Ultrafine Particles Removal and Ozone Generation by In- Duct Electrostatic Precipitators

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ABSTRACT

Human exposure to airborne ultrafine particles (UFP, < 100 nm) has been shown to have adverse health effects and can be elevated in buildings. In-duct electrostatic precipitator filters (ESP) have been shown to be an effective particulate control device for reducing UFP concentrations (20 nm - 100 nm) in buildings, although they have the potential to increase indoor ozone concentrations. This study investigated using residential ESP filters to reduce ultrafine particles between 4 nm to 15 nm, and quantified the resulting ozone generation. In-duct ESPs were operated in the central air handling unit of a test house. Results for the two tested ESP brands indicate that removal efficiency of 8 nm to 14 nm particles was near zero and always less than 10 % (± 15 %), possibly due to particle generation or low charging efficiency. Adding a media filter downstream of the ESP increased the decay rate for particles in the same size range. Continuous operation of one brand of ESP raised indoor ozone concentrations up to 77 ppb_v, and 20 ppb_v for a second brand. Using commercial filters containing activated-carbon downstream of the installed ESP, reduced the indoor steady state ozone concentrations between 6 % and 39 %.

Keywords: electrostatic precipitator; ultrafine particles; ozone; filtration; sustainable buildings

INTRODUCTION

Ultrafine particles (UFP, < 100 nm) have been shown to have adverse health effects such as respiratory symptoms and cardiovascular mortality.[1] UFP concentrations in buildings can be elevated in comparison to outdoor concentrations due to indoor UFP sources such as combustion and chemical reactions between some airborne contaminants.[2] One approach to controlling UFP concentrations within residential buildings is the use of an electrostatic precipitator (ESP), which removes particles while minimally disrupting the airstream through the device.

The particle collection efficiency of an ESP is a function of particle size and several design parameters such as airflow rate, voltage, collection cell area, strength and distribution of the electric field.[3] Although the theory of ESP technology has been extensively studied and experimentally tested in lab scale research,[3-6] few studies have investigated particle removal during the operation of in-duct ESP within a building. Howard-Reed et al. reported on experiments in an townhouse, which showed that an in-duct ESP could reduce particle concentrations between 0.3 µm and 10 µm by 55 % to 85 %.[7] Wallace et al. reported that ESP operation reduced concentrations of particles greater than 18 nm by 50% or more.[8] Morawska et al. observed in laboratory experiments removal efficiency decreased with smaller particle size especially for particles 10 nm to 20 nm.[9] However, few studies have examined the impact of ESP on particles < 15 nm in house scale environments.

Another important issue regarding the use of ESP in residences is potential production of ozone due to corona discharge.[10-16] The amount of ozone generated by ESP depends several factors including current, wire material, and temperature.[12-16] Ozone has adverse health effects such as shortness of breath, chest pain, breathing distress, and severe respiratory discomfort.[17, 18]

The objective of this study was to investigate the performance of typical residential ESPs in removing UFP and the ability of available residential activated carbon media filters to remove the generated ozone in a realistic field installation. Given the measurement and analysis challenges associated with particles around 15 nm in diameter and less, this work presents test procedures and data analysis methods for application in future testing as well. The specific experimental procedures used to meet the study objectives were to: 1) investigate the removal of UFP below 15 nm with in-duct ESPs; 2) examine ozone generation due to ESP operation; and 3) explore the effectiveness of commercially available carbon filters on removing ozone in whole house experiments.

METHODS

Experiments compared particle removal and ozone generation in a manufactured test house with the ESP on and the ESP off. The ESPs were installed the return air side of the air handling system, and the filters with activated carbon were placed immediately downstream of the ESP. Experimental measurements were conducted in a three-bedroom manufactured test house (Supplemental Information, Figure S.1), with a floor area of 140 m^2 and a volume of 340 m^3.[19]

Filters

The ESP and activated carbon filters were selected based on availability at major retailers. These devices were selected to demonstrate the performance of existing systems in residences and are not claimed to represent the best or optimal versions of the technologies. Two commercially available ESP filters were installed in the central forced air return of the house. Brand 1 had collection plates with dimensions of 62 cm × 41 cm × 13 cm and an ionizing voltage of 6.2 kV. Brand 2 had collection plates with dimensions of 51 cm × 32 cm × 11 cm and an ionizing voltage of 8.1 kV.

Three brands of commercially available, in-duct, electrostatically charged activated carbon media filters were also tested to investigate their ability to remove ozone generated by the ESP. The filters were advertised as containing activated carbon to remove odors and chemicals. Each activated carbon filter was 61 cm x 41 x 3 cm and differed in the mass of activated carbon embedded in the filter. The manufacturers ratings for the filters were MERV 11 for filter 1 and MERV 13 for filter 2. No MERV rating was provide for filter 3. According to the manufacturer, Filter 1 contained 118 g of activated carbon; the mass of carbon on the other filters was visibly less than on Filter 1.

Experimental Procedure

A candle was used to generate particles for 20 minutes with the ESP plates removed and the house central air distribution fan on for mixing. The candle, located in the dining area, generated particles 4 nm to 15 nm in size. At the end of the particle generation period, the ESP filter plates were installed, the ESP energized, and the decay of the UFP concentrations were monitored in the master bedroom for at least two hours. The measurements in the master bedroom represent the whole house particle concentration, given the mixing due to operating the central forced-air fan. Ozone concentrations were also measured in the master bedroom until steady state concentrations were achieved. After steady state ozone concentrations were achieved the ESP was turned off and the ozone decay was recorded.

Sixty-seven experiments were conducted under different conditions (Table 1). Parameters varied included the brand of ESPs (1, 2), duplicate ESPs of the same brand (A, B, C), collection plates (a, b. c .d), and the presence and brand of an activated carbon filter (-, 1, 2, 3). Experiments are referred to in the paper and graphs using the abbreviation of the conditions. For

instance (1 A a 1) means the experiment used Brand 1, ESP A, ionization wires/collection plates a, and activated carbon filter 1.

Air Change and Flow Rates

Outdoor air change rates were measured using periodic injection (every 4 h) of a tracer gas (sulfur hexafluoride, SF_6). The decay in tracer gas concentrations was monitored using a custom-built gas chromatograph with an ECD detector at 10 min intervals at seven locations in the house. Air change rates were calculated for each of the seven rooms by regressing the logarithm of the SF_6 concentration against time over a 70 minute period.[20] The average outdoor air change for the test house during the experiments was 0.31 h^{-1} with a 37 % RSD (Table 2 and Figure S.2).

A central air forced-air fan, which is a part of the heating and cooling system in the building, was always on to mix the interior air. The system operated under full recirculation with no outdoor air intake. Air velocities were measured using a hot wire anemometer (TSI 8386) at 40 or 50 grid locations at the face of the ESP. Airflow rates were calculated by multiplying the velocity by the area of the face opening for each ESP. Uncertainty for the airflow rates were calculated from the variation in the measured airflow rates. The fan delivered an average airflow 3,000 ± 500 m^3 h^{-1} without any filters in place; the pressure drop was 9.1 ± 2.4 Pa, and fan power consumption 617 W (in this paper the number following the symbol ± is the numerical value of an expanded uncertainty $U = k\ u_c$, with U determined from a combination of the estimated standard deviation(u_c) and a coverage factor k = 2, with parameters assumed to be approximately normally distributed and the unknown value assumed to lie in the interval defined by U with a level of confidence of approximately 95 %). With ESP A installed, the airflow rate decreased to 2,700 ± 900 m^3 h^{-1} (23.5 ± 1.4 Pa, fan power consumption 605 W, ESP power 42 W); when activated carbon Filter 1 was added in series with ESP A, the airflow rate decreased to 2,300 ± 580 m^3 h^{-1} (110 ± 9.2 Pa, 540 W, 42 W). The average airflow rate through ESP C was 2,800 ± 560 m^3 h^{-1}.

Measurement of Size-Resolved UFP

A Scanning Mobility Particle Sizer (SMPS) Spectrometer (Model 3936, TSI Inc), consisting of a nano-differential mobility analyzer and water-based condensation particle counter (Model

3788), was used to monitor size-resolved UFP ranging from 4 nm to 100 nm. The SMPS used a sheath flow rate of 6 L/s and an aerosol flow rate of 0.6 L/s. The SMPS scanned 97 particle size ranges during each 2.5 minute scan. The SMPS was located in the master bedroom of the house, while the indoor particle source was located in the dining area (Figure S.1). Background UFP concentrations were collected for at least 20 minutes prior to the ignition of the candle. UFP concentration data for each sampling period were summed for every five contiguous particle bin sizes. An example data set is provided in the supplementary information.

Particle concentration decay data was analyzed using a whole house mass balance on each bin size (Equation 1).[21]

$$\frac{dC_{i,in}}{dt} = P\lambda C_{out} - \left[\lambda + \beta_i + \frac{\eta_{i,HVAC} Q_{HVAC}}{V}\right] C_{i,in} = P\lambda C_{out} - (\lambda + L_i) C_{i,in} \qquad \textbf{Equation 1}$$

Where:

$C_{i,in}$ = Indoor size-resolved particle concentration (# m^{-3})

C_{out} = Outdoor size-resolved particle concentration (# m^{-3})

λ = Air change rate (h^{-1})

P = Particle penetration efficiency (-)

β_i = Size resolved particle removal to surfaces (h^{-1})

$\eta_{i,HVAC}$ = Size resolved particle removal efficiency to HVAC filter (-)

Q_{HVAC} = Airflow rate through HVAC system (m^3 h^{-1})

V = Test house volume (m^3)

$L_i = \left[\beta_i + \frac{\eta_{i,HVAC} Q_{HVAC}}{V}\right]$ = Sized resolved particle decay rate (h^{-1})

Decay rates (L_i) for each particle bin size group were calculated from the time-dependent particle concentration using a least sum of squares regression model fit of the measured data:

$$C = C_{i,t=0} e^{-(\lambda + L_i)t} + \frac{\lambda P C_{i,out}}{\lambda + L_i}\left(1 - e^{-(\lambda + L_i)t}\right) \qquad \textbf{Equation 2}$$

Outdoor particle concentrations were not measured during this study. However, previous work thoroughly characterized the particle penetration for outdoor UFP in this test house.[22] Outdoor particle concentrations were estimated in this study from the previously observed infiltration factors (the ratio of indoor concentration to outdoor concentration with no indoor

sources) for the particles of interest.[22] Previous work also showed the impact of coagulation and growth on loss of particles in this size range was minimal in the test house when the total particle concentration was below 20,000 cm^{-3}.[23] Hence, decay rates (L_i) for summed particle bins sizes were determined using particle concentration data for the 32.5 minutes after the total particle concentration dropped below 20,000 cm^{-3}. If peak concentrations did not exceed 20,000 cm^{-3}, decay rates for summed particle bins sizes were determined from data collected from 5 minutes after the candles was extinguished until 37.5 minutes after the candle was extinguished. Decay rate calculations extended only to the point where the UFP concentration was greater than the background concentration. Decay constants were only reported for an experiment when: 1) the R-squared value of the fit between the measured and modeled UFP data was greater than 0.85, and 2) the slope of measured to modeled UFP concentrations was between 0.80 and 1.2. In addition, decay rates were reported only if slopes for each summed bin size were determined from at least two independent experiments.

The efficacy of the ESP was determined by comparing the decay rate (L_i) for three scenarios: 1) the filter on ($\eta_{i,HVAC}=\eta_{i,filter+ducts}$), 2) filter removed but HVAC still running ($\eta_{i,HVAC}=\eta_{i,ducts}$) and 3) HVAC off ($\eta_{i,HVAC}=0$, to determine β_i). Filter efficiencies were determined using Equation 3 only for bin sizes where β_i was measured (8.2 nm to 14.4 nm).[21] Note that equation 3 assumes no duct leakage.

$$\eta_{i,\,filter} = 1 - \frac{1-\eta_{i,\,filter+ducts}}{1-\eta_{i,ducts}} \qquad \textbf{Equation 3}$$

Ozone Concentration Measurements

Ozone concentrations were measured in the master bedroom using a Teledyne ozone analyzer (Model 400 E). One minute average ozone concentrations were logged throughout the duration of each experiment (example in Figure S.6). Prior to each experiment, the indoor and outdoor ozone concentrations were measured (Figure S.4). On average the initial indoor ozone concentration was 2.1 ± 2.7 ppb_v, while the outdoor ozone concentration averaged 13.7 ± 11.3 ppb_v. A mass balance model was applied to determine the effective ozone generation rate of the ESP. The model (Equation 4) assumes the outdoor ozone concentration is constant and equal to the value at start of the experiment. The air change rate is the value measured by tracer gas decay test.

$$\frac{dC}{dt} = p\lambda C_o - \lambda C + \frac{E}{V} - \frac{K_H}{V} C \qquad \textbf{Equation 4}$$

Where:

C = Indoor ozone concentration (ppb_v)

C_o = Outdoor ozone concentration (ppb_v)

p = Ozone penetration factor (-)

λ = Air change rate (h^{-1})

E = Effective ESP ozone emission rate ($m^3\ ppb_v\ h^{-1}$)

V = Test house volume (m^3)

K_H = Average whole house ozone deposition rate ($m^3\ h^{-1}$)

The model was solved for a time dependent solution as shown in Equation 5.

$$C = C_{t=0} e^{-\left(\lambda + \frac{K_H}{V}\right)t} + \frac{\left[\lambda p C_o + \frac{E}{V}\right]}{\lambda + \frac{K_H}{V}} \left(1 - e^{-\left(\lambda + \frac{K_H}{V}\right)t}\right) \qquad \textbf{Equation 5}$$

Using the decay data after the ESP was turned off (E=0, $C_{t=0}$ = maximum ozone concentration), the average whole house ozone deposition rate (K_H) and ozone penetration factor (p) were determined from the time-dependent ozone concentration data using a least sum of squares regression model fit of the measured data. The effective ESP ozone emission rate (E) was determined using a second least sum of squares regression fit of the ozone concentration data measured when the ESP was turned on using the whole house ozone deposition (K_H) and penetration factor (p) values calculated from the ozone decay data. The whole house ozone deposition value (K_H) varied over time (376 ± 171 $m^3\ h^{-1}$, Figure S.7). The ozone penetration rate (p) was restricted to a value between 0 and 1 and the average value (0.52 ± 0.80) was slightly lower than the eight house average (0.79 ± 0.13) previously reported by Stephens et. al.[24] The relative large uncertainty for the ozone penetration factor in this research had minimal impacts on the emission rate values as the curve fit was far more sensitive to the whole house ozone deposition rate (K_H). A sensitivity analysis showed that for a typical experiment on ESP B (inside ozone concentrations 60 ppb_v to 70 ppb_v above outside), changing the penetration factor from 0 to 1 changed the ozone emission rate (E) by only 6%. On ESP C (inside ozone

concentrations 10 ppb_v to 15 ppb_v above outside) the impact on the ozone emission rate (*E*) was a maximum of 7 %.

Quality Control and Measurement Uncertainty

The tracer gas analyzer was calibrated every other week against known concentrations. The calibration parameters of the monitoring instrument (GC/ECD) sometimes drifted between successive calibrations. The error due to drift of the instrument was analyzed by observing the variation of calibration slope and intercept for successive calibrations. Most of the errors due to the calibration drift were less than 5 %, and the maximum error was 13 %. The SMPS was calibrated by the manufacturer before starting measurements for the study. The aerosol sampling flow rate was measured before each experiment and was always within 3 % of the target. The ozone analyzer (Teledyne API Model 400E) was initially calibrated by the manufacturer and then checked periodically using a zero air source and ozone span gas source, which is a gas dilution calibrator with a built-in O_3 generator (Teledyne API Model 700E) to verify the instrument precision. The ozone analyzer had a working range of 0 ppb_v to 500 ppb_v with a lower detection limit <0.6 ppb_v and precision of 0.5 % of reading. [25]

RESULTS AND DISCUSSION

The objective of this research are threefold: 1) determine the effectiveness of residential ESPs at removing particles from 4 nm to 15 nm in size, 2) quantify the ozone production of ESPs in a test house setting, and 3) measure the ability of residential, activated carbon impregnated, in-duct media filters at removing ESP generated ozone.

UFP Decay Rates

ESPs have been shown to be effective at removing particles greater than 20 nm in previous studies.[7-9] Figure 1 and Table 3 shows that in this research the operation of the ESPs does not have a significant impact on the decay rate of particles in the 4 nm to15 nm range. The decay rates were lower when Brand 2 was in-duct and energized than when no filter was present. For Brand 1, the decay rate was higher than no filter (faster removal), for particles less than 7 nm in size, and lower for particles larger than 7 nm. Note there were only three decay data points for Brand 1 for 4.8 nm, 11.8 nm and 14.1 nm particle bin sizes, compared to 6 to 8 data points for the other bin sizes.

To examine the impact of ionization wires and collection plates on UFP removal, the plates were switched between the two units of the same brand. There was minimal difference in UFP removal for particles less than 10 nm in size between the two plates (*a* and *b*, Figure S.8) when used in ESP A. A similar trend was seen when plates *a* and *b* were operated in ESP B (same brand as A) and when plates *c* and *d* were placed in ESP C. When the same plates (*b*) were placed in the duplicate ESP control units, the removal was lower in ESP A than in ESP B **(**Figure S.9). This trend was not seen with the *a* plates. It is not clear if the control module or plates had a bigger impact on the decay rate.

To examine the removal of ozone by activated carbon filters, in-duct media filters were added immediately downstream of the ESPs. Decay rates for particles 4.8 nm to 14.1 nm averaged 3.6 h^{-1} when just the ESP was energized and in place (1 A a -, Experiment 1), 4.0 h^{-1} when the non-energized ESP was in place with a media filter (1 A a 1, Experiment 12), and 4.6 h^{-1} when the energized ESP and media filter were in place (1 A a 1, Experiment 2) (Figure 2). The removal efficiency (Table S.1) for particles from 8.2 nm to 14.1 nm followed the same trends (from 0 % to 27 %), however the expanded uncertainties showed the removal efficiencies were not significantly different from zero for any of the various configurations.

The largest removal efficiency for an energized ESP without a media filter in the particles size range from 8.2 nm to 14.1 nm was 9 % (±15 %). These low removal efficiencies continue a trend of decreasing removal efficiency with decreasing particle size seen in previous ESP research. In experimental lab scale ESP systems testing salt particles, Yoo et. al. demonstrated removal efficiencies falling below 90 % for particles less than 30 nm in size, while Hanley et. al. showed ESP removal efficiencies ranging from 40 % to 65 % for particles of 10 nm in size.[4, 6] Moraska et al. showed ESP removal efficiencies of 50 % to 80 % for environmental tobacco smoke particles ranging between 20 nm to 30 nm at flow rates similar this study.[9] Huang and Chen showed that for low flow rates (6 m^3 h^{-1}) in a lab test and two stage ESPs (similar to the ones used in this research) with an applied voltage of 6 kV, removal efficiencies were less than 20 % for particles 10 nm in diameter.[3] Lin et. al showed that in a lab ESP test system (0.5 m^3 h^{-1}) using potassium sodium tartrate particles removal efficiencies were highly variable for particles less than 10 nm, ranging from greater than 90 % to less than zero.[5] The authors speculate that the tested ESP was generating particles less than 10 nm resulting in the removal efficiencies less than zero. ESPs can generate particles either by shedding of wire material or by

generating ozone which can react with unsaturated organic compounds from which ultrafine particles are byproduct. Particle generation is a possible explanation for the average values of the decay rates for Brand 2 being lower than with no ESP in place. However, the difference in the decay rates between Brand 2 and no ESP in place is not statistically significant.

The low removal efficiency results are also consistent with the voltage on the ionizing wire not being large enough to charge small particles (<15 nm) to the extent necessary to reach the collecting plates in the time frame during which the air passes through the ESP.[3, 16] This is supported by the theoretical conclusions reached by Yoo et al.[4] However, once the charged particles reach the increased surface area associated with the media filter, there is enhanced removal. Hence, the removal process for particles < 15 nm may be due in part to Brownian motion to the media filter (rather than the collection plates). This is consistent with results by Wallace et. al. showing media filters approaching the effectiveness of ESPs for particles in the 10 nm to 30 nm size range and Huang et. al. who showed media filters removed particles less than 10 nm in diameter regardless if the media filters were electrostatically charged.[8, 26]

Ozone Generation

This portion of the study sought to quantify the effective ozone production from ESP operation in the test house, as opposed to a lab environment. The amount of ozone produced by the tested ESPs varied by brand, duplicate tests, and ionization wires/collection plates**.** The brand of the ESP had the largest influence on ozone production. Brand 2 produced 22 ± 4 mg h^{-1} of ozone (Table 1**),** while Brand 1 produced more than double that amount (51 ± 14.2 mg h^{-1} and 60 ± 15.1 mg h^{-1}). These values bracket measurements in previous research by Fugler and Bowser, who showed a single ESP in an occupied house produced 42 mg h^{-1} to 44 mg h^{-1} of ozone.[11] Recent house scale experiments by Morrison et al. showed one brand of ESP generated between 27 mg h^{-1} to 48 mg h^{-1}, while a second brand did not generate ozone above detection limits.[27] Reported ozone generation rates for residential ESPs in lab settings range from 8.3 mg h^{-1} to 24.6 mg h^{-1}.[10, 15, 27]

The two samples of Brand 1 increased the steady state indoor ozone concentration in the master bedroom by 57.6 ± 11.9 ppb_v ((1 A *a* -), nomenclature listed Table 1) and 76.8 ± 5.8 ppb_v (1 B *b* -). For a frame of reference, the U.S. EPA National Ambient Air Quality Standard 8-hour standard for outdoor air is currently 75 ppb_v.[28] The difference in the ozone production between

identical units is likely due to variations in the ionization/collection plates. When the *a* plates were switched between the two control units the steady state ozone concentration rose from 57.6 ± 11.9 ppb_v (1 A *a* -) to 75.6 ± 10.3 ppb_v (1 A *b* -). In contrast, the *b* plates did the opposite as ozone concentration decreased from 76.8 ± 5.8 ppb_v (1 B *b* -) to 65.0 ± 7.1 ppb_v (1 B *a* -).

The variation in the ozone generation for the Brand 1 plates may be the result of the difference in handling of the product during manufacturing, shipping, installation or handling. There was minimal difference in two sets of plates used in the Brand 2 ESP, as both plates increased the indoor ozone concentration by 20.4 ppb_v on average (± 3.8 ppb_v for (2 C *c* -) and ± 5.0 ppb_v for (2 C *d* -)).

The increase in the ozone concentration seen in this study is 2 to 8 times higher than the average 9 ppb_v increase seen by Fugler and Bowser during winter tests of a single occupied home and a single ESP, even though the measured ozone generation rates of these experiments were 0.5 to 1.8 times the value measured by Fugler and Bowser.[11] This discrepancy is possibly due to the unoccupied test house in this study having less reactive surface area, in part due to the fact it was not furnished. The average ozone decay rate (K_H/V) was 1.1 ± 1.0 h^{-1} in this study and 5.6 h^{-1} in the Fugler and Bowser study.

Brand 1 produced more ozone than Brand 2, indicating Brand 1 has a stronger effective ionization field than Brand 2 despite having a lower listed ionization voltage. ESP ozone generation is a not just a function applied voltage but of multiple components including, relative humidity, wire radius, linear current density, polarity of the discharge electrode, electrode spacing, plate contamination, wire contamination and wire temperature.[12-16] Compared to Brand 2, Brand 1 had higher UFP particle decay rates (Table 3, 1.1 h^{-1} on average) for particle bin sizes from 4.8 nm to 9.8 nm. This result suggests that the greater the effective ionization field is the more efficient the ESP is at removing particles with a cost of a greater ozone generation rate. This is consistent with previous conclusions about larger particles.[10, 16, 29]

The ozone levels in the test house were reached when the HVAC fan was run constantly, the air change rate was relatively low (0.31 ± 0.23 h^{-1}), and the house had sparse furnishings. A typical fully furnished house would likely have more reactive surfaces, resulting in lower ozone concentrations and higher concentrations of secondary reaction by-products like aldehydes.[30] The most severe scenario (a steady state ozone concentration increase of 76.8 ppb_v, ((2 B *b* -),

seven replicates) required 2.5 to 5 hours of continuous use for the ozone concentrations to reach ~70 ppb_v. In most weather conditions, the HVAC system in a house would not necessarily operate constantly for that time period, in which case the highest ozone concentrations in a typical house using an ESP would be lower than the peak values from this experiment. For example, Stephens et al. measured eight residences in Austin, TX and found the average system duty cycle of 23.5 %.[31] However, when the difference in the inside and outside temperature was greater than 10 °C, the duty cycle in those same houses often reached 100 %.[31] The hourly duty fraction increased by 6 % for each degree increase in the indoor/outdoor temperature difference.[31] Cases of summer time extreme temperature differences can also be time frames when the outside ozone concentrations are elevated. Hence, there are cases where the added ozone from an ESP could potentially contribute to unhealthy indoor ozone exposure.

Activated Carbon Filters

ESP manufacturers state that the ozone produced by the ESP can be effectively removed by adding an activated carbon filter downstream. Activated carbon has been shown to be an effective mechanism for removing ozone in experimental studies.[32] This study sought to examine this approach using available residential activated carbon impregnated filters in a real world scenario. Three different filter brands were purchased from three leading retailers: a home improvement store, a discount retail store, and an internet retailer. The filters purchased at the stores were the only activated carbon filters available at those stores. The filter purchased on the internet was the first activated carbon filter recommended by a search on the internet retailer website not previously purchased at the stores. The tested activated carbon filters each had varying amounts of activated carbon embedded in the media. The tested filters are all advertised as removing odors and chemicals in general, but not specifically ozone.

Two of the three filters did not reduce the ozone generation rate ((1 A *a* 2) and (1 A *a* 3) compared to (1 A *a* -)) in a statistically significant manner. The third filter reduced the ozone generation rate (38.7 ± 12.5 mg h^{-1}, (1 A *a* 1) by an average of 25 % over the test period compared to experiments without an activated carbon filter (51.3 ± 11.9 mg h^{-1}, (1 A *a* -)), however this reduction was not statistically significant. The ozone removing performance of activated carbon filter 1 decreased over time (Figure 3). In the first day of operation the ozone concentration reduction with the activated carbon filter in place was roughly 50 % compared to

the same system without the activated carbon filter. After two weeks of exposure the activated carbon filter ozone reduction dropped to 30 %. In total, the activated carbon filter experiments show that the tested commercially available activated carbon filters are not effective at removing all of the ozone generated by the tested ESPs. The filters tested had relatively small amounts of activated carbon. Ozone removal efficiencies would likely be higher for filters with more activated carbon. However, filters with more carbon would presumably have a higher cost which could impact the degree to which they are used in residential systems.

Implications

Previous work has demonstrated ESPs as a reliable and effective control option for a wide range of particles with demonstrated removal efficiencies of greater than 90 % for particles larger than 20 nm.[7-9] However, this research has demonstrated that on a household scale the tested ESPs have removal efficiencies less than 10 % for particles smaller than 15 nm. These results were obtained for two brands of ESP and may not be consistent with all ESP brands and technologies. If a user desires to remove particles less than 15 nm using in-duct residential ESP technology, ESP systems may require increased voltages and lower flow rates than the tested models.[5] However, increasing the ionizing voltage in residential systems to remove particles smaller than 20 nm could result in increased ozone generation.[14] On a household scale such emitted ozone may directly impact human health or result in secondary ozone reactions with organic chemicals emitted in the house.[2] This research showed that the tested activated carbon filters are not able to reliably remove a majority of the generated ozone in the existing tested systems. Although three different activated carbon filters were tested, the conclusions are limited to the tested filters and may not apply to all activated carbon filters. Overall, this research indicates that while ESPs are effective at removing particles larger than 20 nm, ozone generation and limitations on existing residential activated carbon filters mean media filters may be a better option to remove particles smaller than 20 nm. More testing is needed to determine if the results are consistent for all ESPs and existing activated carbon filters.

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DISCLAIMER**:** The full description of the procedures used in this paper requires the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials, instruments, software, or suppliers for the purposes described.

TABLE AND FIGURES

Table 1. Experimental Variations and Ozone Results. Expanded uncertainties with a coverage factor of 2 are listed in parenthesis.

Experiment ID	*Brand*	*ESP*	*Plates*[2]	*Activated Carbon Filter*	*Number of Experiments*	*Ozone Conc. Increase (ppb_v)*	*Ozone Generation Rate ($mg\ h^{-1}$)*
1	1	A	a	-	8	57.6 (± 11.4)	51.3 (± 11.9)
2	1	A	a	1	8	35.2 (± 8.9)	38.7 (± 12.5)
3	1	A	a	2	3	54.3 (± 6.2)	51.2 (± 14.2)
4	1	A	a	3	2	53.6 (± 7.3)	56.1 (± 15.4)
5	1	A	b	-	4	75.6 (± 10.3)	58.7 (± 7.2)
6	1	B	a	-	5	65.0 (± 7.1)	50.8 (± 6.2)
7	1	B	b	-	7	76.8 (± 5.8)	60.4 (± 15.0)
8	1	B	b	1	7	59.8 (± 14.6)	53.8 (± 14.5)
9	2	C	c	-	5	20.4 (± 1.9	22.0 (± 4.5)
10	2	C	d	-	5	20.4 (± 5.0)	21.8 (± 3.7)
11	-	-	-	-	7	*NA*	*NA*
12	1	A[1]	a[1]	1[1]	6	*NA*	*NA*

[1]In Experiment 12 the ESP and filter were place, but the ESP was not energized.
[2]Plates a and b were used in Brand 1, Plates c and d were used in Brand 2.

Table 2. Experimental Parameters. Expanded uncertainties with a coverage factor of 2 are listed in parenthesis.

Parameter	*Unit*	*Average*
Air Change Rate	(h^{-1})	0.31 (± 0.20)
Temperature – Inside	(°C)	21.0 (± 3.0)
Temperature – Outside	(°C)	10.5 (± 17.1)
Relative Humidity – Inside	(%)	34.6 (± 31.8)
Relative Humidity – Outside	(%)	63.4 (± 29.3)
Background Particle Concentration (4 nm to 20 nm)	(#/cm^3)	866 (± 2,200)
Peak Particle Concentration (4 nm to 100 nm)[1]	(#/cm^3)	17,700 (± 4,960)
Ozone Concentration – Initial Inside	(ppb_v)	2.1 (± 2.6)
Ozone Concentration – Initial Outside	(ppb_v)	13.7 (± 11.3)

[1]Particle concentration at beginning of curve fit.

Table 3. Median UFP Particle Decay Rates (L_i) of Particle Bin Sizes (h^{-1}). Expanded uncertainties with a coverage factor of 2 are listed in parenthesis.

Experiment ID	*Brand*	*ESP*	*Plate*	*Activated Carbon Filter*	*Median Particle Bin Size (nm)*						
					4.8	**5.7**	**6.9**	**8.2**	**9.8**	**11.8**	**14.1**
1	1	A	*a*	-	6.5 (±2.2)	4.4 (±1.4)	3.9 (±1.1)	3.0 (±0.7)	2.6 (±0.4)	2.0 (±0.9)	2.9 (±3.0)
2	1	A	*a*	1	7.4 (±4.3)	6.2 (±2.4)	4.9 (±1.7)	3.7 (±1.0)	3.5 (±1.3)	3.3 (±1.2)	3.5 (±1.3)
3	1	A	*a*	2	8.1 (±1.7)	5.2 (±2.8)	3.6 (±2.2)	2.7 (±0.2)	N/A	N/A	N/A
4	1	A	*a*	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	1	A	*b*	-	N/A	5.2 (±2.7)	4.2 (±3.1)	3.1 (±1.6)	2.0 (±1.6)	N/A	N/A
6	1	B	*a*	-	N/A	4.8 (±0.7)	3.8 (±1.1)	3.0 (±1.3)	2.5 (±1.0)	2.3 (±0.7)	2.1 (±0.5)
7	1	B	*b*	-	N/A	6.7 (±2.8)	5.0 (±1.7)	3.5 (±0.8)	2.5 (±0.8)	1.7 (±0.8)	1.5 (±0.8)
8	1	B	*b*	1	N/A	6.0 (±2.2)	4.6 (±1.3)	4.0 (±1.1)	3.6 (±1.1)	2.8 (±1.2)	2.4 (±1.3)
9	2	C	*c*	-	4.6 (±0.1)	3.8 (±0.7)	3.2 (±0.7)	2.5 (±0.5)	2.1 (±0.5)	1.5 (±0.3)	N/A
10	2	C	*d*	-	N/A	4.1 (±0.7)	3.3 (±1.1)	2.8 (±0.8)	2.6 (±0.5)	2.6 (±0.8)	2.6 (±1.5)
11	-	-	-	-	5.3 (±1.2)	4.2 (±0.9)	3.4 (±1.2)	3.1 (±0.8)	2.7 (±1.1)	2.6 (±0.7)	2.5 (±1.6)
12	1	A[1]	*a*[1]	1[1]	5.8 (±2.3)	5.0 (±1.0)	4.0 (±0.9)	3.4 (±1.1)	2.9 (±0.8)	3.3 (±2.2)	3.5 (±2.8)
13	-[2]	-[2]	-[2]	-[2]	N/A	N/A	N/A	1.4 (±0.4)	1.0 (±0.2)	0.8 (±0.3)	0.7 (±0.0)

[1]In Experiment 12 the ESP and filter were in place, but the ESP was not energized.

[2]Experiment 13 was identical to Experiment 11, but the HVAC fan was not on.

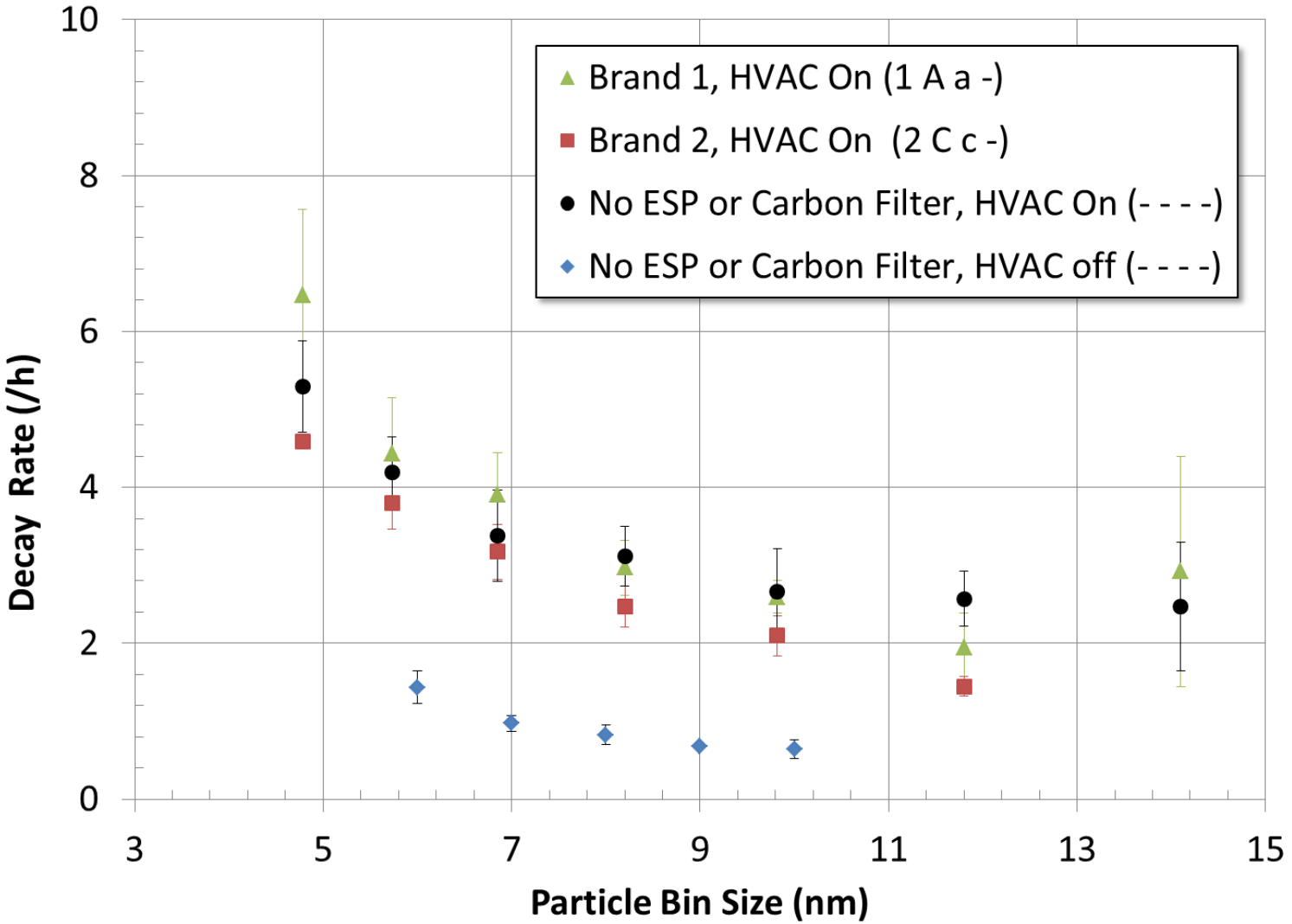

Figure 1: A comparison of particle decay rate (L_i) for each bin size between Brand 1, Brand 2 and no filter in place. Error bars represent expanded uncertainty with a coverage factor of 2.

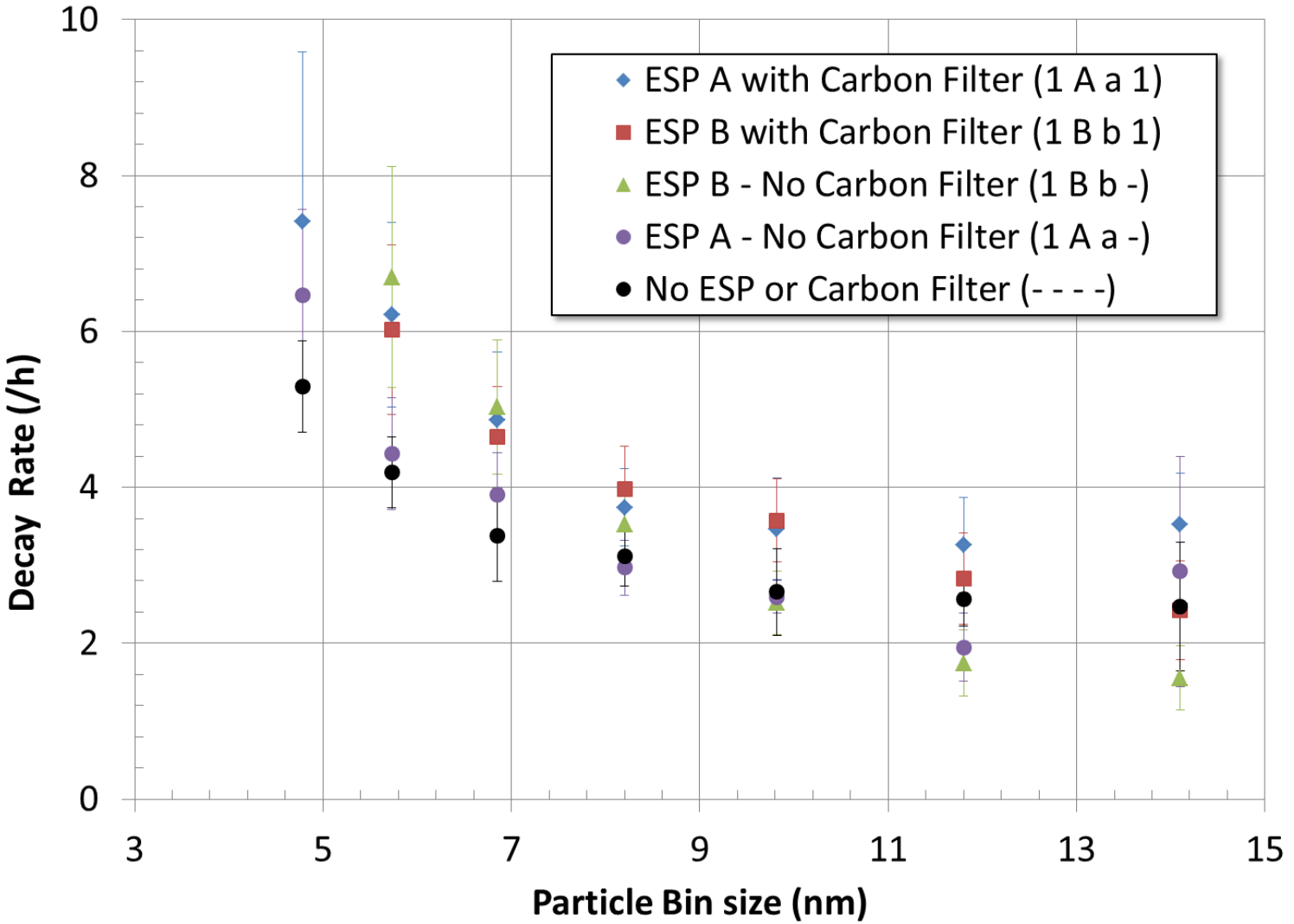

Figure 2: A comparison of particle decay rate for each bin size when media filter is and isn't present. Error bars represent expanded uncertainty with a coverage factor of 2.

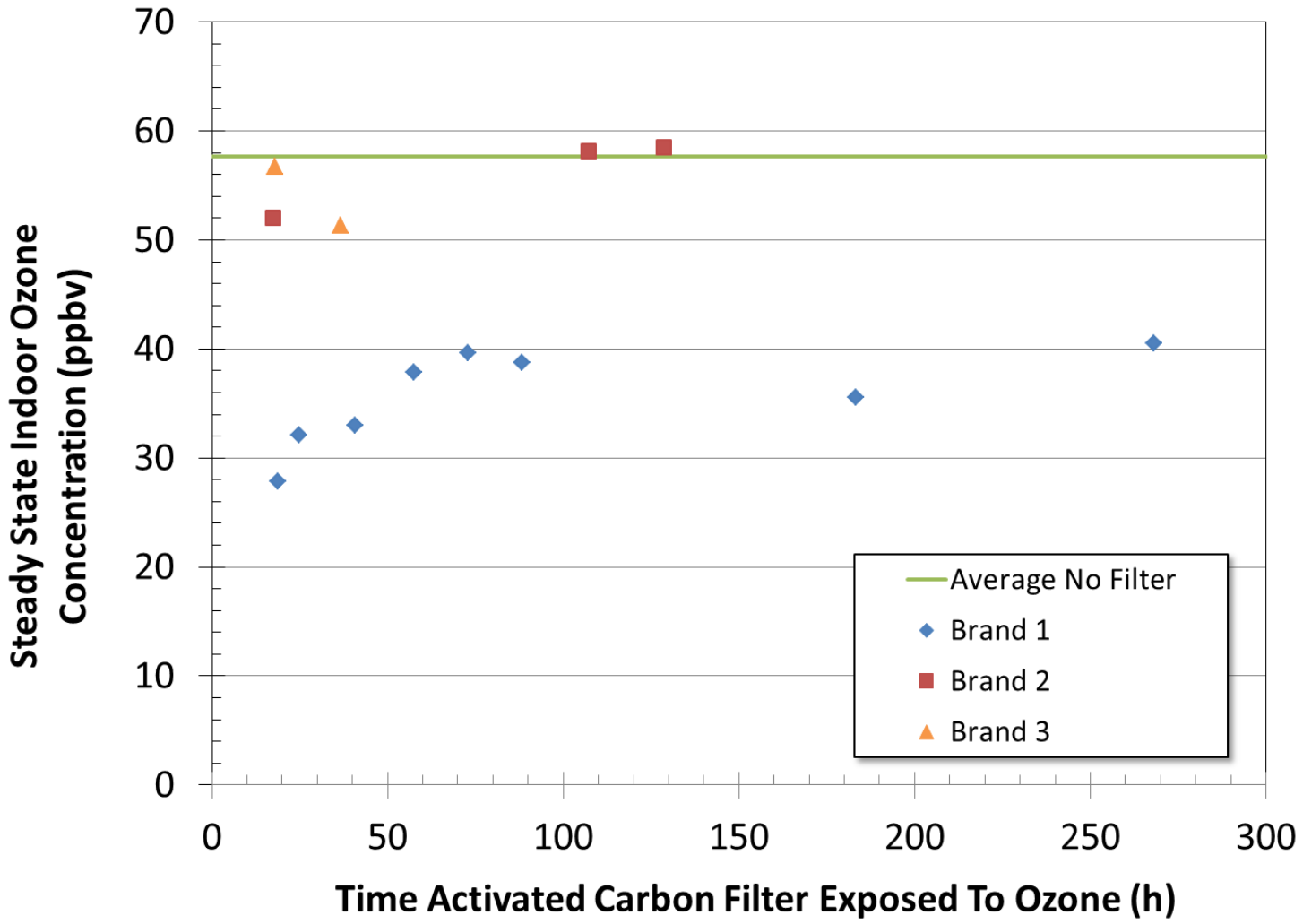

Figure 3: Average ozone concentration in test house when an energized ESP is followed by a commercially available activated carbon filter.

SUPPORTING INFORMATION

The supplement information includes a range of data documenting the experiments and calculations.

Removal Efficiencies

Table S.1 lists the removal efficiencies with expanded uncertainties of the tested systems.

House Layout

The layout of the test house and location of the filters in the HVAC system are shown in Figure S.1.

Variation in Temperature and Relative Humidity

Experiments were run from January until June, during a range of outdoor weather events. Several parameters were recorded throughout the course of the experiments. Average temperature, relative humidity, and air change rate values were recorded during each experiment. Temperature and relative humidity were recorded at 1 min intervals at the same seven locations in the house as the six concentrations. Values were averaged over the duration of each experiment. Temperature was measured using epoxy coated thermistors (uncertainty of 0.5 °C). The relative humidity was measured with capacitive thin-film polymer sensors (uncertainty of 2 %). The temperature varied in response to the test house air conditioning and heating system operation, and the relative humidity varied naturally and increased as the outside temperature increased primarily due to outdoor variations; there was no indoor moisture generation (Figure S.2). Indoor temperatures decreased slightly over the course of the experiments (roughly 24 °C to 20 °C, Figure S.2), while outdoor temperatures increased by 30 °C. Outside relative humidity was erratic, but inside relative humidity increased from 20 % to 30 % in winter months to 60 % in June.

Variation Air Change and Outdoor Ozone Concentrations

Air change rates decreased during that same time frame from 0.4 h^{-1} to 0.2 h^{-1} (Figure S.3). Outdoor ozone concentrations increased by a factor of two from beginning to the end of the

experiments (10 ppb_v to 20 ppb_v, Figure S.4). Initial indoor ozone concentrations also rose, but remained below 5 ppb_v prior to energizing the ESP.

Illustrative UFP profiles

Illustrative UFP particle concentration and ozone concentration profile data are shown in Figure S.5 and Figure S.6 respectively.

Variation Ozone Decay Rate (K_H) and Penetration Pactor (p)

The whole house ozone decay rate (K_H) and penetration factor (p) theoretically should have been constant, provided no new materials were introduced into the house. Figure S.7 illustrates the both parameters varied throughout the experiments.

Impact of Plates

To examine the impact of ionization wires and collection plates on UFP removal efficacy, the plates were switched between the units. There was minimal difference in UFP removal for particles less than 10 nm in size between the two plates (*a* and *b*, Figure S.8) when used in ESP A. A similar trend was seen when plates *a* and *b* were operated in ESP B and when plates *c* and *d* were placed in ESP C. When the same plates (*b*) were placed in two duplicate ESP control units the removal was lower in ESP A than in ESP B **(**Figure S.9). This trend was not seen with the *a* plates. For these samples it is not clear if the control module or plates had a bigger impact on the decay rate.

Table S.1. Removal Efficiency of Particle Bin Sizes (%) for Each Experiment.[1] Expanded uncertainties with a coverage factor of 2 are listed in parenthesis.

Experiment ID	*Brand*	*ESP*	*Plate*	*Activated Carbon Filter*	*Median Particle Bin Size (nm)*			
					8.2	**9.8**	**11.8**	**14.1**
1	1	A	*a*	-	0 (± N/A)	1 ± (2)	0 (± N/A)	9 (± 15)
5	1	A	*b*	-	2 (± 8)	0 ± (N/A)	N/A	N/A
6	1	B	*a*	-	1 (± 3)	0 ± (N/A)	0 (± N/A)	0 (± N/A)
7	1	B	*b*	-	8 (± 31)	0 ± (0)	0 (± N/A)	0 (± N/A)
9	2	C	c	-	0 (± N/A)	0 ± (N/A)	0 (± 0)	N/A
10	2	C	d	-	0 (± N/A)	0 ± (N/A)	2 (± 6)	3 (± 5)
2	1	A	*a*	1	19 (± 67)	22 (± 45)	20 (± 55)	27 (± 34)
8	1	B	*b*	1	23 (± 83)	24 ± (49)	12 (± 34)	7 (± 9)
12	1[2]	A[2]	*a*[2]	1[2]	12 (± 44)	11 ± (22)	22 (± 59)	26 (± 37)

[1]N/A is listed for when no decay rates were calculated. 0% is listed for when the Equation 3 result is less than 0.

[2]In Experiment 12 the ESP and filter were place, but the ESP was not energized.

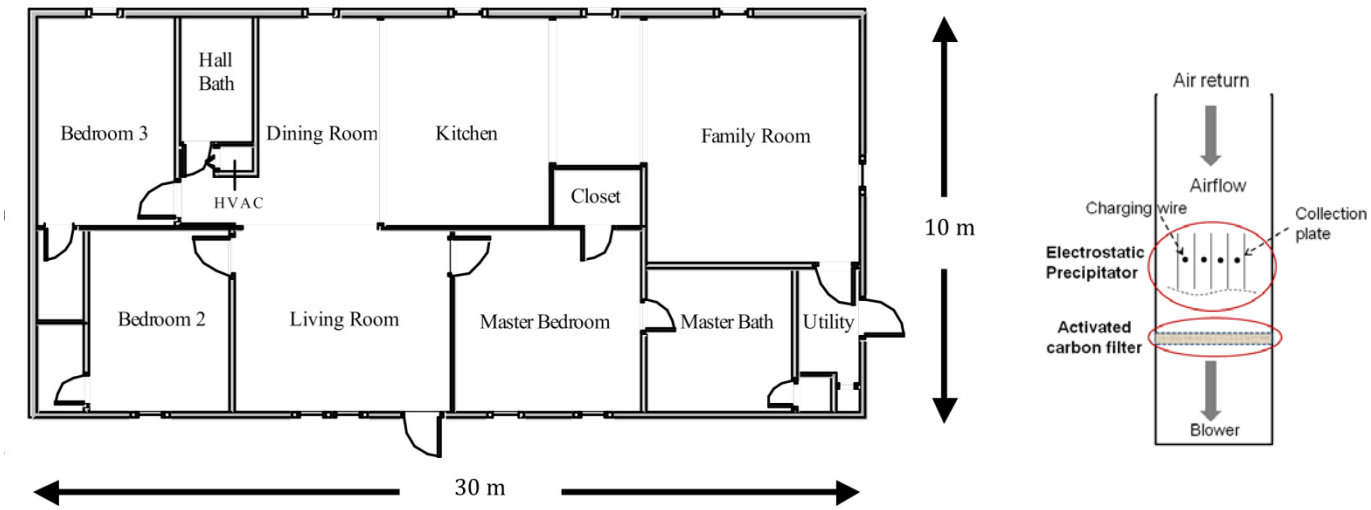

Figure S.1: Layout of Test House and HVAC filter system

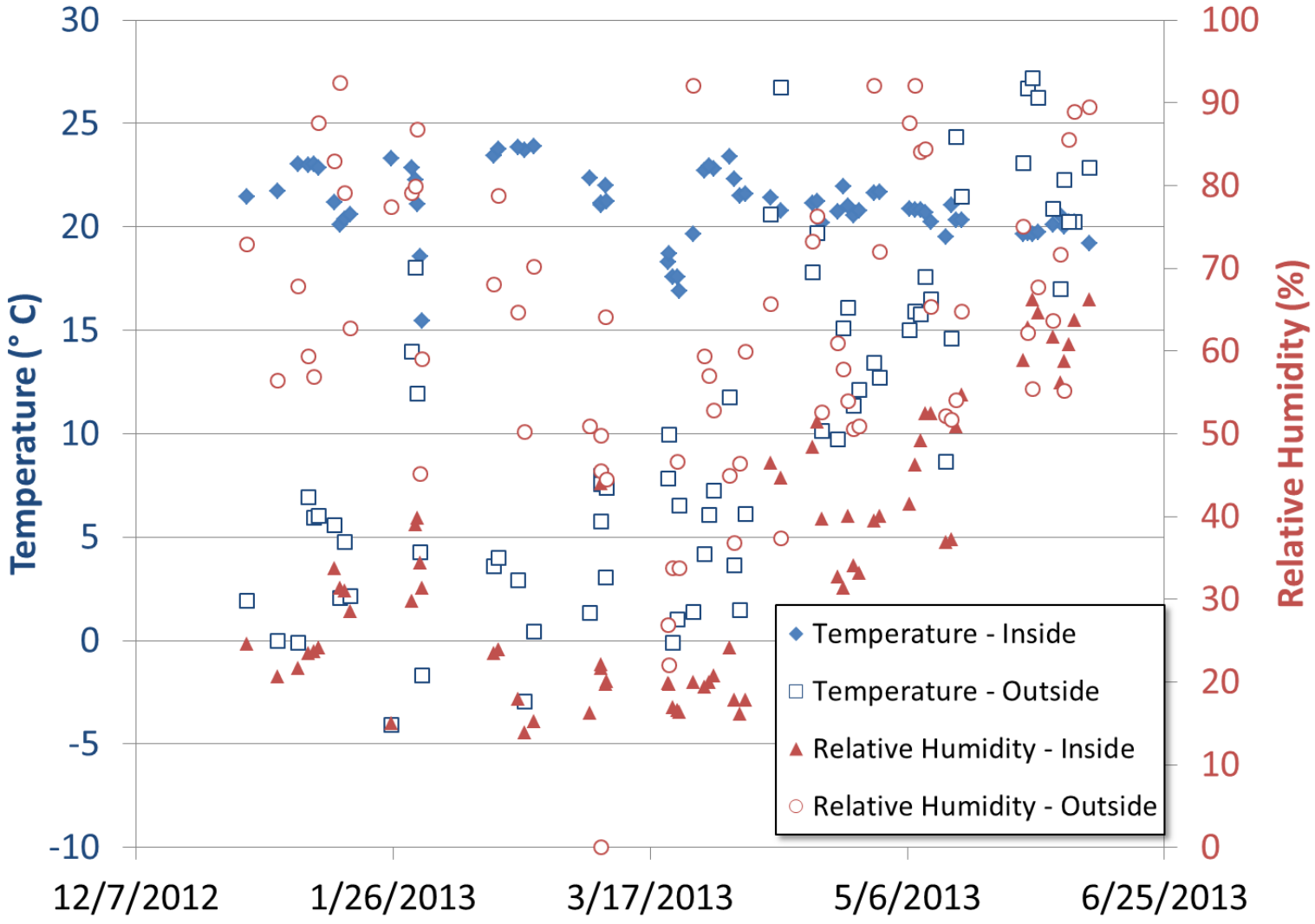

Figure S.2: Variation of average temperature and relative humidity during experiments.

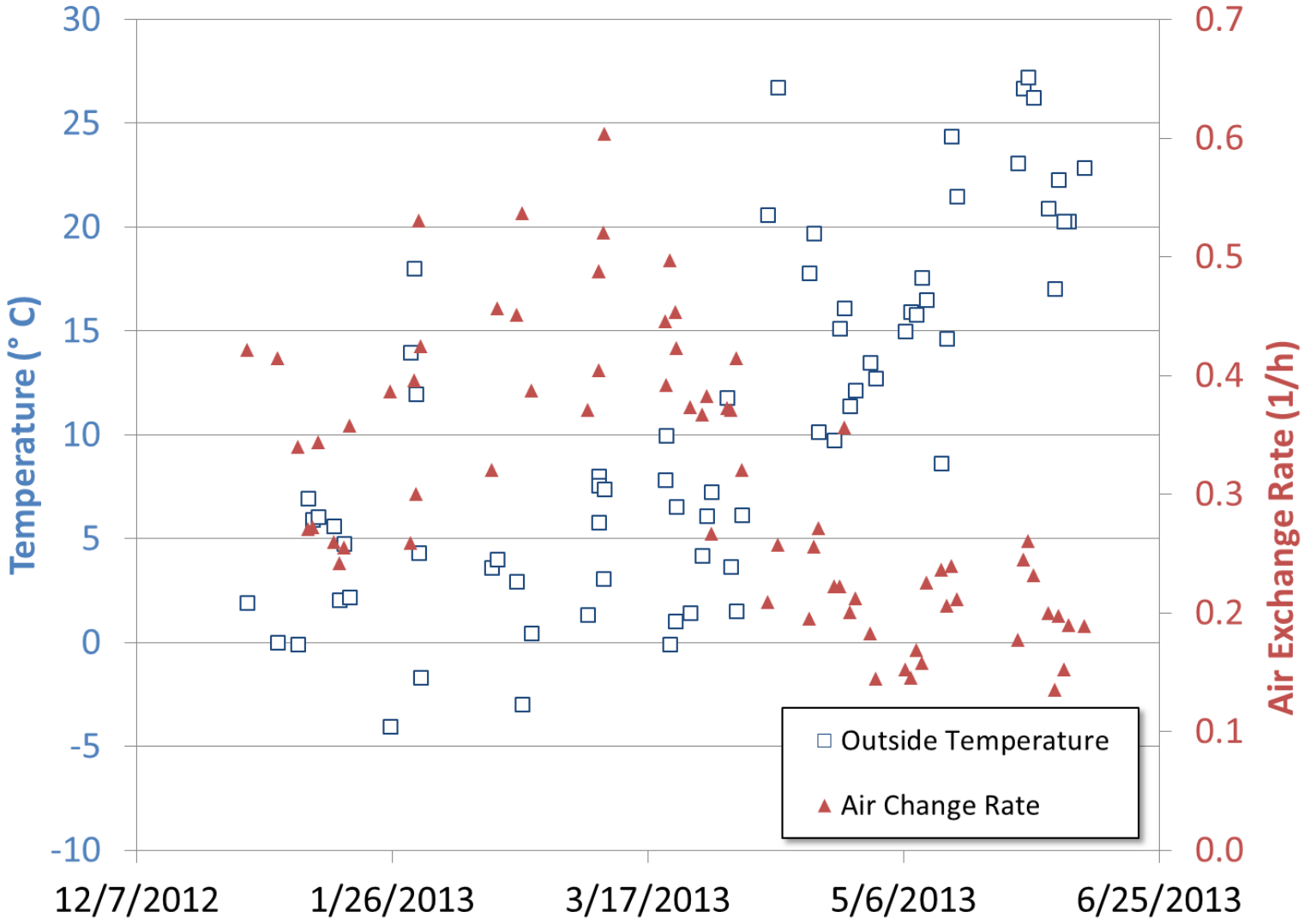

Figure S.3: Variation of average air change rate during experiments.

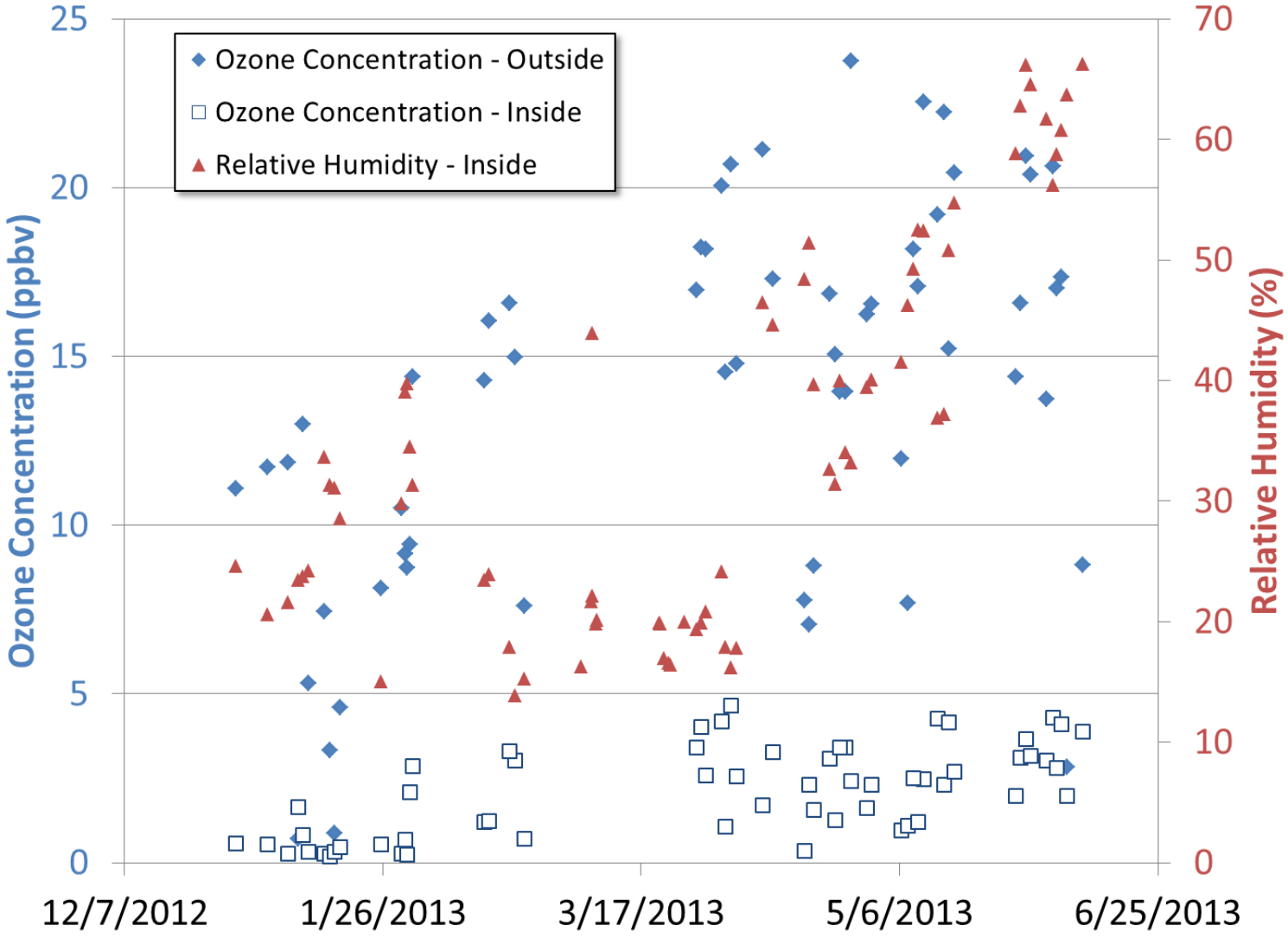

Figure S.4: Variation of average initial ozone concentrations during experiments.

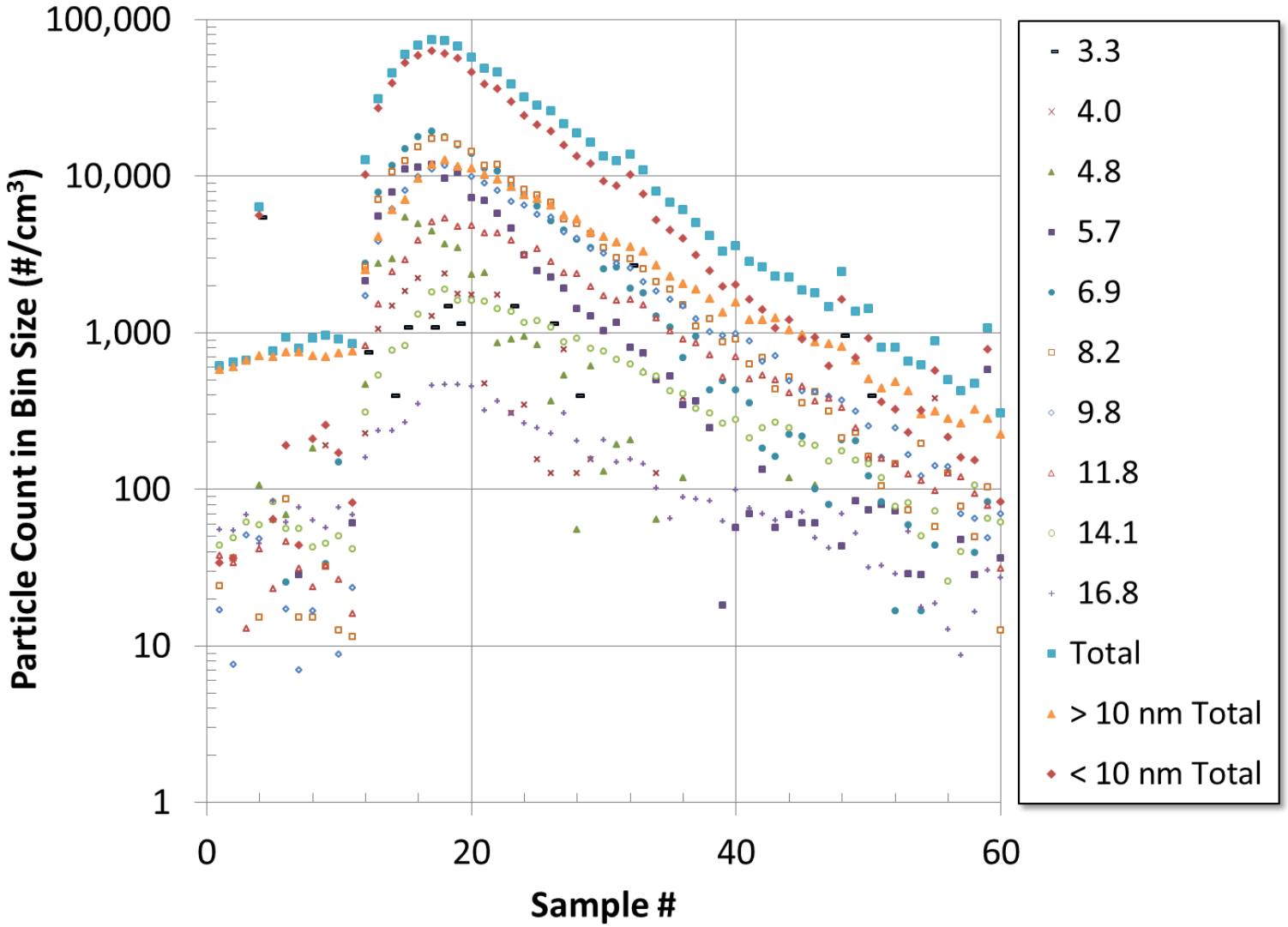

Figure S.5: Illustrative UFP particle concentration for summed bin sizes. Each sample period was 2.5 minutes. Decay rates for this experiment were determined from samples 28-40 (when total concentrations dropped below 20,000/cm^3). Numbers in the legend are the mean particle size for the bin.

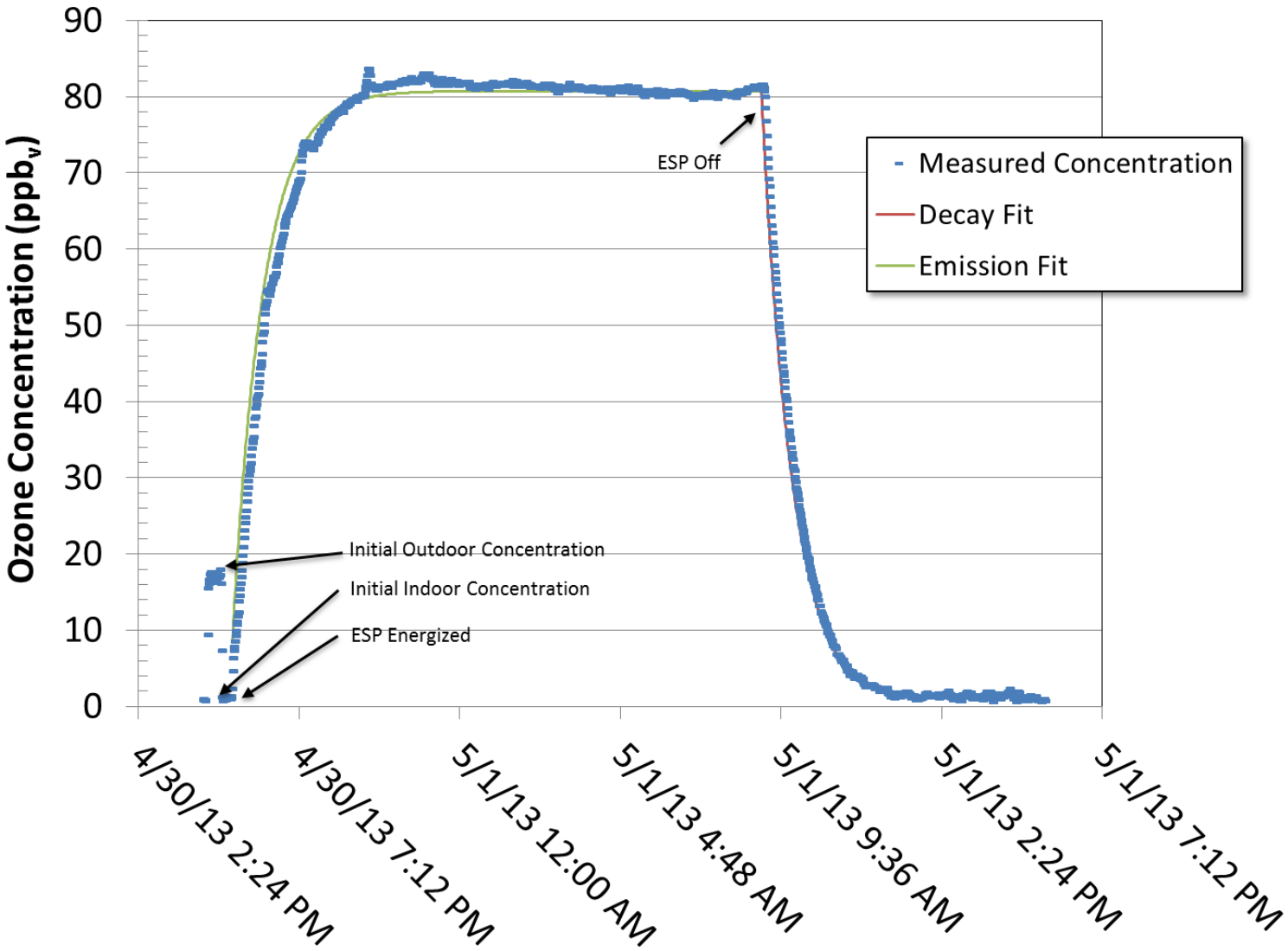

Figure S.6: Illustrative ozone concentration profile for experiment without an activated carbon filter (2 B *b* -).

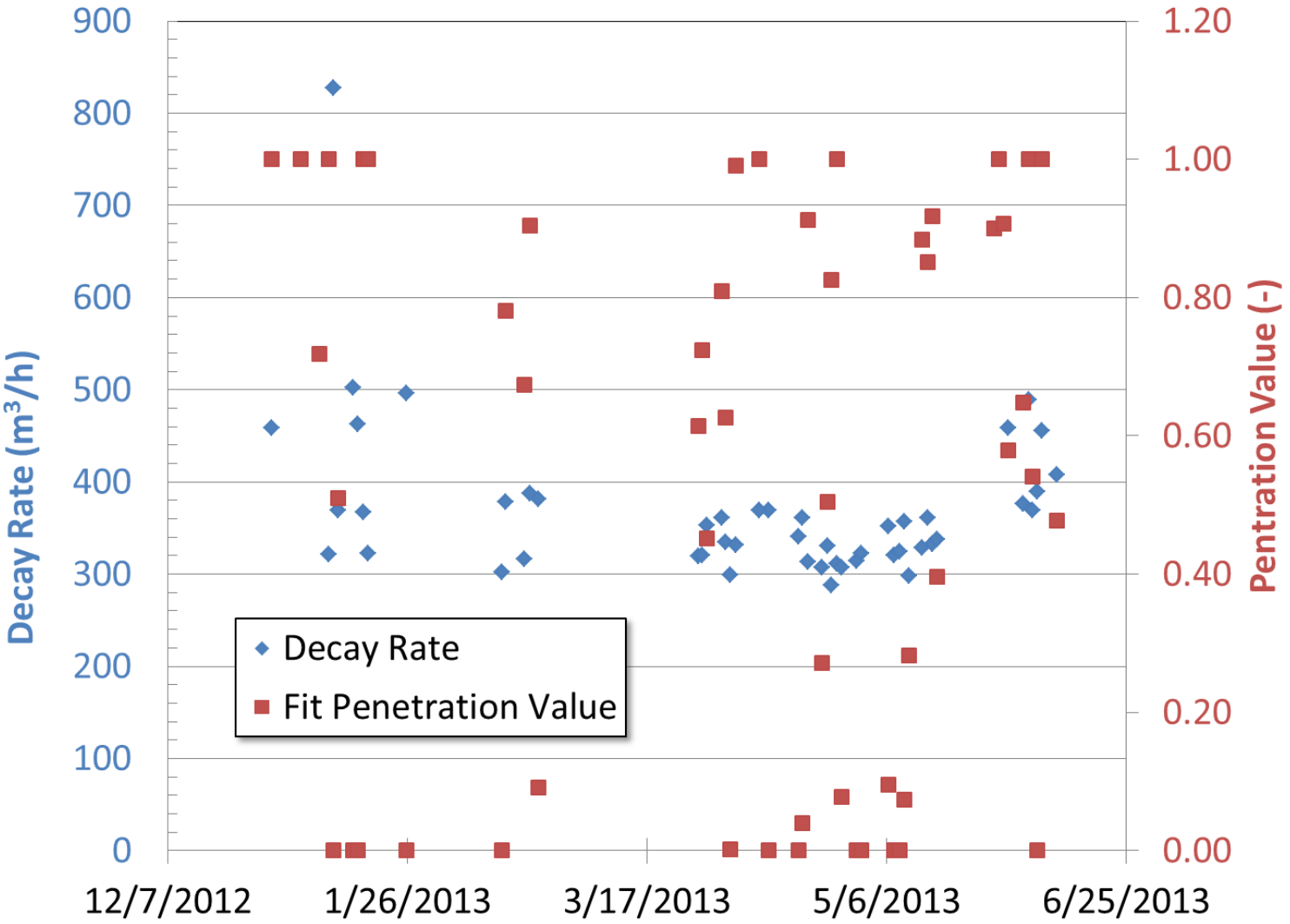

Figure S.7: Variation of whole house decay rate (K_H) and ozone penetration rate (p) during experiments.

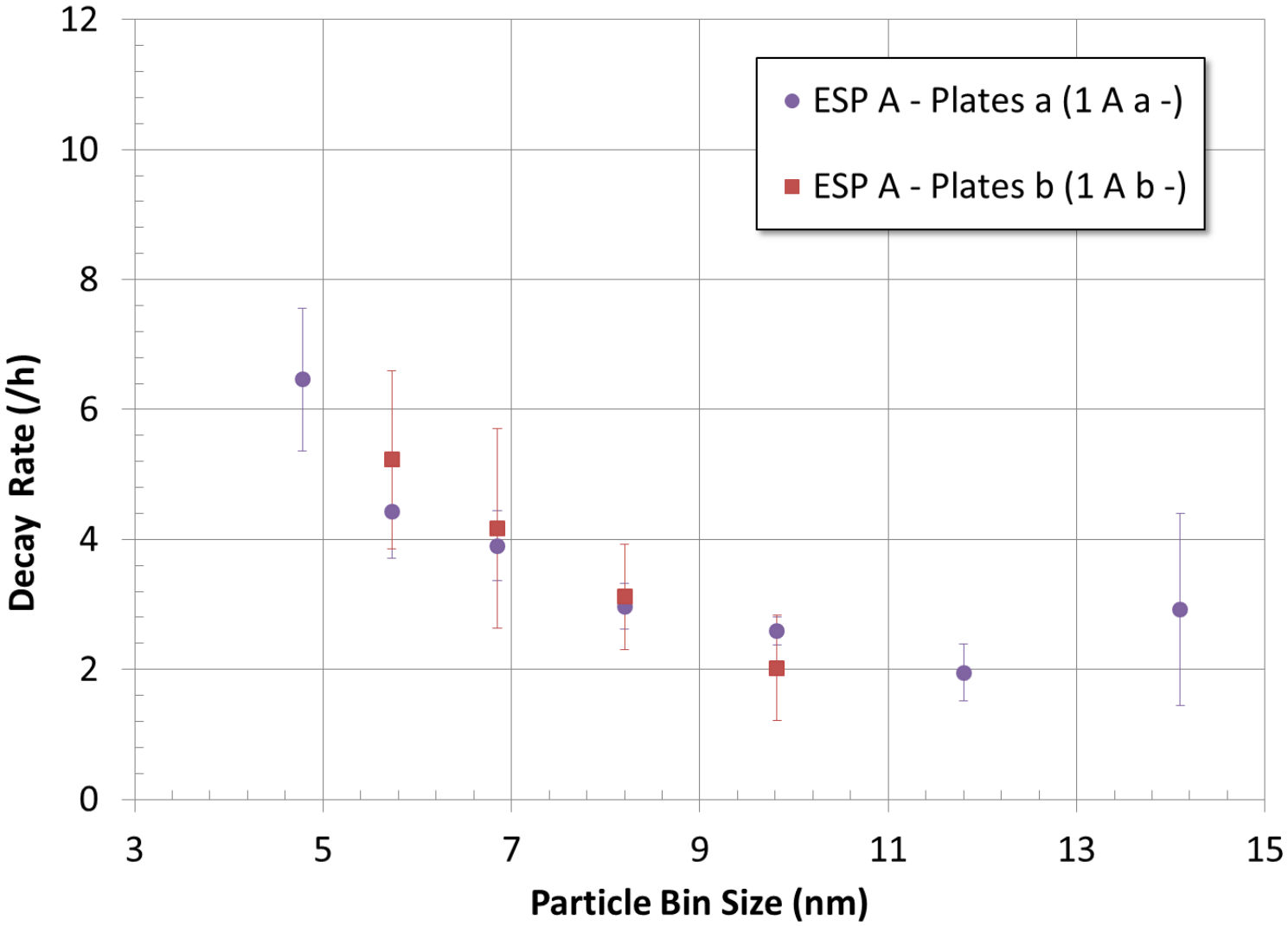

Figure S.8: A comparison of particle decay rate for each bin size for two different plates in the same ESP. Error bars represent expanded uncertainty with a coverage factor of 2.

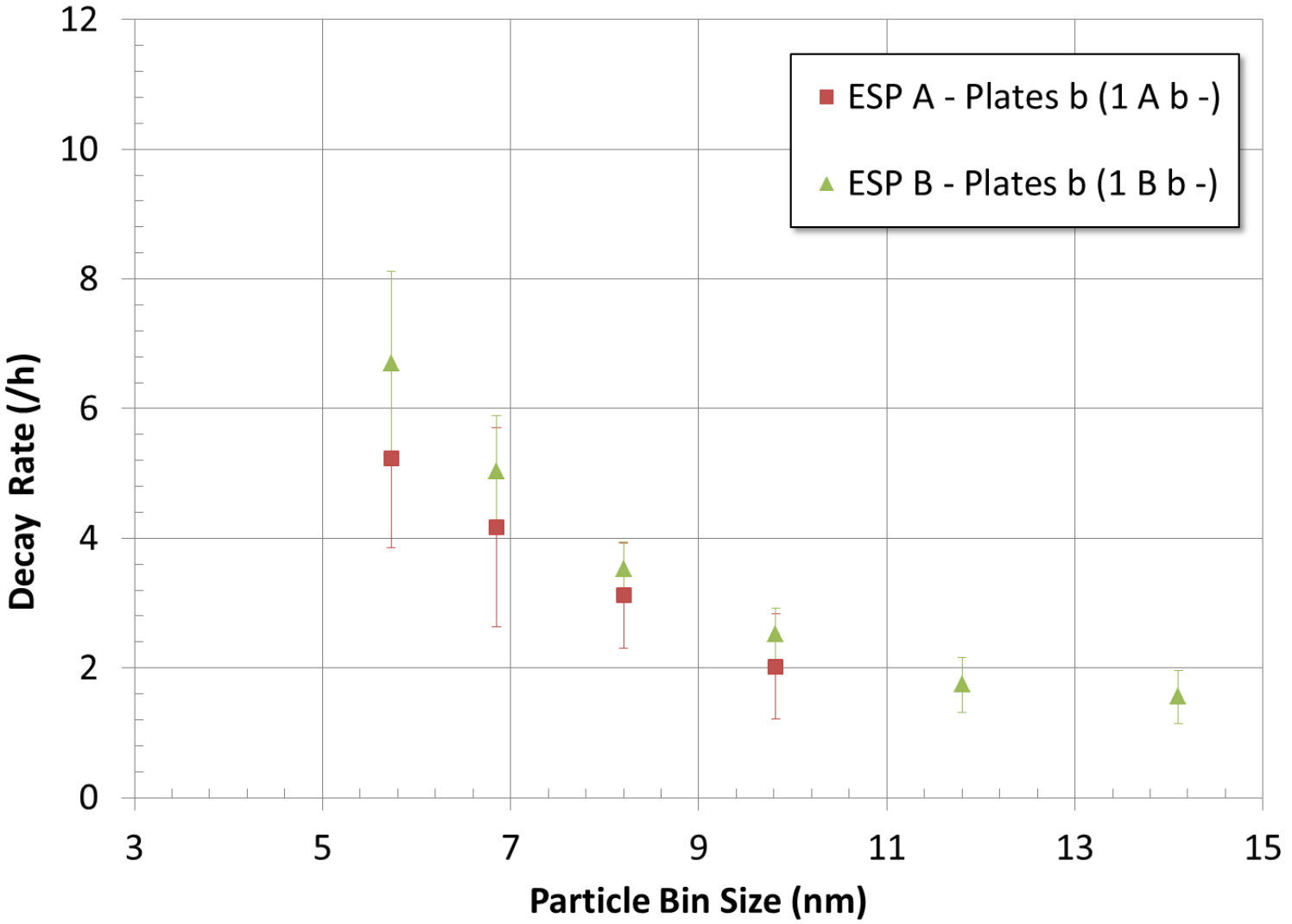

Figure S.9: A comparison of particle decay rate for each bin size for one set of plates in the same ESP. Error bars represent expanded uncertainty with a coverage factor of 2.