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# Energy Implications of In-line Filtration in California Homes

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# Energy implications of in-line filtration in California Homes


## ABSTRACT

*Furnace energy usage and filter pressure drop was measured for forced-air heating/cooling systems in ten California homes. Each home was monitored for at least one year. Measurements were made of the blower energy, filter pressure drop, supply and return plenum pressures and temperatures as well as indoor temperature. At least two filter types were installed, including a MERV 16 filter, in most houses. As the filter became dirty, in some homes the blower energy usage increased and in others the blower energy usage decreased. Increasing blower energy usage was associated with BPM blower motors and decreasing blower energy was associated with PSC blower motors. There was a large pressure drop across the MERV 16 filter as compared to the lower MERV filters. Many homeowners complained of noise because of the large pressure drop and air bypassing the filter.*

*In addition to field measurements, simulations were made for a typical new home in six California climate zones, with combinations of PSC and BPM blowers, and low and high duct leakage. The results indicate that for MERV 10-13 filters, as compared to a baseline of MERV 5, the effects on blower energy use are moderate (<5%) over a wide range of performance conditions and climates. Using MERV 16 filters leads to problems in terms of noise, usability and potential for significantly increased blower energy use (about 20%). In systems that are already close to blower performance limits with low MERV filters, the addition of a MERV 16 filter pushed the blowers to their performance limits. The effect of filter loading on total HVAC system energy performance was small (<1%) for most homes. However, with high filter loading rates for MERV 16 filters the performance deteriorated significantly (up to 20% increases in energy use for a system with leaky duct and a BPM blower) indicating that a filter loading indicator should be required for MERV 16 filters.*


## INTRODUCTION

Occupant concern about indoor air quality (IAQ) issues has led to the increased use of more effective air filters in residential heating and cooling systems. A drawback of improved filtration is that the better filters tend to have more flow resistance. This can lead to lower system airflows that reduce heat exchanger efficiency, increase increased duct pressure differences (leading to increased air leakage for ducts), and increased blower power consumption. Due to a lack of measured data and analysis of energy and performance consequences, there is currently little knowledge on the magnitude of these effects. There is also no guidance for consumers or contractors purchasing filters regarding the related energy impacts.

Filters are tested for particulate removal efficacy with standard laboratory methods. There are several ratings systems resulting from these laboratory tests. Currently, the most common rating method is the Minimum Efficiency Rating Value or MERV. A higher MERV rating means that the filter removes more particles and a larger fraction of smaller particles. All other things being equal, we expect higher MERV ratings to lead to greater airflow resistance. However, this is complicated by geometry issues and selection of filtration method/medium. Filters come in common depths of 1, 2, and 4 inches with consequent increases in filter media surface area and decreases in airflow resistance for the same filter medium. Another complication is that the two kinds of electric motors used in residential forced air system blowers: Permanent Split Capacitor (PSC) and Brushless Permanent Magnet (BPM), have different responses to pressure difference. In general, PSC driven blowers tend to decrease flow and power with increased pressure difference, whereas BPM blowers maintain flow and increase power.

To estimate the magnitude of these effects, this study performed measurements in ten California houses to determine the effects of changing filter performance and related characteristics on the energy use of the heating and cooling systems. Although this is a small sample size, the duct systems are fairly representative of many homes throughout the US and covered a wide range of duct system pressures and, by implication, air flow resistance. Multiple filters were evaluated in ten homes covering a wide range of filter effectiveness from simple low filtration fiberglass filters, up to high efficiency (MERV 16) filters that might be used by occupants concerned about IAQ. This included filter designs that are intended to reduce filter pressure drop such as pleated filters and four-inch deep filters.

To extend the estimates of filtration impacts beyond the ten homes that were field-tested in Northern California, sophisticated analysis and simulation tools were used to determine filter impacts for a wide range of parameters and California climates.

## INTRODUCTION TO RESIDENTIAL AIR FILTRATION

### Filter Ratings

There are national standards that exist to determine the degree of particle removal provided by a filter. ASHRAE Standards 52.2 (1999) and 52.1 (1992) provide test methods that can be used by engineers to specify filters and determine their pressure drop. However, they do not discuss any of the implications of filter airflow resistance. These standards produce a MERV rating. This rating is determined by testing filters in a laboratory and measuring upstream and downstream particle concentrations.

The ratings are based on particles, not on IAQ. In general, residential filters are not used to remove indoor pollutants such as volatile organic compounds (VOCs), aldehydes, or other chemicals produced by cooking and cleaning. The particles are divided into three size categories: 0.3-1 μm, 1-3 μm and 3-10 μm. The two smallest categories are the most critical for human health issues as particles of this size can more easily deposit in the lungs (Hinds, 1999). The MERV ratings of filters readily available for use in residential HVAC systems range from a low of around 3 to a high of 16 – with higher ratings removing more particles at smaller sizes. A MERV 3 filter will capture large particles including clothing fibers, pollen and dust mites but none of the smaller particles. A MERV 16 filter captures more than 95% of all three particle sizes, including bacteria and tobacco smoke (Newell, 2006). The minimum MERV rating to remove 50% of the 1-3 μm size range is MERV 10. Inexpensive glass fiber filters that are very common are approximately MERV 3, and remove essentially zero of the particles of concern for health. The need for particle in residences may be reduced some as Stephens and Siegel (2012) measured envelope penetration factors for non-size-resolved sub-micron particles in 19 non-mechanically ventilated homes. They found a range of penetration factors from 0.17 to 0.72 with a mean of 0.45 indicating that the building envelope can be an effective filter for these small particles. Their results also showed that tighter homes had less particle penetration.

In this study we characterized the filters primarily by their MERV rating because this is the only commonly available information available for filters. Many of the filters we initially found at the test homes were very generic, with minimal labeling. While all filters had the size and name of the manufacturer, most had no other information. Thus determining the MERV rating was difficult, let alone any air flow resistance information. Some manufacturers use their own rating system and converting from the manufacturers rating system to MERV was difficult in some instances. So while other attributes of the filters such as dust holding capacity, pressure drop at rated flow, etc. would have been nice to have, they were nearly impossible to gather for all of the filters we encountered in the homes.

## ENERGY

While better filters will tend to result in improved IAQ by lowering particle concentrations, there is a cost associated with their improved performance. The key issue is that the improved filtration generally results in filters with greater airflow resistance (Kowalski and Bahnfleth 2002). However, the filter geometry in terms of pleating, filter depth and filter area all have strong enough effects that MERV rating (or equivalent filter efficiency rating) alone is not sufficient to estimate filter pressure drop. Springer (2009) tested clean filters rated from MERV 2 (approximately) to MERV 13 and found that filter pressure drop (that ranged from 0.13 to 0.52 inches of water (32 to 129 Pa) at a face velocity of 492 fpm (2.5 m/s)) was not highly correlated with MERV ratings at a fixed airflow. The airflow reduced by 10% for a PSC motor powered blower and did not change for a BPM motor blower as MERV increased – but the BPM motor used 10% more power to maintain the airflow. In contrast to conventional wisdom, this study also reported that extra depth (going from 1 in. (0.025 m) to 2 in. (0.050 m) deep, or 2 in. (0.050 m) to 4 in. (0.10 m) deep) only had a marginal effect on the pressure drop from clean filters.

For commercial HVAC systems, previous work has shown how these changes in system pressure drop lead to extra blower power requirements (e.g., Fisk et al. 2002). However, these highly simplified approaches for commercial systems assumed constant blower efficiencies and airflow. In residential systems the blower performance is strongly dependent on system pressures. Previous studies (Walker 2005, Walker 2008, and Lutz et al. 2006) have shown that residential furnace airflow and power consumption can change significantly by changing system static pressures. These flow changes result in lower air conditioner efficiencies. A simple method of estimating these changes is given in ASHRAE Standard 152 (ASHRAE 2007). It is also accounted for in the California Building Energy Code (also known as Title 24) (CEC 2008) in the ACM Appendix RE and Section 4, that have a 7.5% SEER adjustment for low airflow. Furthermore, the two current motor technologies available in residential HVAC systems have very different reactions to increased system pressures. The Permanent Split Capacitor (PSC) motors (that are about 90% of the market) show reduced airflow and power draw with increasing system pressures. Conversely, brushless permanent magnet (BPM) motors maintain airflow but have increases in power with increased system pressures. Therefore the impact of filtration is different for these two motor types. These impacts of blower technology have not been investigated in previous studies that usually assume constant blower efficiency.

Some studies have looked at the cost of using furnace blowers to continuously filter indoor air and distribute ventilation air. These studies have shown energy savings of factors of five or more for BPM motors compared to PSC motors, when operated at low speed. For example, the Energy Center of Wisconsin (Pigg (2003) and Pigg and Talerico (2004)) tested 31 houses with new (less than three years old) furnaces during the heating season. Almost all the BPM furnaces used more electricity in these real installations than their DOE test procedure ratings suggested: with a median of 82% above rated values. This was attributed to the static pressures in these field installations being much higher than those used in the rating procedures. Test procedure external static pressures are typically 0.20 or 0.23 inches of water (50 or 57.5 Pa) depending on the capacity (DOE Furnace Test procedure (Code of Federal Regulations, Title 10, Part 430, Subpart B, Appendix N, Uniform Test Method for Measuring the Energy Consumption of Furnaces and Boilers) and ARI (2003)). The measured field data showed a range of 0.24 to 1.90 inches of water (60 to 475 Pa) with an average of 0.5 inches of water (125 Pa) at the high fire rate. Natural Resources Canada (Gusdorf et al. (2003)) tested two side-by-side calibrated test houses to evaluate the change in energy for using a BPM rather than a PSC motor for continuous blower operation as required in many Canadian houses. Laboratory tests of the air handlers used in the study showed PSC efficiencies in the range of 10 to 15% with BPM efficiencies of 17 to 18% over the range of flows used for heating and cooling. The biggest differences were for continuous operation where the BPM was six times more efficient than the PSC by being able to operate at about half the flow rate of the PSC. The results of this study showed that for a continuously operating blower in the heating season there was a 74% reduction in electricity use for using a BPM (26% of the whole-house electricity use). There was a corresponding increase in natural gas usage in the heating season of 14% to account for the reduction in waste heat from the electric motor. For cooling the savings were 48% of blower energy and 21% of all air conditioner energy.

In terms of overall static pressure in duct systems, a summary (Walker and Dickerhoff (2008)) of many studies concurred on external static pressure differences of 0.5 in. of water (125 Pa) for heating only systems, and 0.8 in. of water (200 Pa) for systems with cooling coils.

## FILTER FOULING

Filter pressure drop increases as filters become dirty or fouled. Also, as this pressure drop increases more air goes around the filter instead of through it (called bypass) and does not get filtered, thus reducing the overall filtration in the system. This is why it is important to change the filters periodically. Currently there are rough guidelines for changing filters that are usually time based, with a few exceptions that call for more frequent changes such as: unusually dirty ductwork, construction in progress, furniture or drywall sanding, pets, smokers and blower running continuously.

Although energy use associated with air filtration is a recognized issue that is mentioned in sales literature of filter manufacturers[1] there is little information on the magnitude of impacts in typical residential systems, the sensitivity of these impacts to system specifications (e.g., use of different blowers) or how these impacts can be reduced or controlled.

Work by Walker (2006a) and Lutz et al. (2006) on the energy and power consumption of residential central forced air system blowers has shown in detail the dependence of blower performance on system pressures. Because BPM motors are much more efficient at lower system pressures, low pressure drop filters can contribute significantly to the energy savings potential of variable speed motor technologies. Combining these results with the information in Table 1, it is clear that filter performance has the potential to significantly change blower and heating/cooling equipment energy and power use.

In addition to the energy use implications of filtration there can be serious consequences of changing filters that are poorly understood. Most HVAC systems in existing homes were designed and installed for use with simple glass fiber filters that have low airflow resistance. Changing to higher MERV filtration can cause filter pressure drop to increase and system airflow to decrease. This can result in the premature failure of blowers as they struggle to overcome system pressures beyond their design specification. For heating systems the furnaces may operate on high limit switches and overheat. For cooling systems the potential for coil icing and premature compressor failure may increase. The performance of air conditioning systems rapidly declines below approximately 200 cfm/ton (1.04E-4 $m^3/s/kg$) (Rodriguez (1995) and Parker et al. (1997)). Systems that are close to this limit may be pushed over the edge with the addition of increased pressure drop filters.

## FIELD TESTING OF FILTER IMPACTS IN HVAC SYSTEM PERFORMANCE

Ten homes were tested for this study. They were selected to cover a range of parameters of interest: different filter thicknesses including large four-inch pleated filters, variable speed motors, single speed motors, filters at return grilles, filters at the furnace/blower, filters in both locations, systems with heat only, a multispeed heating

[1] http://www.allergybuyersclubshopping.com/as-ap-aircleen-furnace-filters.html

system, and systems with both heating and cooling. The houses were located in several California climates including San Francisco Bay Area (including both mild coastal and warm inland), northern California coast, and the California Central Valley. The limited nature of this study means that the test houses were not necessarily a statistically valid sample from the point of view of inferring implications with great precision. However, these homes provide baseline sample data on filter energy implications that does not currently exist.

The field-testing had two parts. The first part was diagnostic testing to characterize the home and HVAC system(s). The second part was long-term testing over approximately one year. The long term testing was used to observe rates of filter fouling, changes in filter pressure drop and associated system performance changes.

## Diagnostic Testing

For each house/system the following diagnostic tests were performed:

### Air Flow

The system airflow was measured using the supply plenum pressure matching techniques in ASTM Standard E1554-07 (ASTM 2007) and ASHRAE Standard 152 (ASHRAE 2007). In this method, the pressure difference between the supply plenum and house was measured with the system operating normally. The return airflow path was blocked and a large fan connected at the blower access. The combination of furnace blower and fan were used to recreate the same supply plenum to house pressure difference. The resulting airflow through the large fan was the system operating flow. Additional tests were performed for systems that had different airflows for heating or cooling, or had multi-speed/multi-capacity systems. One home had a zoned system and further tests were performed to determine air flows in each zoning mode. In order to estimate the duct system airflow characteristics in more detail, data were recorded over a range of pressure differences and air flows. Results of these initial tests were used with continuously measured pressure measurements, to calculate continuous airflow rates in each home assuming that the airflow through the system followed the relationship measured during the initial tests and that the airflow resistance downstream of the furnace did not change.

### Duct Leakage

The duct leakage was determined using the test methods in ASTM E1554 test method A (commonly called DeltaQ) because this test method determines the air leakage at operating conditions as required for energy use calculations.

### Envelope Leakage

The house envelope leakage was determined from the envelope pressurization part of the DeltaQ test, in which the envelope pressure difference and the air flow through a blower door fan required to achieve the pressure difference, are recorded over a range of house pressure differences from about 10  to 60 Pa (0.04 to 0.24 in. water). A least squares fit to the data was used to determine the flow coefficient and pressure exponent. This procedure closely follows that of ASTM E779-10 (ASTM 2010).

### Other Information

For each home the following information was recorded: age of house, house characteristics (floor area and volume, number of stories), dust generation characteristics (presence of carpet, number of occupants, number of pets, type of furnishings, and geographical location.

## LONG-TERM TESTING

The long term testing was over a period of approximately one year and covered both heating and cooling seasons to observe the changes in both heating and cooling system performance. The long sampling period also allowed the evaluation of both high and low MERV filters for each individual system. The filter loading was from the air in the homes and there was no additional loading during the experiments. The raw data were recorded every ten seconds. They were then averaged for each blower cycle and the blower cycle averages were summarized in timelines so we could observe the step changes in performance as well as changes in time due to filter loading. Although the small sample size of homes means that it is not necessarily a statistically rigorous sample of homes, they were located in different locations (both rural and urban) and covered a range of occupancies – including the presence of pets in several homes. Therefore, the results can give some guidance on filter loading rates in homes.

Each house was equipped with a set of instruments to monitor the HVAC system that communicated wirelessly to a central computer. This computer recorded all the data and communicated via the internet so that it was possible to remotely check on the progress of the experiments as well as get access to the data at any time. This allowed for data to be recorded in fine time increments and gave us the ability to estimate changes in filter performance as a function of operating time and airflow. It also helped to troubleshoot homes remotely so that very little data was lost during the experiments.

### Duct System Pressures

The pressure drop across the filter, as well as at supply and return plenums and at selected locations in the supply and return duct system, were measured using static pressure probes and digital manometers with a pressure resolution of 0.1 Pa (4.0E-4 in. of water) and an accuracy of ± 1%. These measurements isolated the components of total system pressure into filter, supply ducts, return ducts, and the cooling coil.

### Power Consumption of System Blower

This was measured using true power meters (in conjunction with current transformers and voltage readings) to avoid errors associated with low power factor operation (particularly for BPM motors). The uncertainty of the power measurements was ± 0.5% of the reading for most measurements, but could be as high as ±4.5% for blower motors with a high power factor.

### Air Temperatures

The air temperature was measured in the supply and return plenum as well as the occupied space. The air temperature in the occupied space was usually measured at the thermostat. If there were two floors, then the air temperature was measured on both. The temperature sensors were wireless and the temperatures were recorded by the same computer that recorded all of the data. The accuracy of the temperature measurements was +/- 0.5°C ( 0.9°F).

### Initial Filters

Most of the homes were tested with two levels of filtration: MERV 11 and MERV 16 filters. Approximately four to six months of operation was recorded for each filter. We installed these new filters in the home, and in three homes some initial data was taken with filters in their "as-found" condition. House 2 had a dirty filter at the start of the measurements, but after the MERV 16 filter was removed, a new filter of the same rating as the original, was installed for the conclusion of the data acquisition. House 1 started with a dirty filter then changed to a new filter about 1 month after start of measurements. House 5 started with filters that were 2 months old. Roughly half way through each year of testing the filters were changed. The intent was to have part of a heating season and part of a cooling season for each filter. In most cases a MERV 16 filter was used as a replacement. In homes 3 and 7 the MERV 16 filter created too much noise and was replaced with a less restrictive filter after a few days of operation.

### House Summary

Table 1 summarizes the age, floor area and volume of each home. Table 2 summarizes details of the heating and cooling systems and the filters found in each home. In addition to these summaries, more details can be found in Walker et al. (2012).

**Table 1. Summary of House Characteristics**

| House | Year Built | Location | Floor Area, $ft^2$ ($m^2$) | Volume, $ft^3$ ($m^3$) |
|---|---|---|---|---|
| 1 | 1962; major addition 1992 | Moraga | 3,500 (325) | 29,160 (826) |
| 2 | 1997 | Lafayette | 1,600 (149) | 13,430 (380) |
| 3 | 2007 | Elk Grove | 3,280 (305) | 36,090 (1022) |
| 4 | 2000 | Sacramento | 2,240 (208) | 22,440 (635) |
| 5 | 1978 | Fair Oaks | 3,500 (325) | 37,570 (1064) |
| 6 | 1975 | Concord | 2,700 (251) | 21,600 (612) |
| 7 | 1939 | Fort Bragg | 1,800 (167) | 14,400 (408) |
| 8 | 1943 | Berkeley | 1,000 (93) | 8,000 (227) |
| 9 | 2007 | Sausalito | 2,550 (237) | 25,500 (722) |
| 10 | 1904 | Berkeley | 1,950 (181) | 16,600 (470) |

**Table 2. Summary of HVAC system characteristics**

| House | Furnace Installed | Furnace Model | Blower Motor Type | Initial Filter Dimensions, in (cm) & Rating | Area, $in^2$ ($m^2$) |
|---|---|---|---|---|---|
| 1 | 1996 | TRANE: Plus80 Day and Night Model 376CAV024000 | PSC | 20x25x4 (51x64x10) MERV 8 | MERV 8: 2,611 (1.68) MERV 16: 12,235 (7.89) |
| 2 | 1997 | Trane: XE 80, Model TDD080C945C4 | Unknown, but assume PSC | 14x30x1 (36x76x3) MERV 8 | MERV 8: 627 (0.40) MERV 16: 4,490 (2.90) |
| 3 | 2007 | York: LY8S100C20UH11C | PSC | Main: 20x36x1(51x91x3) MERV 11 | MERV 11: 1,290 (0.83) MERV 4: 693 (0.45) |
| | | | | Bedroom: 14x14x1 (36x36x3) MERV 11 | MERV 11: 374 (0.24) MERV 4: 183 (0.12) |
| 4 | 2000 | York: Diamond 80, model: P3HUB16L064D1C | Unknown, but assume PSC | 20x30x1 (51x76x3) MERV 6 | MERV 6: 575 (0.37) MERV 16: 7,108 (4.59) |
| 5 | 2005 | Trane: YCY060G1M0AD | Variable speed, BPM | Hallway: 20x20x1 (51x51x3) MERV 11 Wall: 18x24x1 (46x61x3) MERV 11 | Hallway (11): 753 (0.49) Hallway (16): 4,581 (2.96) Wall (11): 910 (0.59) Wall (16): 4,955 (3.20) |
| 6 | 2002 | Amana: Air Command 95IIQ GUVA, variable speed two-stage, GUVA070BX40 | BPM | 20x30x1 (51x76x3) MERV 11 | MERV 11: 3,424 (2.21) MERV 16: 14,297 (9.22) (4" thick) |
| 7 | 2007 | Carrier 58MVP080 | Variable speed; BPM | Furnace: 20x25x1 (51x54x3) MERV 11 Ceiling: 22x22x1 (56x56x3) MERV 5 | Furnace (11): 955 (0.62) Furnace (16): 5,678 (3.66) Ceiling (5): 474 (0.31) |
| 8 | 2010 | York TG95040A08MP11A | Unknown, but | 27x16x4 (69x41x10) | MERV 13: 3,650 (2.35) |

| | | | | | |
|---|---|---|---|---|---|
| | | | assume PSC | MERV 13 | MERV 16: 13,221 (8.53) |
| 9 | 2007 | York: GY9S100C16UP11H | PSC-four speed | 20x30x1 (51x76x3) MERV 7 | MERV 7: 575 (0.37) MERV 16: 6,841 (4.41) |
| 10 | 2010 | TM9T060B12MP11A | PSC | 27x16x4 (69x41x10) MERV 11 | MERV 11: 3,650 (2.35) MERV 16: 13,221 (8.53) |

## FIELD TEST RESULTS

This paper summarizes key results of the field-testing. More details are available in Walker et al. (2012). To determine trends of pressure, power and airflow as filters become loaded, it is insufficient to look at time since installation, because the parameter of interest is the quantity of particles that have entered the filter. For simplicity, it is assumed that the indoor particle concentrations do not change significantly with time. It is also assumed that the ability of the filters to trap the larger particles (that contribute most to increased airflow resistance) does not change as the filter fouls. In this way, the cumulative air mass flow through the filter can be used as a surrogate for particle mass flowing through the filter. For multi-speed systems, or those with different airflow rates for heating and cooling, the different mass flow rates in different modes were used to calculate the cumulative mass flow.

The first data recorded in each house was with the filter type that the homeowner had installed. In most homes, new filters of this type were installed (see Table 2). After about 6 months of data collection, the filters were replaced with MERV 16 filters. In some of the houses, the MERV 16 filters caused the pressure drop to be so high that a whistling sound was produced when the furnace blower was on. This whistling was annoying to some homeowners, and at Houses 3 and 7 they were removed after a few days. They were replaced with the previous model of filter. In House 3, some very low quality filters (about MERV 4) were installed so that we could record data with two different filter qualities. At House 7, there were two filters in series. After MERV 16 filters were installed in both locations for a few days the one at the ceiling was changed back to a low quality filter. The MERV 16 filter at the furnace remained.

Example results are shown for two houses. Figures 1-3 are from House 4 that had a PSC motor and Figures 4-6 are from House 7 that had a BPM motor. The results show that filter, blower, and plenum pressures, and blower power appear to change in a linear fashion with cumulative mass. This indicates that our assumptions about indoor particle concentrations and changes in filtration with filter loading were reasonable. The individual points in each figure represent the average value from each heating or cooling cycle, where the initial and final values in the cycle have not been included in the average.

A summary of the field-testing results is shown in Table 3. The results of these measurements showed that installation of the highly pleated MERV 16 filters resulted in large increases in the pressure drop across these filters, often causing noise levels that were unacceptable to occupants. Corresponding flow rates could drop to levels significantly lower than the rates under lower MERV filters. For the MERV 16 filters, the four-inch deep filters had less pressure drop and less restricted flow than shallower (one-inch deep) filters. Filter loading rates varied more from house to house than by MERV rating, and overall were quite low in many of the homes.

For PSC motors the flow generally decreased with filter loading, with low MERV filters averaging a decrease of 11 cfm/$10^6$ kg , and MERV 16 filters averaging 38 cfm/$10^6$ kg . For BPMs the flow did not change significantly until the fan was at maximum output at which point they decayed at rates similar to PSC motors. No BPM motor using a low MERV filter reached its maximum output. Changing from a low MERV filter to a MERV 16 filter in PSC motors decreased the flow rate by an average of 188 cfm or 22%. With BPM motors the speed adjusted to keep the flow constant except at high speed settings when the maximum speed was reached. On average, BPM motors had their flows decrease by 178 cfm or 15%. This decrease was dominated by the two systems that were already at maximum output before the addition of high performance filters. On low speed operation over all BPMs the flow actually increased a slight amount. These results are interesting because they show large changes in flow for BPM blowers that has not been observed in other studies. We speculate that this is because we imposed higher air flow resistance with the high MERV filters such that the BPM blowers were operating outside their normal control range. This supposition is supported by the two instances where BPM blowers were already operating at maximum output before the higher MERV filters were installed.

The test results from this study indicate that for replacing low MERV filters with MERV 10-13 filters the effects on blower energy use are moderate (< 5%) over a wide range of performance conditions and climates often with small decreases in blower power for PSC blowers. Using higher MERV 16 filters leads to problems in terms of potential for significantly increased blower energy use for BPM blowers (about 20%) and usability. In systems that are already close to blower performance limits with low MERV (< 6) filters, the addition of a MERV 16 filter pushed the blowers to their limits. In a couple of cases even BPM driven blowers were unable to maintain airflow because the motors were operating at maximum output before the required airflow rate was met. Other complications for predicting the system performance were that BPM driven blower increased flow with a MERV 16 filter. This shows how the particulars of the BPM control algorithm can confound predictions of performance.

The effects of duct system leakage were found to be significant. The changes in duct pressures due to changing filters are not straightforward. In general, higher airflow resistance filters lead to reduced airflow. This causes the pressure in the supply ducts to decrease, leading to lower supply leakage. For return ducts the change depends on the filter location. When the filter is located at the furnace/blower compartment, installing higher MERV filters will cause the return duct pressure to decrease, leading to lower leakage (as with the supply ducts). However, most California duct systems have filters at the grilles. So higher MERV filters cause the whole return system pressure difference to increase. This increases the return duct leakage. The pressure difference across the blower compartment itself will always increase, independently of where the filter is located. This causes higher compartment leakage.

## ENERGY USE ESTIMATES AND SIMULATIONS

To expand the results beyond the limited sample of California homes that were field-tested, we used an energy model specifically focused on HVAC system performance. The model is called REGCAP and has been validated and used in many previous studies – including studies for the California Energy Commission (Walker and Sherman 2006). REGCAP is a minute-by-minute simulation tool that accounts for interactions between airflow, ventilation and equipment performance in homes. It has a two-zone model for including furnaces and duct systems in attics, and to account for the effect of attic heat transfer on home energy loads. It contains an airflow model that combines natural ventilation, mechanical ventilation and heating and cooling system air flows. The airflow model is coupled to a heat transfer model that includes solar loads and attic-house interactions. This paper summarizes key results of the simulations. More details are available in Walker et al. (2012).

The simulated house was based on the 2,100 $ft^2$ (195 $m^2$) Title 24 Prototype C home. An envelope air leakage of 4.8 $ACH_{50}$ was used based on the results of recent studies for new construction in California (Offerman 2009 and Proctor et al. 2011). Six California climates were used, ranging from heating dominated Climate Zone 1 (corresponding to DOE Climate Zone 3 Marine) to cooling dominated Climate Zone 15 (corresponding to DOE Climate Zone 2 hot and dry). The other four climates were mixed heating and cooling Weather data files used were the Title 24 compliant TMY3 hourly weather data files. These were converted to minute-by-minute format by linear interpolation for use in REGCAP.

The vertical axis scale varies from house to house because of the large range of values. For instance, the supply leakage in House 7 was about 3% of the blower flow but in House 5 it was over 25% (due to damage caused by raccoons!) and the filter pressures in the houses ranged from 16 Pa to over 300 Pa. The vertical lines in the plots indicate an important event, usually a filter change or cleaning.

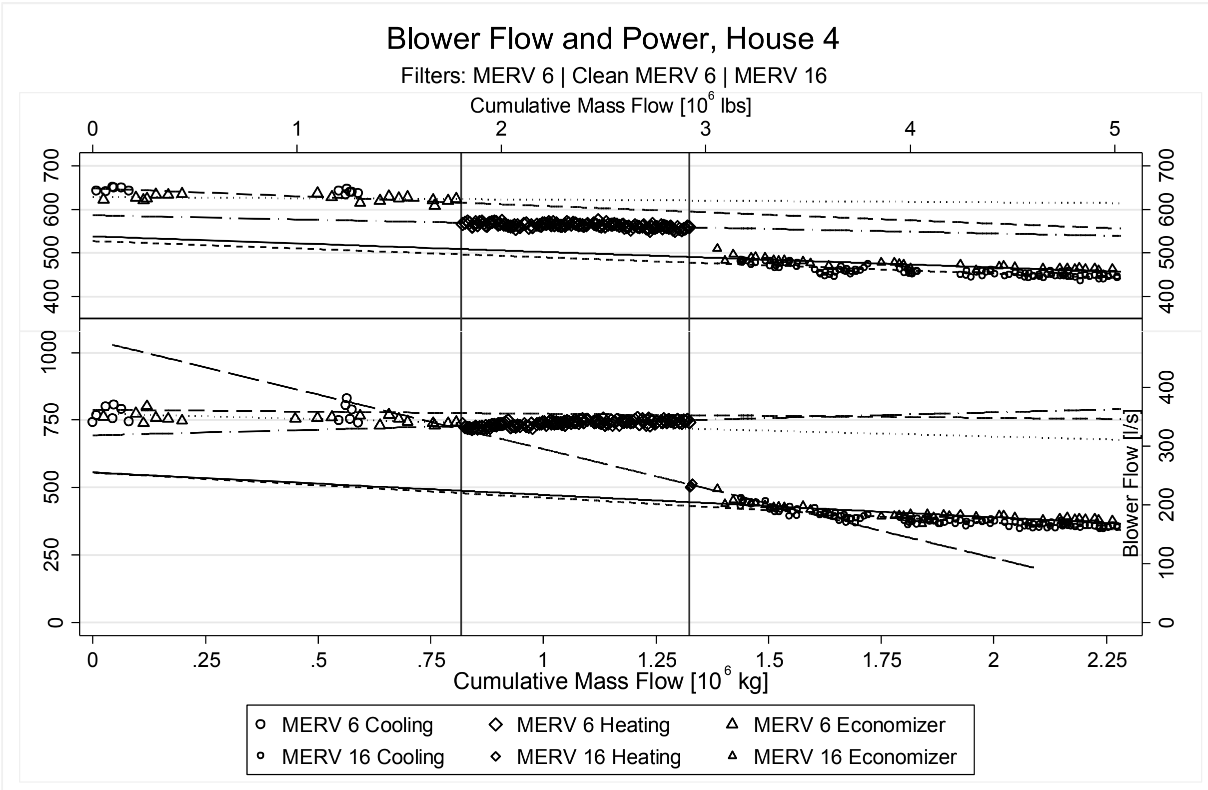



**Figure 1: Blower flow (PSC) and power changes from House 4. The vertical lines show when the MERV 11 filter was replaced with a new MERV 11 filter and then changed to MERV 16. The house had an Economizer in addition to cooling and heating modes.**

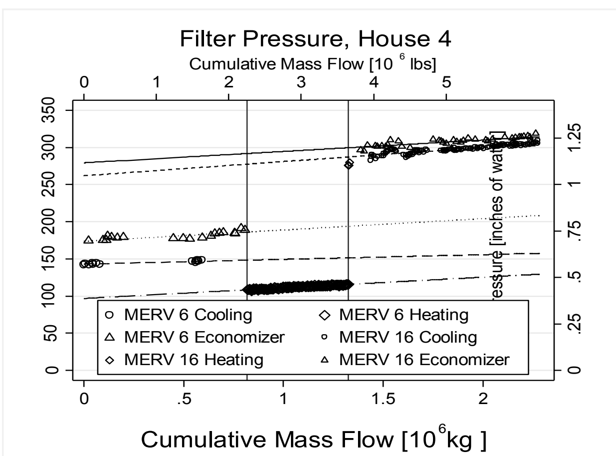



**Figure 2: Pressure across the filter for House 4.**

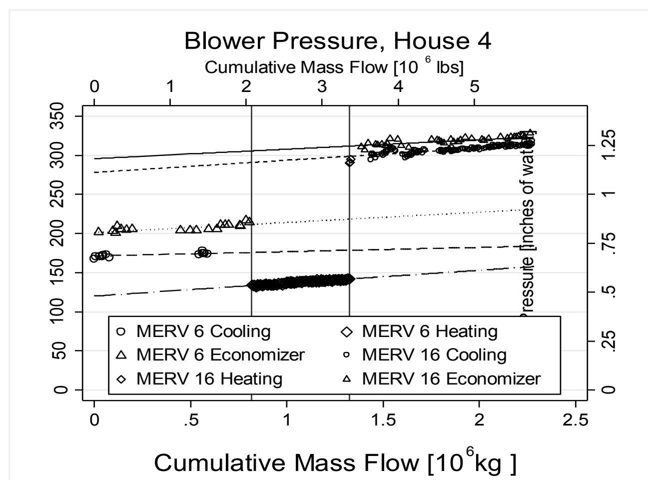



**Figure 3: Pressure across the blower for House 4.**

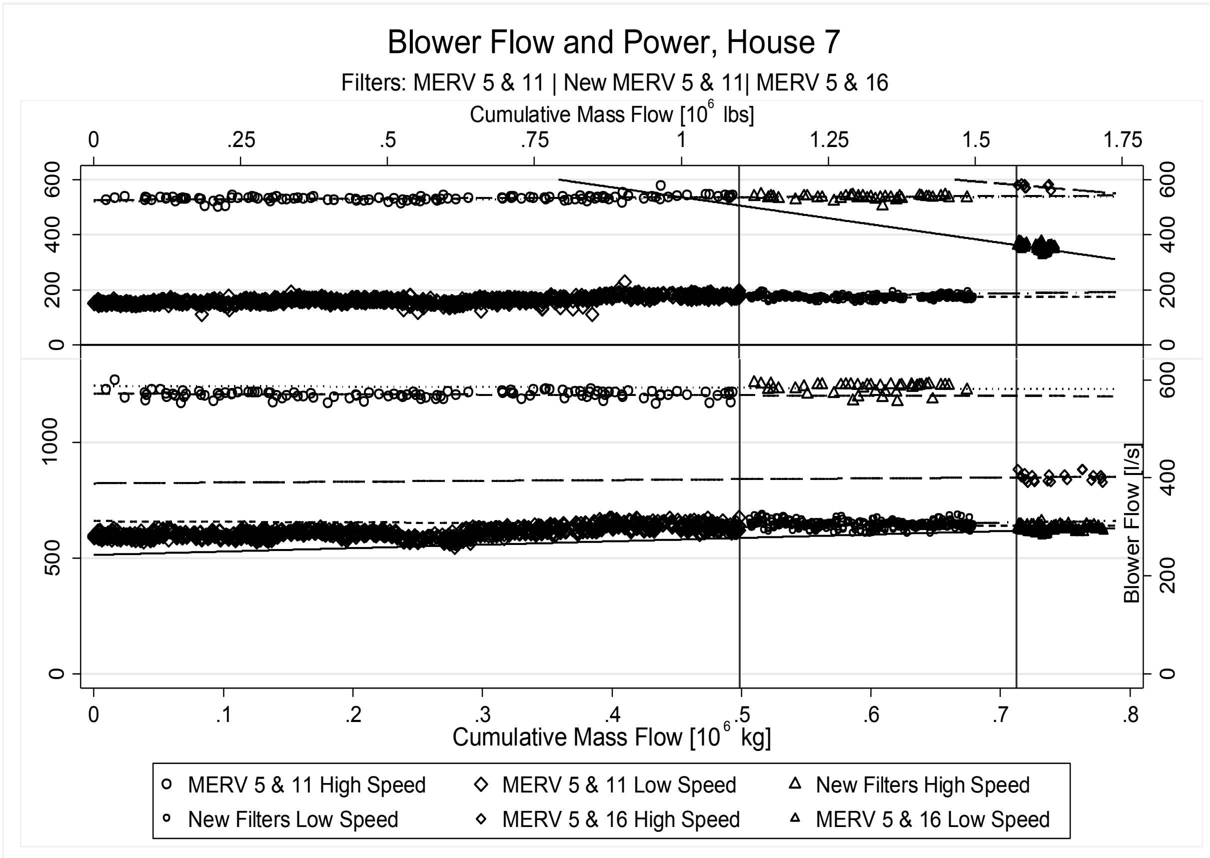



**Figure 4: Blower flow (BPM) and power changes from House 7. There are two filters in series in this house; initially a MERV 5 and 11, which were replaced about half way through with new ones, then these were replaced with a MERV 5 & 16 combination.**

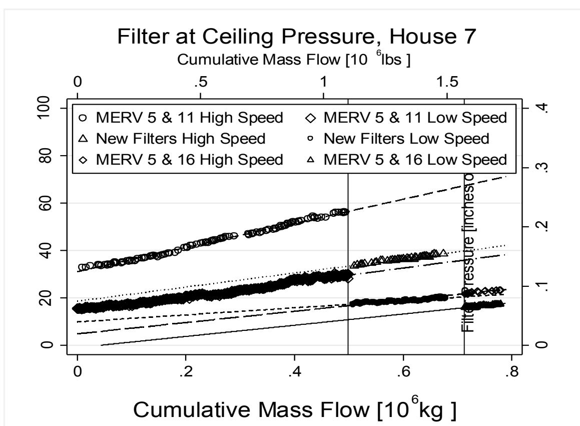



**Figure 5: Pressure across the ceiling filter for House 7.**

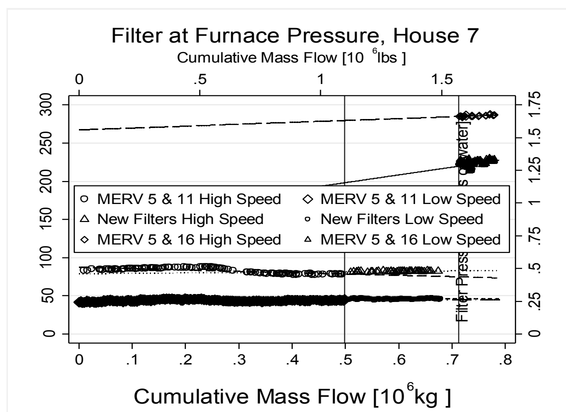



**Figure 6: Pressure across the plenum filter for House 7.**

| Table 3: Changes in filter pressure difference and blower performance | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| House | Motor type | Yearly Cumulative Air Mass Flow Rate [$10^6$ kg / year] | Mode | Filter Pressure, Pa (psf) | | Blower Flow, cfm (lps) | | Blower Power, Watts (Btu/h) | |
| | | | | Initial | Slope [Pa/$10^6$ kg] | Initial | Slope [cfm/$10^6$ kg] | Initial | Slope [W/$10^6$ kg] |
| 1 | PSC | 1400 | MERV 8 Cooling | 64 (1.3) | -3.1 | 731 (345) | -13.3 | 351 (103) | 4.6 |
| | | | MERV 8 Heating | 48 (1.0) | 0.7 | 651 (307) | -14.3 | 224 (66) | -5.6 |
| | | | MERV 16 Cooling | 89 (1.9) | 3.9 | 659 (311) | -16.7 | 327 (96) | -17.7 |
| | | | MERV 16 Heating | 72 (1.5) | 0.5 | 597 (282) | -11.7 | 211 (62) | -6.0 |
| 2 | PSC | 1000 | MERV 8 Cooling | 129 (2.7) | n/a | 695 (328) | n/a | 413 (121) | n/a |
| | | | MERV 8 Heating | 118 (2.5) | 32.9 | 736 (347) | -56.9 | 325 (95) | -22.7 |
| | | | MERV 16 Cooling | 226 (4.7) | n/a | 470 (222) | n/a | 347 (102) | n/a |
| | | | MERV 16 Heating | 210 (4.4) | 23.1 | 557 (263) | -178.7 | 262 (77) | -35.5 |
| 3 | PSC | 2500 | Original MERV 11 Cooling | 99 (2.1) | 2.1 | 1334 (630) | 20.0 | 1027 (301) | 6.3 |
| | | | Replacement MERV 11 Heat | 88 (1.8) | 1.3 | 1392 (657) | -2.8 | 775 (227) | 0.3 |
| | | | MERV 16 Cooling | 183 (3.8) | n/a | 967 (456) | n/a | 864 (253) | n/a |
| | | | MERV 4 Heating | 65 (1.4) | 0.3 | 1423 (672) | -31.2 | 739 (217) | -14.2 |
| | | | MERV 4 Cooling | 80 (1.7) | 2.6 | 1419 (670) | 6.7 | 1047 (307) | -19.4 |
| 4 | PSC | 2300 | MERV 6 Cooling | 143 (3.0) | 6.3 | 790 (373) | -15.2 | 646 (189) | -40.5 |
| | | | MERV 6 Heating | 108 (2.3) | 14.3 | 727 (343) | 42.6 | 568 (166) | -20.8 |
| | | | MERV 6 Ventilation | 173 (3.6) | 15.3 | 789 (372) | -42.9 | 624 (183) | -6.2 |
| | | | MERV 16 Cooling | 289 (6.1) | 19.1 | 451 (213) | -93.1 | 487 (143) | -37.2 |
| | | | MERV 16 Heating | 277 (5.8) | n/a | 509 (240) | -n/a | n/a | n/a |
| | | | MERV 16 Ventilation | 300 (6.3) | 15.3 | 482 (227) | -83.1 | 495 (145) | -35.6 |
| 5 | BPM | 9400 | MERV 11 Blower ON | 31 (0.7) | 1.6 | 1079 (509) | -14.2 | 193 (57) | 0.6 |
| | | | MERV 11 Heat & Cool | 45 (0.9) | 2.3 | 1730 (816) | -22.4 | 398 (117) | 0.7 |
| | | | MERV 16 Blower ON | 167 (3.5) | 10.2 | 877 (414) | -9.4 | 263 (77) | 4.0 |
| | | | MERV 16 Heat & Cool | 190 (4.0) | 8.1 | 1113 (525) | -34.8 | 345 (101) | -3.7 |
| 6 | BPM | 890 | MERV 11, Zone: Up & Downstairs | 38 (0.8) | 6.8 | 1276 (602) | 21.2 | 129 (38) | 10.3 |
| | | | MERV 11, Zone: Upstairs | 87 (1.8) | 11.2 | 1072 (506) | -123.6 | 348 (102) | -4.2 |
| | | | MERV 11, Zone: Downstairs | 66 (1.4) | 9.0 | 1095 (517) | 0.9 | 348 (102) | 17.6 |
| | | | MERV 16, Zone: Up & Downstairs | 83 (1.7) | 2.6 | 1278 (603) | -4.9 | 162 (47) | -0.4 |
| | | | MERV 16, Zone: Upstairs | 165 (3.5) | 9.3 | 1002 (473) | 17.2 | 424 (124) | 9.1 |
| | | | MERV 16, Zone: Downstairs | 139 (2.9) | 6.6 | 1063 (502) | 9.2 | 422 (124) | 1.2 |

| House | Motor type | Yearly Cumulative Air Mass Flow Rate [$10^6$ kg / year] | Mode | Filter Pressure, Pa (psf) | | Blower Flow, cfm (lps) | | Blower Power, Watts (Btu/h) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Initial | Slope [Pa/$10^6$ kg] | Initial | Slope [cfm/$10^6$ kg] | Initial | Slope [W/$10^6$ kg] |
| 7 | BPM | 690 | Upstream filter data: | Filter at ceiling | | | | | |
| | | | MERV 5 High Speed | 32 (0.7) | 50.9 | 1231 (581) | -12.9 | 534 (156) | 20.3 |
| | | | MERV 5 Low Speed | 16 (0.3) | 30.2 | 591 (279) | 94.7 | 153 (45) | 53.5 |
| | | | New MERV 5 Filter High Speed | 34 (0.7) | 29.8 | 1252 (591) | -17.9 | 533 (156) | 23.8 |
| | | | New MERV 5 Filter Low Speed | 17 (0.4) | 14.8 | 660 (311) | -26.3 | 175 (51) | 11.2 |
| | | | Plenum MERV 16 High Speed | 22 (0.5) | n/a | 863 (407) | n/a | 588 (172) | n/a |
| | | | Plenum MERV 16 Low Speed | 16 (0.3) | 23.7 | 631 (298) | 147.4 | 362 (106) | -672.2 |
| | | | The downstream filter data: | Filter at furnace | | | | | |
| | | | MERV 5 & 11 High Speed | 83 (1.7) | -17.8 | | | | |
| | | | MERV 5 & 11 Low Speed | 42 (0.9) | 1.4 | | | | |
| | | | New Filters High Speed | 82 (1.7) | 5.4 | | | | |
| | | | New Filters Low Speed | 46 (1.0) | 3.1 | | | | |
| | | | Plenum MERV 16 High Speed | 286 (6.0) | n/a | | | | |
| | | | Plenum MERV 16 Low Speed | 224 (4.7) | 101.4 | | | | |
| 8 | PSC | 900 | MERV 13 Heating | 132 (2.8) | 1.9 | 921 (435) | 9.4 | 398 (116) | -8.1 |
| | | | MERV 16 Heating | 176 (3.7) | 7.9 | 827 (390) | -7.1 | 352 (103) | -22.0 |
| 9 | PSC | 690 | MERV 7 Heating | 57 (1.2) | -2.1 | 1088 (513) | 28.9 | 716 (210) | -12.5 |
| | | | MERV 16 Heating | 22 (0.5) | 13.2 | 875 (413) | 103.7 | 570 (167) | 15.9 |
| 10 | PSC | 600 | MERV 10 High Heating | 31 (0.7) | 4.7 | 1062 (501) | -40.5 | 489 (143) | -45.3 |
| | | | MERV 10 Low Heating | 23 (0.5) | 3.1 | 824 (389) | -43.6 | 382 (112) | -40.4 |
| | | | MERV 16 High Heating | 112 (2.4) | 15.7 | 926 (437) | -51.6 | 432 (127) | -43.7 |
| | | | MERV 16 Low Heating | 92 (1.9) | 18.7 | 775 (366) | -5.2 | 354 (104) | -20.1 |

The initial blower airflow rate, $Q_0$, was 350 cfm/ton for cooling and 17 cfm/kBtu for heating. The initial blower power draw, $W_0$, was 0.58 W/cfm for both PSC and BPM blowers. A key point about blower power is that the blowers only operate at an efficiency of 15% (based on the results of laboratory testing in Walker 2006) and the remaining blower power is lost as heat to the system air stream. The efficiency depends on total system static pressure difference (i.e., not just the filter pressure difference), motor type, and selected motor speed. These complications were considered to add complexities to the calculations that might unnecessarily mask other performance attributes so a fixed value was used. The initial total duct leakage was 6% for new construction and 28% for existing housing stock, both evenly split between supply and return i.e. 3% supply + 3% return and 14% supply + 14% return. The simulations were run for a year. However, in some cases, this lead to unrealistically low air flow in high loading rate cases. Therefore, we limited the drops in air flow to 50% of initial air flow. After which it was assumed that a new filter was installed. This caused some discontinuities in experimental results but prevented the simulation of extremely unrealistic scenarios that would normally lead to equipment failure in a real HVAC system. More details about the simulated house and HVAC systems can be found in Walker et al. (2012).

For this study a new calculation procedure was added to REGCAP to account for changes in airflow, blower power and duct leakage for different MERV filters. Two effects were included: firstly the step-change in performance due to changing filters and secondly, the effects of filter loading. Using the results of the field-testing, three scenarios were developed:

1. Low change in performance. This corresponds to homes in the study that exhibited small loading effects
2. Moderate change in performance. This corresponds to homes in the middle of the range of responses observed in the field data
3. Large changes in performance. This corresponds to a worst case of very fast loading from the fastest loading house in the study

The simulations were performed for MERV 8, 11 and 16 filters using MERV 5 with no loading effects as a baseline for reference. The model included calculations to change the blower power, airflow, return duct leakage (assuming the filter was located at the grille), and air conditioner performance relative to the MERV 5 baseline with no filter loading. The initial conditions were set to values commonly found in residential systems. The following equations were used to determine how these parameters change with cumulative mass flow through the filter, m:

$$Q_{AH}(m) = A_{Q,M_n} Q_0 + \kappa_{Q,M_{nf}} Q_0 \cdot m \tag{1}$$

$$W_{AH}(m) = A_{W,M_n} W_0 + \kappa_{W,M_{nf}} W_0 \cdot m \tag{2}$$

$$Q_{leak}(m) = A_{Q_{leak},M_n} Q_{leak,0} + \kappa_{Q_{leak},M_{nf}} Q_{leak,0} \cdot m \tag{3}$$

Where:

$Q_{AH}$ = Airflow rate of the blower

$W_{AH}$ = Power draw of blower

$Q_{leak}$ = Return duct leakage

$f$ = Fouling rate (low, medium or high)

$M_n$ = MERV rating of filter ($n$ = 8, 11, 16)

The K coefficients are expressed as a fractional change in performance after $10^6$ kg of air mass flow through the filter. The A coefficients are expressed as a fractional change in initial performance, or step-change, from installing

Figure 7 illustrates both changes in initial system performance from installing a new filter and changes due to filter loading for PSC motors and BPM motor respectively. The filter is changed from MERV 5 to MERV 11 after $10^6$ kg of mass flow. For the PSC motor note the step change decrease in airflow rate and power, and the increase in duct leakage as the filter is changed, plus the gradual decrease in performance as the filter loads. In the case of the BPM motor note the airflow rate remains constant but the air handler increases its power consumption to compensate for the increased flow resistance due to loading.

## MODELING RESULTS AND DISCUSSION

For convenience, the natural gas use has been converted from therms to kilowatt-hours using a ratio of 29.3 kWh/therm, so that it can be combined with the electricity use. Heating energy use dominates cooling, blower and mechanical ventilation electricity consumption in all climate zones except El Centro (Climate Zone 15) which is extremely hot. Increasing the duct leakage causes the total energy use to go up in all climate zones.

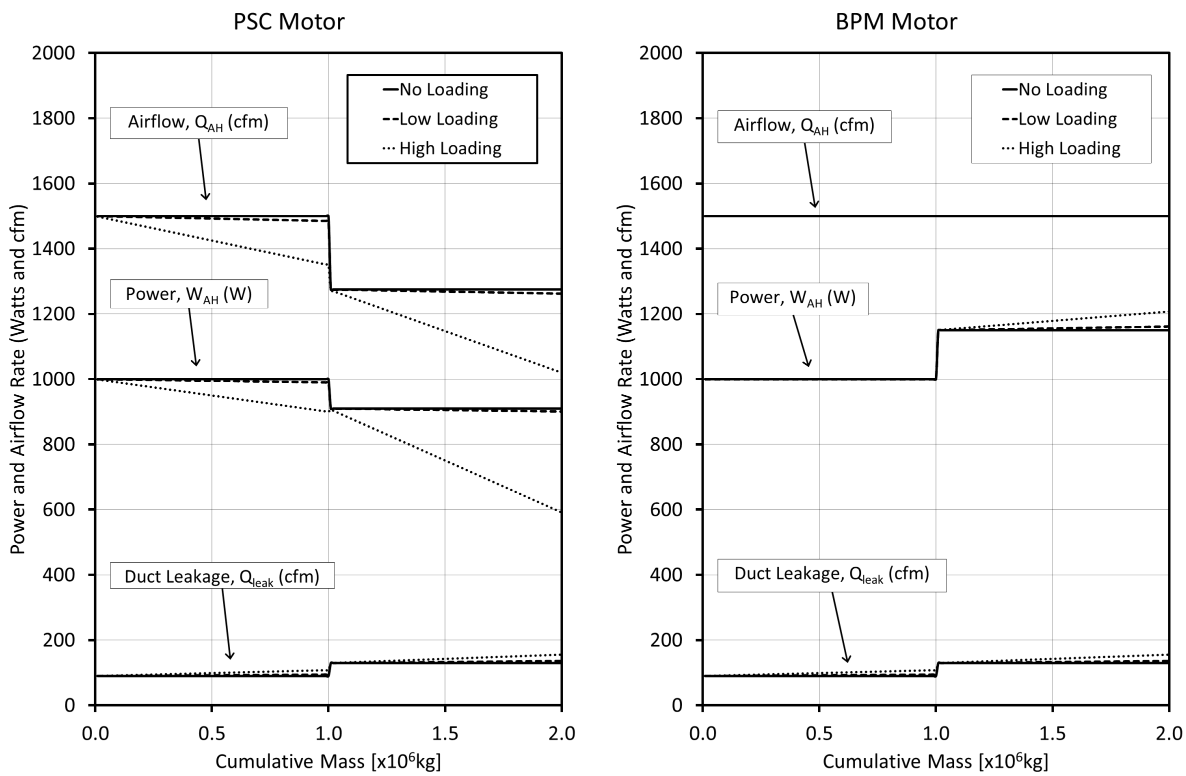



**Figure 7: Simulated filter loading effects on system performance for PSC and BPM motors under no, low and high loading conditions. There is a change in filter from MERV 5 to MERV 11 after 106 kg of cumulative air mass flow.**

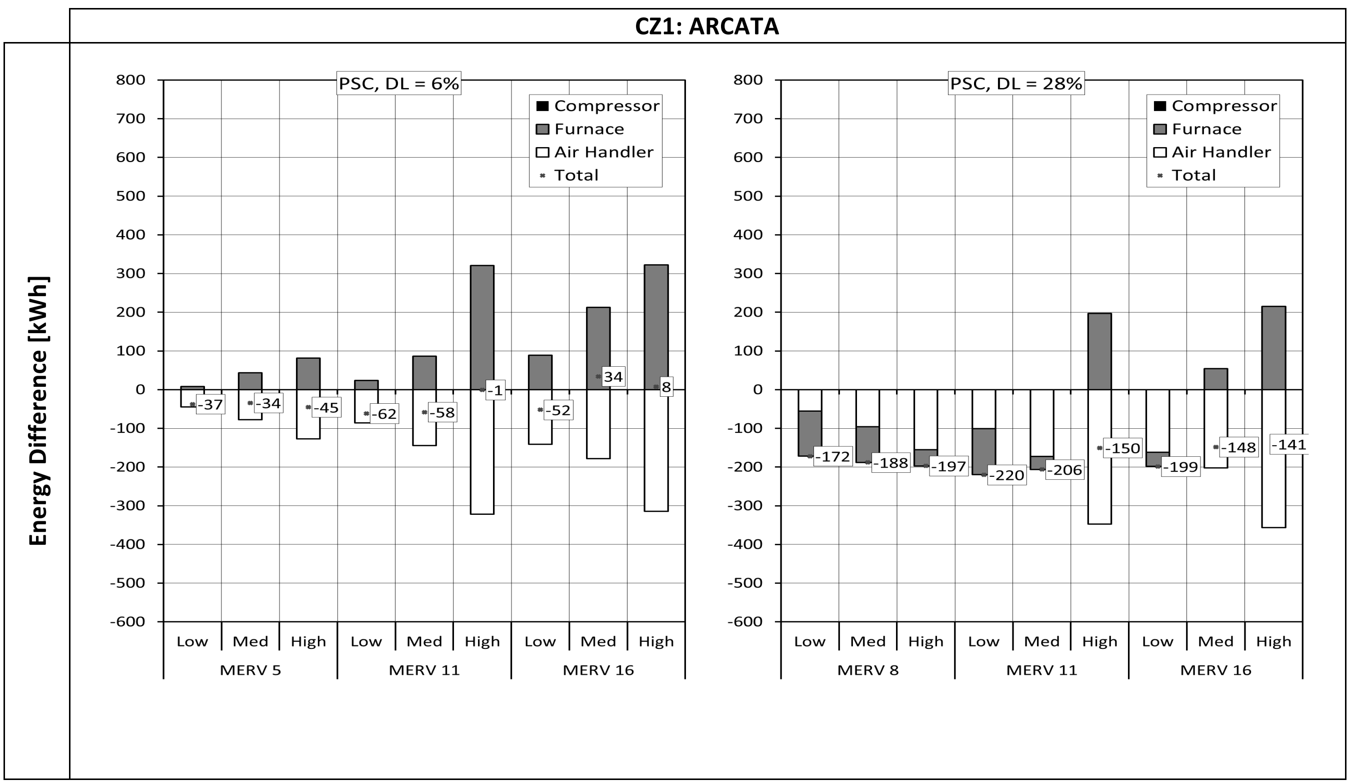
Figures 8 and 9 show the effects of filter loading rate and increasing MERV rating on system energy performance on the climates with the most heating (Climate Zone 1) and cooling (Climate Zone 15). The other climates have results between these two extremes. The displayed results show the difference in annual energy use when comparing the baseline simulations (MERV 5 filter with no loading) with the higher MERV rated filters and increasing loading effects. A negative number means that the system has used less energy than the baseline case.

For Climate Zone 1 for the PSC motor, as the filter loads, the system pressure increases causing the return duct leakage to increase, the blower power draw to decrease, and the system airflow rate to decrease. For heating operation, the decreased power draw reduces the energy consumption of the air handler, but this increases the heating load on the furnace because there is a smaller contribution of heat to the airstream from blower power (due to blower mechanical inefficiencies). Also, as the duct leakage increases the energy consumption of the furnace increases because cold attic air is being drawn into the system. Essentially, the electrical power of the blower is being swapped for the combustion of more gas by the furnace. The net change in energy over the year goes from -37 kWh (-0.14%) to 8 kWh (0.03%). When the duct leakage is increased to 28% the furnace energy use actually goes down compared to the baseline case. This is because the increased return duct leakage with the higher MERV filters is large enough that it pressurizes the whole house with attic air. Because the attic is warmer than outside (by about 6°F) all the air entering the house is at a higher temperature than the air entering the house for the baseline case with balanced supply and return leakage. This higher entering air temperature significantly reduces the ventilation related loads (by about 200 W).

In the case of Climate Zone 15 the blower energy drops from -64 kWh (-6%) to -394 kWh (-34%). The furnace gas consumption decreases but it is negligible due to the very low heating demand of the climate. The compressor electricity use, however, increases from 37 kWh (1%) to 486 kWh (9%) over the year. This is for two reasons: the reduced airflow rate over the air conditioning coil reduces the cooling efficiency, and the increased duct leakage brings more hot air from the attic into the cooling system, thus increasing the cooling load. Comparing the two worst cases between the 6% duct leakage house and the 28% duct leakage house (MERV 16 with medium loading), the air conditioning energy increases from 535 kWh (10%) up to 763 kWh (12%) annually. The extra filter change in the high loading house means it performs better over a calendar year compared with the medium loading house.

For the BPM motor the effects of filter loading are different. For the heating dominated Climate Zone 1, the BPM motor increases its power draw to maintain the airflow rate with increasing system pressure. As the filter loads, the system pressure increases, the return duct leakage increases, but the power draw of the BPM motor also increases and so the system airflow rate remains constant. Consequentially we see the opposite effect displayed from the PSC motor simulations. The electricity used by the blower increases and the heating load on the furnace decreases. The increased power draw of the blower motor is now contributing excess heat to the airstream and reducing the heating burden on the furnace. The net effect on the energy consumption of the system is small. Going from the low loading MERV 8 filter to the high loading MERV 16 filter the net energy difference from the baseline case changes from -7 kWh (-0.02%) to -13 kWh (-0.05%). The system actually uses less energy than the baseline of MERV 5 with no loading in both cases. For Climate Zone 15 the BPM motor does not perform so well. The increased power draw of the BPM motor increases the load on the air conditioner. In the 6% duct leakage house the low loading MERV 8 system increased the net annual energy consumption by 160 kWh (1.5%). The high loading MERV 16 system increased the net annual energy consumption by 535 kWh (5%). For the 28% duct leakage case, the high loading MERV 16 system increases net annual energy use by 2,385 kWh (20%) suggesting that when using a BPM motor in a cooling dominated climate (where the system airflow rates are high) the homeowner should ensure that they use a low-pressure system with tight ducts unless they are willing to pay a heavy energy penalty for filtration.

The other climate zones display changes in system performance somewhere between the two extreme climate zones 1 and 15. Climate Zone 6 (Los Angeles) has very little heating or cooling operation (approximately 200 hours per year) and so filter loading and increasing MERV have very little effect in terms of energy. Climate Zones 10 (Riverside), 12 (Sacramento), and 13 (Fresno) all require a mixture of heating and cooling operation. The PSC motors continue to cause power swapping between the furnace and the blower, but with the addition of increased cooling demand due to reduced air conditioner efficiency. The BPM motor-driven systems exhibit less energy use dependence on filter MERV and loading rate. The energy penalty from filtration increases with cooling load (and hence system airflow rate) for both PSC and BPM motors.



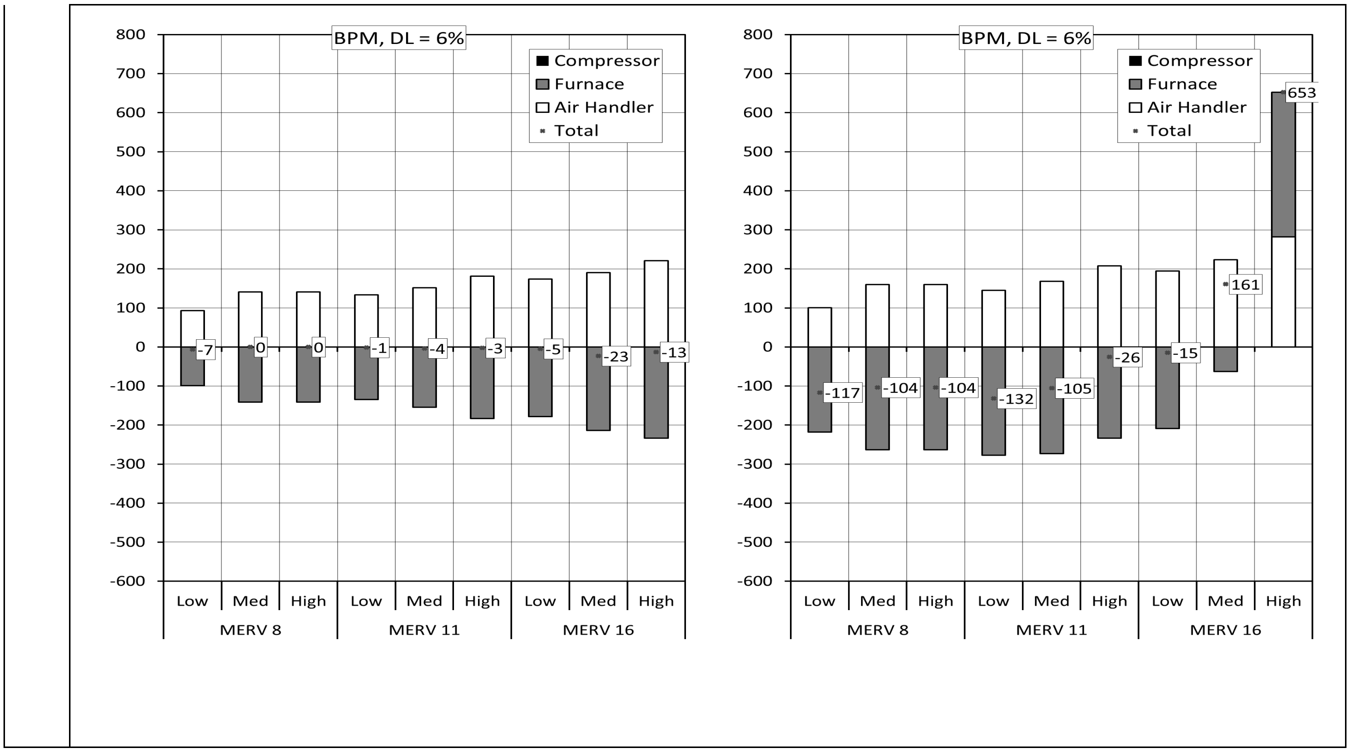
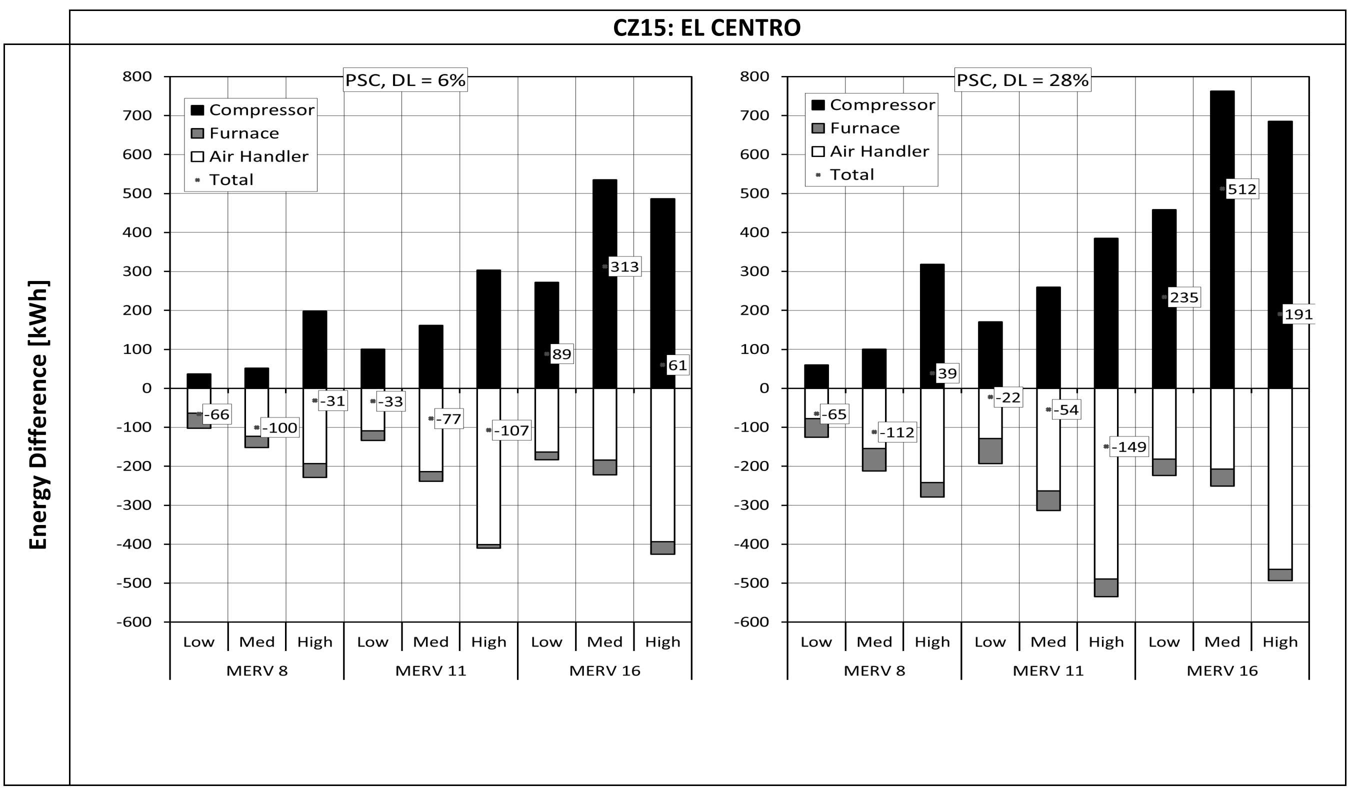



**Figure 8: Filter loading and increasing MERV effects on system energy performance in Climate Zone 1 Arcata. PSC and BPM motors in both new (6% duct leakage) and old (28% duct leakage) construction.**



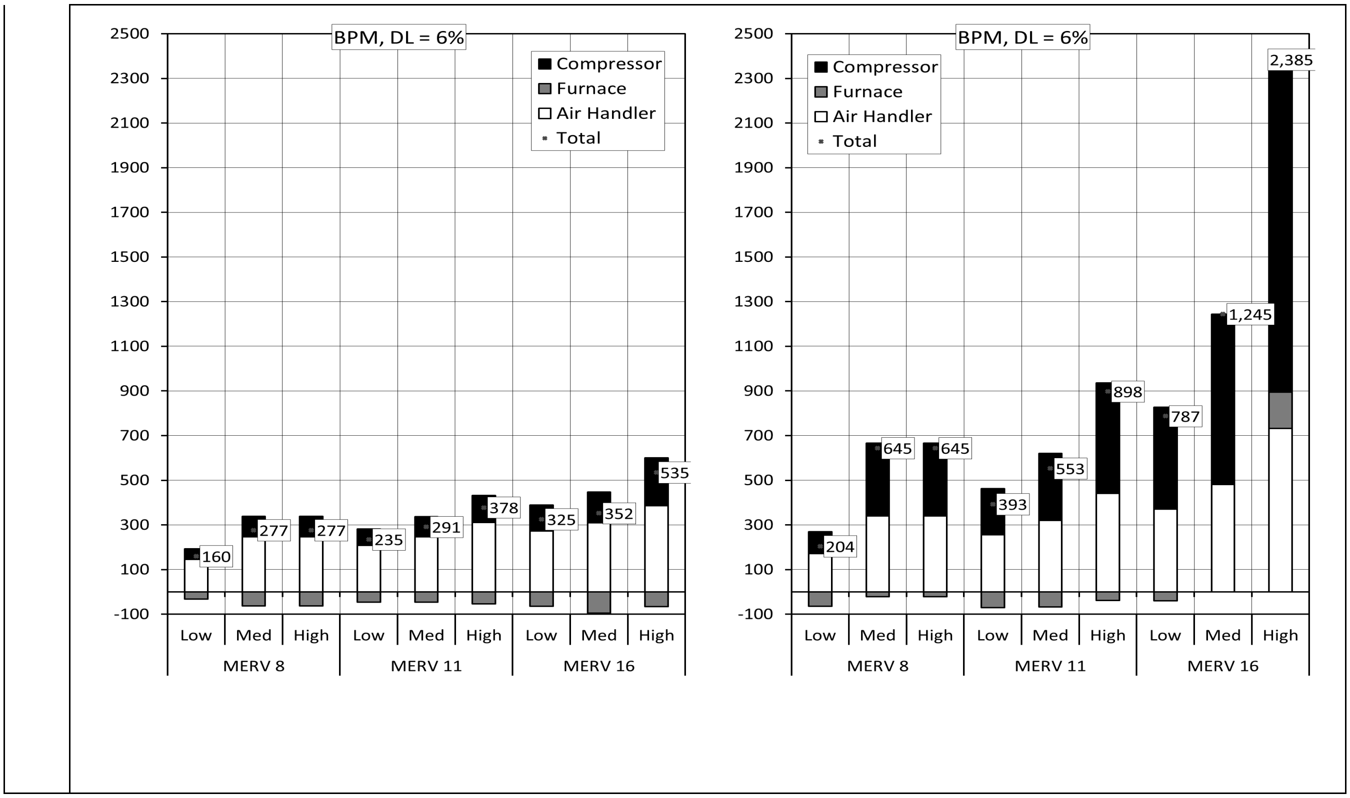



**Figure 9: Filter loading and increasing MERV effects on system energy performance in Climate Zone 15 El Centro. PSC and BPM motors in both new (6% duct leakage) and old (28% duct leakage) construction. (Note the scale change for the BPM motor)**

The result of averaging the energy penalty for all loading rates and all six climate zones, but distinguishing between filter MERV rating are shown in Table 4 (absolute values) and Table 5 (fractional values in percent). This table also shows the energy penalty as a fraction of the baseline HVAC energy averaged over all climates.

**Table 4: Min, Mean and Max Energy Penalties (kWh) for MERV changes**

| MERV Change | PSC | | | | | | BPM | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Duct Leakage = 6% | | | Duct Leakage = 28% | | | Duct Leakage = 6% | | | Duct Leakage = 28% | | |
| | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max |
| 5 → 8 | -100 | -7 | 65 | -197 | -63 | 39 | -7 | 75 | 277 | -117 | 98 | 645 |
| 5 → 11 | -107 | 18 | 175 | -220 | -58 | 91 | -6 | 93 | 378 | -132 | 139 | 898 |
| 5 → 16 | -52 | 153 | 350 | -199 | 104 | 512 | -23 | 126 | 535 | -15 | 512 | 2385 |

**Table 5: Min, Mean and Max Energy Penalties (fraction of baseline HVAC energy consumption in percent) for MERV changes**

| MERV Change | PSC | | | | | | BPM | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Duct Leakage = 6% | | | Duct Leakage = 28% | | | Duct Leakage = 6% | | | Duct Leakage = 28% | | |
| | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 → 8 | 1.0 | 0.0 | 0.4 | 0.7 | 0.3 | 0.3 | 0.0 | 0.5 | 2.7 | 0.4 | 0.6 | 5.5 |
| 5 → 11 | 1.0 | 0.1 | 1.0 | 0.8 | 0.4 | 0.7 | 0.1 | 0.6 | 3.6 | 0.5 | 0.9 | 7.6 |
| 5 → 16 | 0.2 | 1.1 | 3.1 | 0.7 | 0.6 | 4.3 | 0.1 | 0.9 | 5.1 | 0.1 | 3.1 | 20.2 |

The main conclusions from the simulations, related to heating and cooling system performance from adding filtration with varying degrees of loading are:

- In heating and cooling dominated climates a PSC motor-driven blower will cause power swapping between the air handler and either the furnace or the air conditioner, resulting in a low net energy penalty from filtration
  - A BPM motor-driven blower operates best in heating dominated climates with a low pressure drop system, and shows less variability in total system energy performance with filter loading rate and MERV rating than a PSC motor-driven system
  - The effects of filtration on system energy use are small in climates that have both low cooling and heating loads
  - The effects of filtration are about 1% or less, averaged over all climates and loading situations, with the exception of MERV 16 filters with leaky ducts and a BPM.
  - Climate specific results are:
  - Climate Zone 1 (Arcata): Filter effects are negligible except for MERV 16, high loading with leaky ducts and a BPM
  - Climate Zones 10, 12 and 13 (Riverside, Sacramento and Fresno): The impact of cooling operation is significant and makes the BPM perform better than the PSC (because waste motor heat is additional cooling load). Filter effects are generally only significant (> 2%) for MERV 16 filters with the PSC motor, or BPM with high duct leakage. As the climate gets hotter the effects become greater. The worst case is a 6% penalty in Fresno for a high filter loading, leaky ducts and a BPM. This combination should be avoided
- Climate Zone 15 (El Centro): This climate had the most sensitivity of all. The cooling load being larger than the heating load. The energy penalties were higher for the BPM and for leaky ducts. The BPM with MERV 11 in this climate, had energy penalties of about 3.5%. The worst case was the high filter loading, leaky ducts with a BPM where the penalty was 20%. This climate requires the most care when selecting filters.

## SUMMARY OF FILTRATION ISSUES

### System Pressures

The large variability in system installations in terms of the available filter area, filter depth and airflow led to large ranges of measured field performance. The filters that occupants had installed had MERV ratings ranging from 4 to 13 and had pressure drops of 16 to 173 Pa with an average of 71 Pa. When these were replaced by MERV 16 filters the pressures ranged from 16 to 300 Pa with an average of 149 Pa. This large range indicates that it is possible to install MERV16 filters with little change to system pressures (and therefore air flows, air leakage and blower power). Selecting a reasonable pressure limit for acceptable performance cannot be done precisely when considering all the other factors that influence system performance. For comparison, Stephens et al. 2010a measured pressure drops in 17 residential and light commercial systems that changed from a median of 34 Pa for MERV 2 to 55 Pa for MERV 11, which falls within our range for lower (<MERV 16 filters). We selected a reasonable target of 50 Pa for a pressure drop for MERV 16 filters because this is shown to be achievable in these field test results, and is close to the median of 38 Pa reported in other California field surveys (Proctor et al. (2011)). This low value from other field surveys is due the commonest filters in homes being very low MERV and of low flow resistance, compared to the filters used in this study. For the homes in our study, blower flows in heating mode are usually lower than in cooling mode with corresponding lower filter pressures. Furnace filter pressure drops of occupant-installed filters in the heating mode ranged from 22 to 132 Pa, with an average of 72 Pa. In cooling mode the pressures ranged from 45 to 142 Pa with an average of 95 Pa. Some houses had blower only or economizer modes that account for values below heating and above cooling mode pressures. When the MERV 16 filters were installed, heating mode filter pressures ranged from 21 to 277 Pa with an average of 143 Pa, and cooling modes ranged from 89 to 289 Pa with an average of 195 Pa.

Systems with low initial filter pressure drops could have dramatic increases in their filter pressures when MERV 16 filters were installed, in the extreme case by over a factor of 10. Although there is a lot of variability, generally changing to a MERV 16 filter almost doubled the pressure across the filter.

### Filter Loading

For PSC motors the flow generally decreased with filter loading, with low MERV filters averaging a decrease of 11 cfm/$10^6$ kg, and MERV 16 filters averaging 38 cfm/$10^6$ kg. For BPMs the flow did not change significantly until the blower was at maximum output at which point they decayed at rates similar to PSC motors. No BPM motor using a low MERV filter reached its maximum output. Changing from a low MERV filter to a MERV 16 filter in PSC motors decreased the flow rate by an average of 188 cfm or 22%. With BPM motors the speed adjusted to keep the flow constant, except at high-speed settings when the maximum speed was reached. On average, BPM motors had their flows decrease by 178 cfm or 15%. This decrease was dominated by the two systems that were already at maximum output before the addition of high performance filters. On low-speed operation, over all BPMs the flow actually increased a slight amount. For a couple of systems we found large changes in flow for BPM blowers that have not been observed in other studies. We speculate that this is because we imposed higher airflow resistance with the high MERV filters such that the BPM blowers were operating outside their normal control range. This supposition is supported by the two instances where BPM blowers were already operating at maximum output before the higher MERV filters were installed.

When the filter was changed to a MERV 16 filter blowers with PSC motors saw an increase in filter pressure and a decrease in flow and a decrease in power consumption. BPM motors at high-speed settings had similar decreases in flow but an increase in power as these motors attempt to keep the flow constant. At low-speed the BPM motor controls could result in an increase in both power and flow.

We used the results of the field data to determine fouling rates. The fractional changes in airflow, blower power and return duct leakage were calculated for every $10^6$ kg of airflow through the system. This magnitude was chosen as it represents typical airflow magnitude over a year of HVAC system operation for a home. In seven of the homes the fouling effects with a MERV 16 filter were low with filter pressure changes of less than 5Pa (about 5% of filter pressure). Two homes had a medium rate of fouling with pressures changing by about 30 Pa (15% of filter pressure). A single home, with a MERV 8 filter, fouled at what we considered a high rate, saw a pressure change of 40 Pa, roughly a 40% change in the filter pressure. Lower MERV rated filters generally had lower fouling rates. We used these results to provide input to the simulations that evaluated loading at three rates (low, medium and high), with the effects on blower power, airflow and duct leakage determined from the measured field data. Generally, the effects on blower power and airflow depend on blower motor type. As fouling increases, the PSC blower has decreasing blower power and airflow and the BPM has constant airflow and increasing blower power. The specific values form the field data are approximations because the field data did not show distinct fouling rates that clearly correlated with other system parameters.

The simulation results showed that for the low loading rate the effects on energy use are small (5% or less) for all blower types and climate. For the medium loading rate, the PSC motor systems experience reductions in blower power and airflow of about 5-15%, but an increase in duct leakage of 10 -20% - with bigger effects for higher MERV filters. The BPM systems has small (2.5% or less) changes in blower flow and power consumption and the same increases in duct leakage as the PSC blowers. The high filter loading scenario for the PSC blower had very large changes in flow and power (up to 60% for MERV 16) as well as duct leakage (up to 50% for MERV 16). For the BPM the effects on flow and power were still less than 5% but the duct leakage showed the same large changes as for the PSC blowers. These results indicate that performance is a strong function of fouling rate and that changing filters more often in high fouling situations is essential.

## Energy Impacts

The general trend for energy use is that climates with more cooling had bigger impacts with a change to higher MERV filtration. This is because cooling systems are adversely affected by lowering the system airflow and because any increase in lost motor heat increases the cooling load (it displaces furnace gas use in heating and has little net effect). The test results from this study indicate that for replacing low MERV filters with MERV 10-13 filters the effects on blower energy use are moderate (< 5%) over a wide range of performance conditions and climates, but MERV 16 filters can introduce significant blower power increases (about 20%). In most situations MERV 10/11/13 filters had a negligible (< 1%) effect on energy use. Energy use only became an issue for MERV16 filters. In the hottest climates it becomes essential to avoid using MERV 16 filters with leaky ducts and a BPM blower because the energy penalties can get as high as 20%. In many climates the high filter loading cases stood out as having significantly worse performance. This indicates the need for some sort of indictor that a filter is fouled that can be observed by home occupants.

These overall results are comparable with previous studies. For example, Parker et al. (1997) used modeling of airflow reduction effects to estimate about a 2% change in energy use. Stephens et al. (2010a) used periodic field measurements of air conditioner use to examine the change in air conditioner performance when going from low MERV filters to MERV 11/12 filters. Taking their median energy reduction of 0.26 kWh/ton/day and the air conditioner capacities and energy use from the current study, implies a change of about 1%. However, it should be noted that the Stephens et al. study found large variations of +/- 4.4 kWh/ton/day (or a variability of about +/- 15% using the same conversion as above) making comparisons difficult. Despite the differences in methodology and

MERV ratings of filters it seems like there is a fair consensus that energy changes are not large on average, and depend very much on individual system characteristics such as duct leakage, starting system air flow resistance, etc. More detailed monitoring of two systems by Stephens et al. 2010b again showed very small overall impacts for MERV 11 filters that are similar to the results of the current study. It appears that the extension to MERV 16 filters in the current study has shown that energy use issues may only be significant at these higher filtration levels given the relative agreement between this and previous studies at lower MERV 11 levels.

## RECOMMENDATIONS

The large variability seen in the field test results and simulations limited our ability to make large numbers of recommendations – although the knowledge that results are highly variable is valuable itself. The following recommendations are therefore relatively narrow in scope and limited to issues for which there is a reasonable amount of certainty.

1. No building energy code requirements are needed for MERV 11 or lower filters
2. If MERV 16 filters are used a duct leakage test is needed and ducts need to have 6%, or less, leakage, and an alarm should be used to indicate when filter has exceeded its loading limit
3. Require filter manufacturers to label filters with static pressure drop at one or more rating points (similar to European Standards). This would allow contractors and consumers to make filter replacement decisions based on air flow resistance rather than simply referring to MERV rating as we have done here due to limited information available.
4. Require filters, furnaces and blowers to track filter pressure changes and give an alarm when filters have become critically loaded
5. Be aware of potential noise issues with MERV 16 filters
6. Increase filter surface areas (install second/third returns in single return systems) such that filter pressure difference at the highest operating speed is less than 50 Pa
7. Only install MERV 16 filters after reducing the system airflow resistance and check that the addition of a MERV 16 filter will not exceed the allowed static pressure of the system.

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