliland, J. Peters and R. McConnell. 2005. Childhood Asthma and Exposure to Traffic and Nitrogen Dioxide. Epidemiology 16(6): 737-743.
19. Bay Area Air Quality Management District. 2014. Improving Air Quality & Health in Bay Area Communities. Community Air Risk Evaluation Program Retrospective & Path Forward (2004-2013). Available at: http://www.baaqmd.gov/plans-and-climate/community-air-risk-evaluation-care-program/documents
20. Detailed information regarding Article 38 is available at San Francisco Department of Public Health web site: https://www.SFDPH.org/dph/EH/Air/Article38.asp
21. Klepeis, NE, et al. 2001. *The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants.* J Expon Anal Environ Epidemiol. 11(3): 231-52. Downloaded on July 6, 2016 from: http://www.ncbi.nlm.nih.gov/pubmed/11477521
22. CRRP is described in detailed in Section 4.6 of the Air District's Improving Air Quality & Health in Bay Area Communities. Community Air Risk Evaluation Program Retrospective & Path Forward (2004 – 2013).
23. Bay Area Air Quality Management District. 2012. California Environmental Quality Act. Air Quality Guidelines. Updated May 2012. Available for download at: http://www.baaqmd.gov/plans-and-climate/california-environmental-quality-act-ceqa/updated-ceqa-guidelines
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SAN FRANCISCO DEPARTMENT OF PUBLIC HEALTH
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