

# The By-Product of Ozone from Electrostatic Air Cleaners

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## ABSTRACT

Indoor Air Quality (IAQ) contributes to the health and comfort of people living and working indoors. Poor IAQ can be linked to indoor and outdoor sources of contaminants. One recent solution for improving IAQ is the use of Electrostatic (ES) air cleaning technology. An ES air cleaner can be installed in a heating, ventilation, and air conditioning system where it pre-filters large dust particles and shocks smaller particles into a collection tray. However, ES air cleaners have been known to give off ozone as a by-product, which is, itself, an air contaminant. Ozone is found outdoors as product of sunlight combining nitrogen oxides and volatile organic compounds generated from man-made pollution. Indoor ozone concentration will depend on the introduction of outdoor ozone indoors through natural ventilation, mechanical ventilation, and infiltration through the building's envelope (in order of importance). Two different ES air cleaners, A and B, were installed in the air conditioning system of research house #2 of the TRANE Residential Heating and Cooling Research Lab at the University of Texas at Tyler. A series of ozone experiments were conducted, which included measuring the baseline ozone levels at the research houses with different levels of insulation, observing the increase in ozone due to the powering on of mechanical ventilation, and observing the increase in ozone due to the powering on of the installed ES air cleaners. The baseline ozone levels observed in research house #2, whose envelope is more tightly insulated, was found to be lower than in research house #1 whose envelope is less tightly insulated. With regards to mechanical ventilation, an increase in ozone levels were seen in addition to an even higher increase in ozone levels when the ES air cleaners were powered on in tandem. In terms of the single contribution of the ES air cleaners in raising indoor ozone levels, the data shows that although the ES air cleaners increased the ozone concentration in the house, the levels are not of concern as they were less than the FDA limit on indoor ozone generation.

## KEYWORDS

Indoor Air Quality; Ozone; Electrostatic Air Cleaner; Infiltration; Mechanical Ventilation; HVAC; Pollutant; Indoor Contaminant

## INTRODUCTION

Indoor Air Quality (IAQ) refers to the quality of air within and around buildings and structures.<sup>1</sup> IAQ contributes to the health and comfort of people living and working indoors where most of our lives, around 90%, are spent. Indoor concentrations of pollutants can be up to two to five times the concentration found outdoors, depending on indoor sources, which can lead to lack of productivity and negative health effects for indoor residents.<sup>2,3</sup> The primary causes for a deficiency in IAQ include indoor sources of air pollutants, and the infiltration of outdoor pollution. Outdoor air contamination enters a residential house through cracks and openings in the house's envelope. The most common indoor pollutants include fine particulate matter (PM), volatile organic compounds (VOCs), and carbon dioxide (CO<sub>2</sub>); in addition to ozone (O<sub>3</sub>), which is the contaminant of consideration in this study.

One solution for improving IAQ, in the abatement of indoor contaminants, have been air cleaners. There are different technologies for air cleaners such as photocatalytic oxidizers (PCO) air cleaners and electrostatic (ES) air cleaners, etc. However, even though air cleaners assist in reducing contaminants, some are known to give by-products of another contaminant.<sup>4</sup> Electrostatic air cleaners work to reduce PM in an indoor environment; however, they are known to produce ozone as a by-product. They are sold as portable air cleaners placed in singular locations and air cleaners installed in-duct that work to clean the air in all rooms integrated in the heating, ventilation, and air conditioning (HVAC) system.

Ozone is a highly reactive gas, composed of three oxygen atoms. At the stratospheric level, the earth's upper atmosphere, ozone is formed through the interaction of solar radiation with molecular oxygen. Stratospheric ozone is essential as it protects the surface of the earth from harmful ultraviolet (UV) radiation from the sun. Tropospheric ozone is harmful because of its proximity to humans at ground or "breathing" level as an air contaminant. The EPA has an air quality index (AQI) related to 8-hour averages of ozone concentrations separated in categories classified as good (0-54 ppb), moderate (55-70 ppb), unhealthy for sensitive groups

(71-85 ppb), unhealthy (86-105 ppb), very unhealthy (106-200 ppb), and hazardous (201+ ppb). The EPA also states that a 2-hour average of 600 ppb ozone concentration is considered a significant harmful level with imminent effects.<sup>5</sup> Tropospheric ozone is considered the outdoor ozone that surrounds buildings and structures. Outdoor ozone is found outdoors as product of sunlight combining nitrogen oxide (NO<sub>x</sub>) and VOCs generated from automobiles and coal-fired power plants. In addition to VOCs generated from trees and vegetation. This leads to urban areas having higher levels of outdoor ozone than rural areas where there is less pollution. This is also why outdoor ozone is higher in the daytime and, seasonally, in the summertime where there is more sunlight in comparison to wintertime. Geographical location and meteorological conditions are also factors in outdoor ozone concentrations in terms of the production and transport of outdoor ozone.<sup>6</sup>

Indoor ozone concentration will depend on the introduction of outdoor ozone indoors through natural or mechanical ventilation, and infiltration through the envelope. Indoor ozone concentrations will also depend on known indoor sources of ozone by some electrical devices that give off ozone as by-products. Such as electrostatic (ES) air cleaners, photocopiers, laser printers, etc.<sup>7</sup> FDA standard (21CFR801) is related to products that emit ozone as a by-product. The standard states that devices that generate ozone as a by-product should not generate ozone in excess of 50 ppb or parts-per-billion. This concentration is related to both the volume of air circulating through the device or an accumulation of ozone in an enclosed space intended to be occupied by humans. Enclosed spaces include houses, apartments, hospitals, and offices.<sup>8</sup>

This paper focuses on the contribution that two in-duct ES air cleaners, A and B, had in raising indoor ozone concentrations. This paper also presents literature on meteorological factors that influence outdoor ozone, and the effect of envelope characteristics on the indoor infiltration of outdoor ozone. Two ES air cleaners, identified as A and B to avoid mentioning brands, were evaluated for their contributions in raising the indoor ozone concentration at one of the two test and research houses at the University of Texas at Tyler. Additional ozone experiments were run to read baseline indoor ozone levels, indoor ozone levels with the introduction of mechanical ventilation, and a comparison of indoor ozone concentrations between the two houses that have different construction characteristics.

*Characterization of the tropospheric boundary layer and outdoor ozone*

The earth's surface layer is a part of the tropospheric boundary level (BL) which is the lower-level atmosphere that is affected by the friction and transfer of heat from the earth's surface. The tropospheric BL develops periodically throughout the day. In the morning, sunlight heats the earth's surface creating a transfer of heat into the atmosphere; eroding the stable layer formed overnight through radiational cooling. The new BL combines surface heating and wind turbulence and creates what is known as the mixed layer, reaching its maximum depth in the afternoon. The rapid growth of the mixed layer coincides with the mixture of outdoor pollutants.<sup>9</sup> As the sun sets, and solar radiation decreases, a new stable nocturnal BL is established which leads to the discontinuity of pollutants at this level. However, there is a residual layer at a higher elevation that contains pollutants from the daytime. An example of the diurnal cycle can be found in *Jacob, J. D.*<sup>10</sup>

Ozone is produced photochemically by the oxidation of methane, carbon monoxide (CO), and non-methane hydrocarbons (NMHCs) in the presence of nitrogen oxides and sunlight. This process leads to ozone having strong diurnal variations near the earth's surface layer. During the afternoon, mixing ratios of outdoor ozone increase at its highest coinciding with the combined effect of photochemical production and the mixing of ozone rich air masses from the residual BL. At nighttime, mixing ratios of outdoor ozone are at its minimum due to dry deposition and a lack of solar radiation in the shallow nocturnal BL.<sup>11</sup> Dry deposition is when particles are removed from the atmosphere due to gravity.<sup>12</sup>

*Diurnal and seasonal characteristics of outdoor ozone*

The diurnal and seasonal cycle of outdoor ozone can be related, generally, to solar radiation as stated in the *introduction*. This correlation is illustrated by a study that was conducted by the Department of Environmental Sciences at King Abdulaziz University (KAU) which observed the diurnal and seasonal variations in Yanbu, Saudi Arabia. **Table 1** shows the minimum and maximum outdoor VOC concentrations seen in a diurnal cycle for four seasons, respectively.<sup>13</sup>

	Winter	Spring	Summer	Autumn
Maximum VOC concentration (ppb) / Hour of occurrence	28/17.5	39/12.5	36/11.5	32/14.5
Minimum VOC concentration (ppb) / Hour of occurrence	8/8.5	12/7.5	13/7.5	10/7.5

Table 1. Maximum and minimum VOC concentrations seen in a diurnal cycle for four seasons.<sup>13</sup>

A couple of things can be concluded from **Table 1**. One is related to the diurnal cycle of outdoor ozone. The minimum concentrations of ozone occurred at early hours (7:30 or 8:30 AM) for every season. The maximum concentrations of ozone

occurred at later hours (11:30 AM, 12:30 PM, 2:20 PM, or 5:30 PM) for every season. This is consistent with the characteristics of the diurnal cycle of outdoor ozone, showed to follow the development of the tropospheric BL mentioned in the *Characterization of the Tropospheric Boundary Layer and Outdoor Ozone* section. Outdoor ozone from the residual BL is further mixed and created as solar radiation increases throughout the day. Outdoor ozone levels reach their peak at the height of sunlight. As the sun sets, and solar radiation decreases, outdoor ozone concentrations begin to diminish and stabilize into the nocturnal BL. Another conclusion from **Table 1** is that outdoor ozone has a seasonal cycle. The highest range of outdoor ozone concentrations is seen in the spring followed by summer, autumn, and is lowest in the winter. A ranking of months which can also be related to the amount of solar radiation seen in those months.

#### *Trends of outdoor ozone in areas of different urbanization*

For the most part, outdoor ozone levels are higher in urban areas than rural areas. Higher levels of nitrogen oxides and man-made VOCs are found in urbanized areas which combine under sunlight to produce ozone. This process is as follows and is shown in **Equations 1 through 3**. Nitric oxide (NO) from the oxides of nitrogen (emitted mainly from fossil fuel combustion) mix with existing ozone (O<sub>3</sub>) into nitrogen dioxide (NO<sub>2</sub>) and oxygen (O<sub>2</sub>). The nitrogen dioxide is later photo-dissociated (hv) back into nitric oxide and a singular oxygen atom. The singular oxygen atom then combines with oxygen compounds to form ozone with a third stabilizing molecule (M) that works to remove excess energy.<sup>14</sup>



The Greek research article “Indoor Air Pollution: The Case of Ozone in Three Regions in Greece” included the dependence of outdoor to indoor ozone concentration ratios on the degree of urbanization.<sup>15</sup> A full diurnal cycle of data was taken from the metropolitan city of Athens and the less-urbanized Zakynthos Island. Outdoor ozone levels peak much higher in Athens than Zakynthos island. The maximum outdoor ozone concentration seen in Athens was 90 ppb and 55 ppb in Zakynthos. Higher levels of outdoor ozone translate to higher indoor levels of ozone as well. The maximum indoor concentrations of ozone seen in Athens was 55 ppb and 25 ppb in Zakynthos Island. The comparison of the two cities illustrates how more urbanized areas with more pollution contribute to higher levels of outdoor ozone which translate to higher indoor levels of ozone. It is important to state that high outdoor ozone concentrations can be seen in rural areas due to the transportation of ozone which will be discussed in the following section.<sup>16</sup>

#### *The effect of wind on the transportation of outdoor ozone*

Ozone can be transported from major cities into rural areas with the downwind of ozone and its precursors (NO<sub>x</sub> and VOCs). Outdoor ozone levels in urban areas peak during afternoon hours at the height of sunlight intensity. Rural areas where outdoor ozone levels are high, usually peak in outdoor ozone levels in the late afternoon or evening from the ozone transported from more urbanized areas. Depending on wind speeds and patterns, outdoor ozone levels can be transported hundreds of miles downwind. There is a map in **EPA** that shows a map of the US with four colors representing four ranges in outdoor ozone concentration. The darker colors highlight areas which have higher levels of outdoor ozone.<sup>6</sup> For the most part, the darker colors are seen in areas with major cities that are highly urbanized. However, the rural areas around the urbanized areas experience heightened levels of outdoor ozone. Just at lower concentrations. This effect can be linked to wind patterns.<sup>6</sup> The Commission for Environmental Cooperation (CEC) has a report on the long-range transport of ground level ozone and its pre-cursors. The report states the regional extent of high outdoor ozone concentrations from urbanized regions with high pre-cursor emissions is highly dependent on wind patterns. During low-speed wind cycles, heightened ozone levels tend to remain near the region of formation<sup>14</sup>.

A study named “Influence of local meteorology and NO<sub>2</sub> conditions on ground-level ozone concentrations in the eastern part of Texas, USA” included an analysis on the effect that wind speed, wind direction, and nitrogen dioxide had in the concentrations of outdoor ozone. The study collected data from various monitoring stations in east Texas counties. In the correlation analysis, it was found that increases in nitrogen dioxide levels led to higher levels of outdoor ozone. The two variables had positive correlation coefficients through the course of a week in May. The coefficients were significant at a significance level of 1%. Variations were seen in the locations of maximum ozone with respect to time, even though the maximum concentrations of nitric dioxide were measured near the region of formation. Which leads back to the principle of the transportation of ozone due to wind.

The study observed the transportation of high outdoor ozone concentrations from regions of high nitric dioxide levels based off wind speed and direction. Seven days were chosen for observation with the help of spatial distribution maps of ozone, which were used to identify the movement of high outdoor ozone levels. On days that significant wind patterns were observed, high levels of outdoor ozone were observed in areas around the regions of formation. These areas were found to be in the direction of wind moving from the regions of formation. On the days that wind speeds intensified; high outdoor ozone levels were transported to a greater extent in the direction of the prevailing winds. On days that the wind speed were not as strong, no significant transportation of ozone was seen. The study concluded that the distribution patterns of outdoor ozone were definitely influenced by wind speed and direction.<sup>17</sup>

*Infiltration of outdoor ozone into an indoor environment*

Outdoor ozone can infiltrate a building’s envelope in three different ways. Through cracks and openings in the exterior, natural ventilation, and mechanical ventilation. A parameter used for measuring the infiltration of outdoor in an indoor environment is the I/O ratio. The I/O ratio relates the concentration of indoor ozone as a percentage of outdoor ozone concentrations. Each of the three paths of infiltration have different I/O ratios. Differences in I/O ratios between the two types of ventilation are due to the fact that outdoor ozone will pass through more filtering in mechanical ventilation than natural ventilation. Infiltrations through cracks and exterior opening have the smallest effect in raising the I/O ratio and will depend on the tightness of the building’s envelope.

A study called “Study of outdoor ozone penetration into buildings through ventilation and infiltration” observed I/O ratios under the three paths of outdoor ozone infiltration. The study included the summary of a literature review on I/O ratio values seen in 385 houses for the three paths of infiltration. I/O ratios were listed as 0.09, 0.19, and 0.47 for infiltration, mechanical ventilation, and natural ventilation respectively. These values corresponded to median air exchange rates, or air changes per hour (ACH), and surface deposition rates. The study concludes listing the paths of infiltration in order from lowest to highest I/O ratios. This means that natural ventilation led to the biggest infiltration of outdoor ozone indoors, followed by mechanical ventilation, and infiltrations through cracks.<sup>18</sup>

Another study investigated, “The impacts of building envelope design on indoor ozone and health exposures in residential houses”.<sup>19</sup> Data was recorded in four rooms, from three houses with old construction, with different exterior finishes and levels of tightness. None of the houses had any significant sources of indoor ozone such as photocopiers or printers. The houses were occupied with no restriction on their daily routines, and data was taken over the period of 10 days. The constructions of the four envelopes with their respective I/O ratios are summarized in **Table 2**.

Envelope	Exterior Wall Finish	Wall surface area (ft <sup>2</sup> )	Window Perimeter (ft)	Window to Wall Ratio	Wall Thickness (in)	I/O ratios
1	Stucco	143	33	0.21	11.0	0.49±0.24
2	Brick	134	33	0.22	16.0	0.52±0.18
3	Brick	176	61	0.30	12.5	0.68±0.19
4	Painted fiber cement siding	79	31	0.95	9.8	0.48±0.2

**Table 2.** Construction of envelopes 1, 2, 3, and 4.<sup>19</sup>

The factors of the envelopes were statistically analyzed and correlated with indoor ozone concentrations. The study found that the envelope construction variables that played important roles in influencing indoor ozone concentrations were exterior wall finishing and window to wall ratio. Exterior materials can chemically react with outdoor ozone and diffuse ozone before it penetrates indoors. The study reveals mixed effects from the window to wall ratio. The study concluded that the construction variables observed in the study are reasonable predictors of indoor ozone levels.

*Generation of ozone from ES air cleaners*

In-duct ES air cleaners, installed in HVAC systems, are manufactured to remove a wide range of airborne particles. The standard operating procedure for ES air cleaners consists of three parts which include ionization, collection, and filtering. ES air cleaners first ionize incoming contaminant particles by generating a field of static electricity. The particles are then collected in a series of discharge plates with laminated film envelopes which are separated by a small intermediate distance. The film is a high dielectric material used as an electrical barrier to prevent electric sparks from an electrical discharge.<sup>20</sup> Carbon filters, positioned as the final step in ES air cleaners, are filters that contain granular pieces of carbon. Remaining contaminated particles react chemically with the carbon material and stick to the filter.<sup>21</sup> Thus, preventing the particles from recirculating back into the house. The ionization of the contaminant particles also leads the ionization of oxygen passing through the ES air cleaner. The formation of ozone through ionization can be simplified in a two-step process as seen in **Equations 4 and 5** where M is a third stabilizing molecule (M).<sup>22</sup>



There is a literature review paper named “Electrostatic Precipitators as an Indoor Air Cleaner—A Literature Review” which summarized publications on ES air cleaners. The paper summarizes aspects related to ES air cleaners design that lead to higher generation rates of ozone, methods of ES air cleaner testing, and results to the extent that in-duct ES air cleaners had in raising indoor ozone levels in a manufactured test house. The extent to which ozone is generated can be related to product design and operating conditions of the ES air cleaner. Some design factors include charging wire diameter and material, geometry of the ES air cleaner, and the applied voltage. With respect to operating conditions of the ES air cleaner, a higher operating setting could lead up to a 50% increase in ozone generation as opposed to a lower setting.<sup>23</sup> A poorly designed ES air cleaner could raise indoor ozone levels above the recommended limit of 50 ppb. For this reason, there are standards given by the California Air Resources Board (CARB) and UL (an accredited standards developer) that are used to certify ES air cleaners in terms of ozone generation with approved test methods.<sup>24</sup> The literature review paper mentioned a study that found the use of the two studied ES air cleaners raised indoors ozone levels by 77 and 20 ppb, respectively, with the study concluding that the largest influence in ozone production was the brand of the respective ES air cleaner.<sup>25</sup>

Another study, “Characterization of potential indoor sources of ozone”, included the observation of indoor ozone levels in homes with permanently installed ES air cleaners. The study first measured indoor background ozone levels downstream of the air cleaner, powered off. A total of eight in-duct ES air cleaners were evaluated. The blower ran continuously. Then the ES air cleaner was powered on, and downstream ozone was measured. The study decided to measure ozone downstream and near supply registers to measure the maximum possible ozone before dissipating into the house. Two of the measured air cleaners produced ozone. However, these measurable quantities of ozone decayed to non-detectable levels as it passed through the ventilation ducts. The study concludes by stating that the ozone emission rates of the ES air cleaners would not produce concentrations greater than 10 to 30 ppb above background indoor ozone levels.<sup>26</sup>

## MATERIALS AND METHODS

The ozone experiments were conducted at the two test and research houses at the University of Texas at Tyler. The test houses are identical in size and layout with an area schedule of 1,470 square feet (excluding the garage, covered porch, and covered patio). The houses have an interior volume of 11,939 cubic feet and are shown in **Figure 1**. Test house #2 (on the left) has a tight building envelope, while test house #1 (on the right) is draftier. They have a brick exterior finish with a total of nine windows for each house. Neither test houses have regular occupants, nor are they furnished.



**Figure 1.** Test houses at the University of Texas at Tyler.

All experiments included the fan being powered on continuously at 100% allowing for good air mixing within the test house at 4.03 air changes per hour (ACH). Experiment 1 was set to show baseline indoor ozone levels (due to infiltrations only) in house #2. Experiment 2 compared the baseline indoor ozone concentrations of the test and research houses. Experiment 3 highlighted the increase in indoor ozone from experiment 1 due to ventilation, and in experiment 4, the ES air cleaner is powered on. In experiment 5, ventilation was powered off to show the increase in indoor ozone due only to the powering on of an ES air cleaner.

Experimental 6 is identical to experiment 5 with the only difference being that indoor ozone concentrations were measured near supply registers. Experiments 3 through 5 were repeated for both ES air cleaners A and B. Both ES air cleaners were set to their respective max on setting. It important to note that ES air cleaner A had an actual distinction between on and max-on, while ES air cleaner B only had an on option.

The Model 202 ozone monitor from 2B Technologies was used to monitor ozone in the living room. The ozone monitor was zeroed out for every experiment (see Appendix A). Readings from the ozone monitor have an uncertainty of  $\pm 1$  ppb or 2% of the reading. Since all readings inside the house are below 50 ppb, the uncertainty associate to reading inside the house is 1 ppb. The ozone monitor was stationed inside the test house and placed in two different positions throughout all the ozone experiments. For ozone experiments 1 through 4, the ozone monitor was placed on a stool underneath the supply registers as illustrated in **Figure 2**. In ozone experiment 5, the ozone monitor was placed on a ladder about an inch and a half from the ceiling close to the supply registers as illustrated in **Figure 3**. The location of the stool setup was determined as the result of a stratification test and a test that measured the critical point of ozone in the test house (see Appendix B).

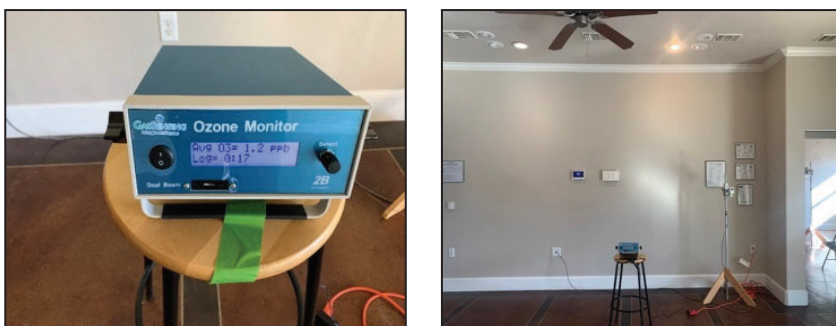


Figure 2. Stool setup for the ozone monitor.



Figure 3. Ladder setup for the ozone monitor.

Figure 4 shows the location of the ozone monitor and the four nearest supply registers with respect to the house layout.

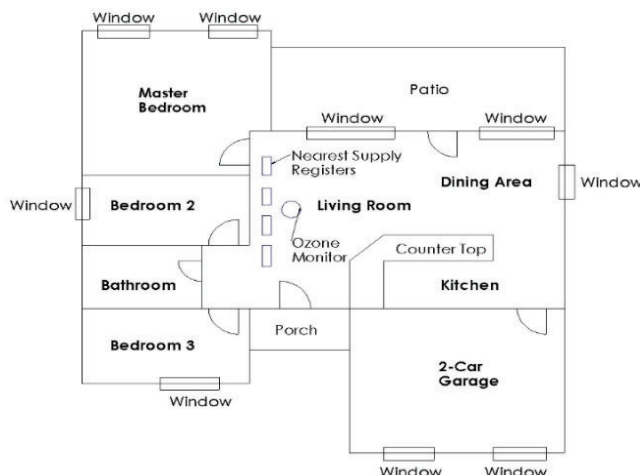


Figure 4. Ozone monitor location and nearest supply registers in house layout.

Table 3 summarizes the purpose of all six ozone experiments.

Experiment	Description	Duration (Days)
1	Baseline indoor ozone levels (due to infiltrations only) in house #2	1
2	Baseline indoor ozone concentrations of both test houses	1
3	Increase in indoor ozone from baseline ozone levels due to mechanical ventilation	ES air cleaner A: 1 ES air cleaner B: 1
4	Indoor ozone levels with ES air cleaner powered on and with mechanical ventilation	ES air cleaner A: 1 ES air cleaner B: 1
5	Indoor ozone levels with ES air cleaner powered on	ES air cleaner A: 2 ES air cleaner B: 3
6	Indoor ozone levels with ES air cleaner powered on (measured at the supply register)	ES air cleaner A: 2 ES air cleaner B: 3

Table 3. Description of ozone experiments.

### RESULTS AND DISCUSSION

For all plots in the results section, the horizontal green line represents the FDA standard 21CFR801 mentioned in the *introduction* and the vertical red line separates days of data.

Baseline indoor ozone levels in UTT house #2

Figure 5 shows the ozone data for ozone experiment 1, which had a duration of 48 hours.

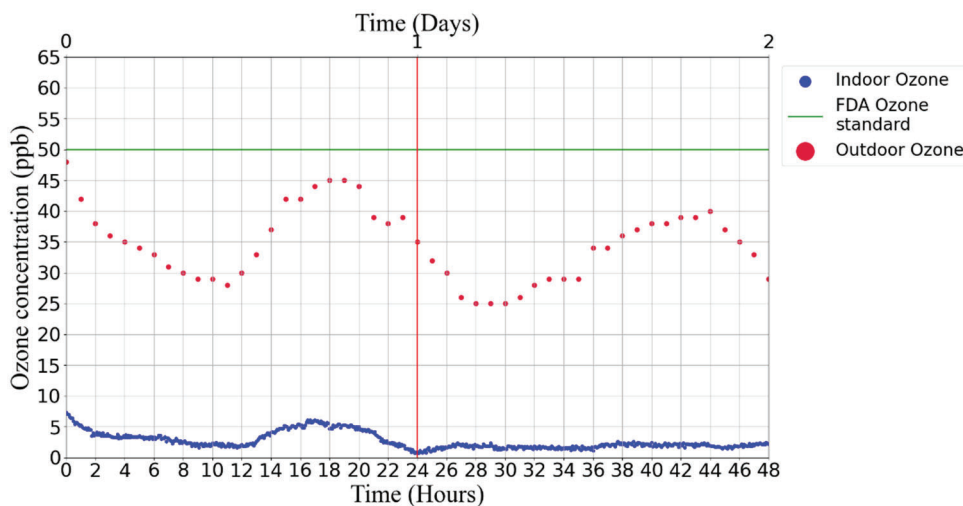


Figure 5. Ozone experiment 1 results for house #2.

Since there is no source of ozone inside the house with the electrostatic filter is off, and no ventilation, levels of ozone can only be affected by infiltrations in house #2. As discussed in the *Infiltration of Outdoor Ozone into an indoors environment* section, I/O ratios tend to be affected the least due to infiltrations and will depend on the tightness of the building’s envelope. This seems to be the case from the data in **Figure 5**. The indoor ozone levels are following the outdoor trend at a very low magnitude. This is representative of the fact that house #2 is constructed with a tight envelope. The average baseline concentration of indoor ozone seen in the house is  $2.7 \pm 1$  ppb, which will be used as a reference for comparison in determining the increase in indoor ozone when the ES air cleaner is powered on.

*Comparison of baseline indoor ozone levels in the UTT test houses*

**Figure 6** shows the baseline indoor levels of ozone in test house 1 and 2 for a period of 24 hours where the outdoor ozone levels were similar.

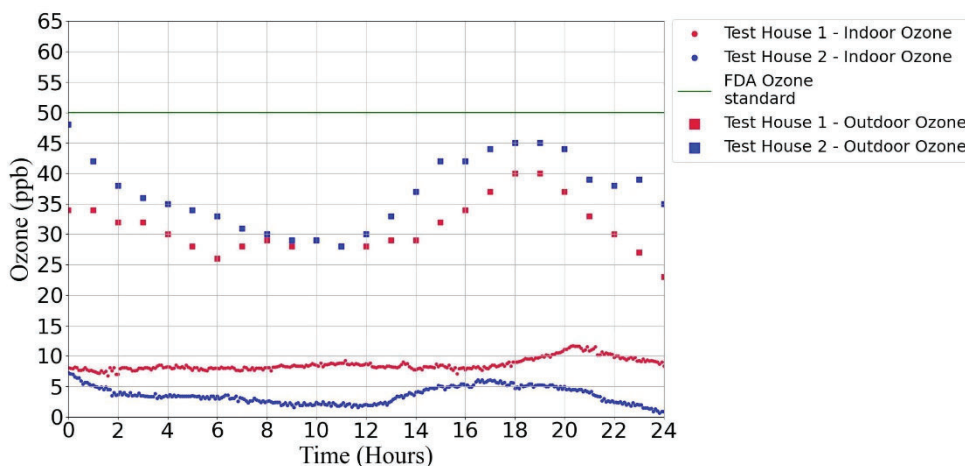


Figure 6. Ozone experiment 2 results for test houses #1 and #2.

Both houses are identical in layout, window to wall ratio, and size (factors related to infiltrations in a house envelope discussed in the *Infiltration of outdoor ozone into an indoors environment* section) with the only difference being that house #2 has a tighter envelope than house #1. Therefore, it can be expected that house #2 will have lower indoor ozone levels than house #1. As seen in the data from **Figure 6**, the indoor ozone levels in house #2 followed outdoor levels at a low concentration (around an average of  $3.6 \pm 1$  ppb), while the indoor levels in house #1 had a higher concentration (around an average of  $8.6 \pm 1$  ppb).

**Figure 7** shows normalized results of both houses in continuity, where the vertical black line separates house #2 (hours 0-48) and house #1 (hours 48-168). The indoor and outdoor ozone levels are normalized in a range from zero to one in percentage of their highest value seen from house #1 and house #2.



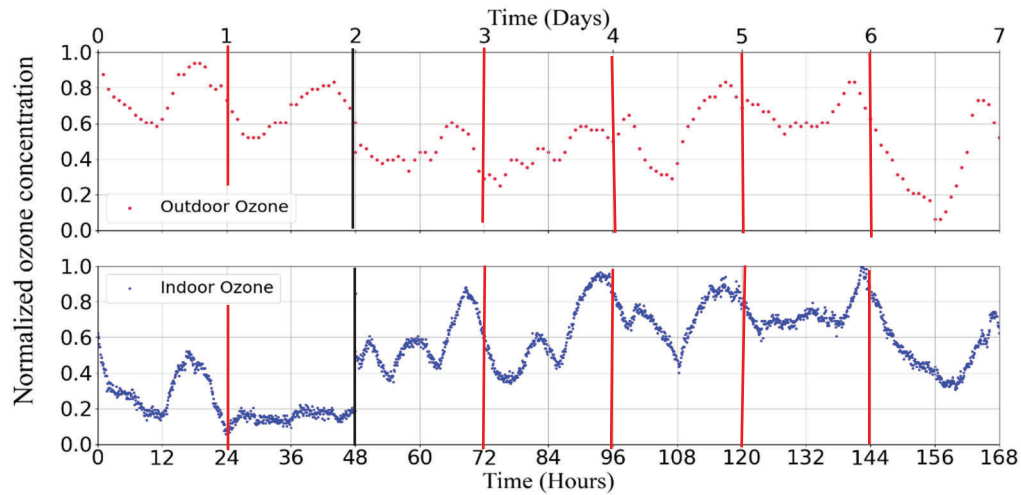


Figure 7. Normalized baseline indoor ozone levels for houses #1 (0-48 hours) and house #2 (48-168 hours).

Figure 7 provides a different visual for the same trends illustrated in Figure 6. House #2 is more air-tight, so the indoor ozone levels follow the outdoor ozone levels at a lower concentration than after the 48-hour mark when the ozone monitor was moved to test house #1.

*Indoor ozone levels with mechanical ventilation in house #2*

Figures 8 and 9 shows the indoor ozone data for ozone experiment 2, which had durations of 24 hours for ES air cleaners A and B respectively.

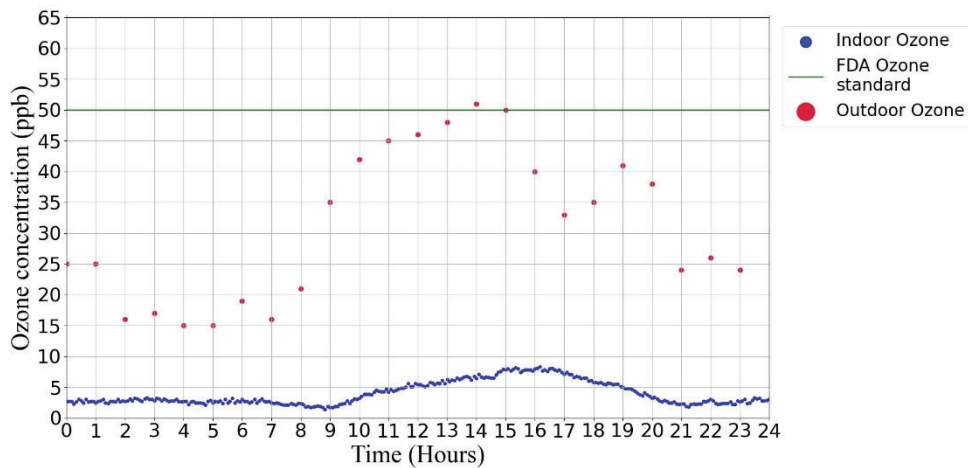


Figure 8. Ozone experiment 3 results during ES air cleaner A's testing.

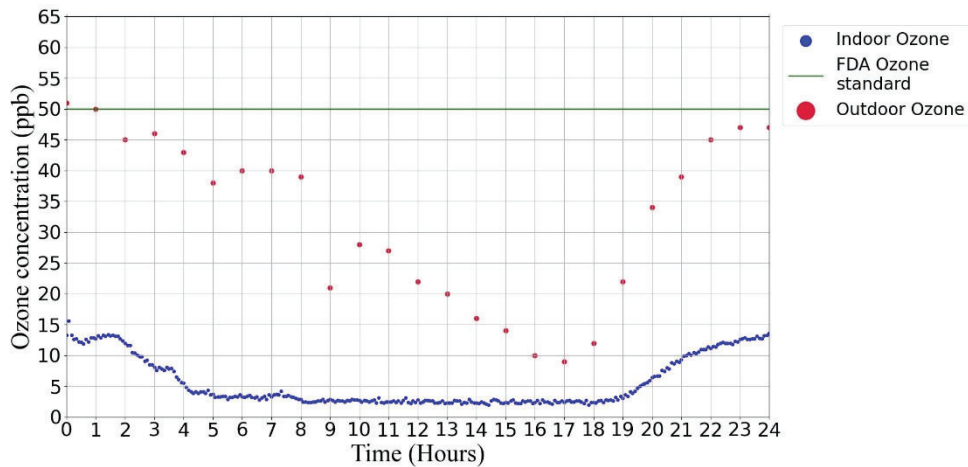


Figure 9. Ozone experiment 3 results during ES air cleaner B's testing.

As discussed in the *Infiltration of outdoor ozone into an indoors environment* section, infiltration through mechanical ventilation and natural ventilation (through the opening of windows and doors) lead to higher I/O ratios. Ozone experiment 3 observes indoor ozone levels in test house #2 based on the influence of mechanical ventilation. With the intake and exhaust ventilators in test house #2 being powered on, outdoor air is being directly introduced into the test house which has higher levels of ozone that is being mixed with indoor air. This causes the indoor ozone level trends to follow outdoor ozone level trends more closely. In terms of magnitude, the I/O ratio increases from baseline indoor ozone levels. One can see higher peaks (hour 16 in **Figure 8** and hours 0 and 24 in **Figure 9**) of indoor ozone levels in ozone experiment 3 as opposed to the peak in indoor ozone levels (hour 17 in **Figure 5**) seen in experiment 1.

*Indoor ozone levels with mechanical ventilation and the powering on of two ES air cleaners in UTT test house #2*

**Figures 10 and 11** shows the indoor ozone data for ozone experiment 4, which had durations of 24 hours for ES air cleaners A and B respectively.

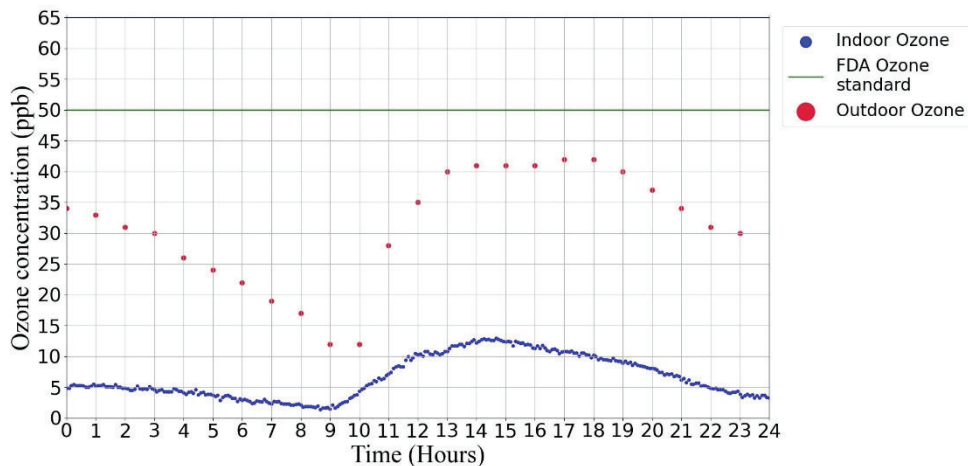


Figure 10. Ozone experiment 4 results during ES air cleaner A's testing.

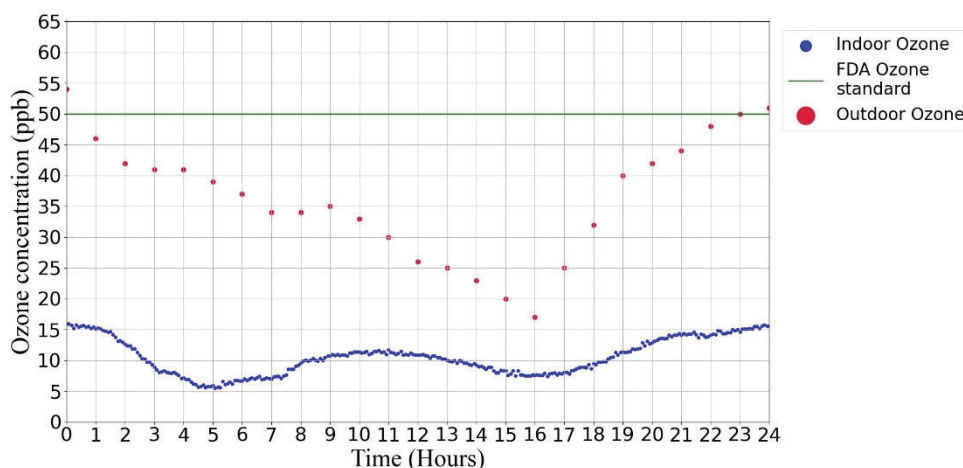


Figure 11. Ozone experiment 4 results during ES air cleaner B's testing.

In ozone experiment 4, outdoor ozone is still being directly introduced into the test house through mechanical ventilation. However, in this ozone experiment, there should be an indication that indoor ozone levels are higher than in ozone experiment 3 since the ES air cleaner is powered on. There is such an indication when comparing ozone experiments 3 and 4 for ES air cleaner A (Figures 8 and 10). Even though lower outdoor ozone levels are seen in ozone experiment 4 in comparison to experiment 3, the indoor ozone levels in the house were higher. A distinction also seen in the testing of ES air cleaner B (Figures 9 and 11) as there was a clear increase in indoor ozone from ozone experiment 3 to 4.

*Indoor ozone levels with the powering on of two ES air cleaners in UTT test house #2*

The results from ozone experiment 5 are shown in Figures 12 and 13 for ES air cleaners A and B respectively. The duration of experiment 5 was 48 hours for ES air cleaner A and 72 for ES air cleaner B.

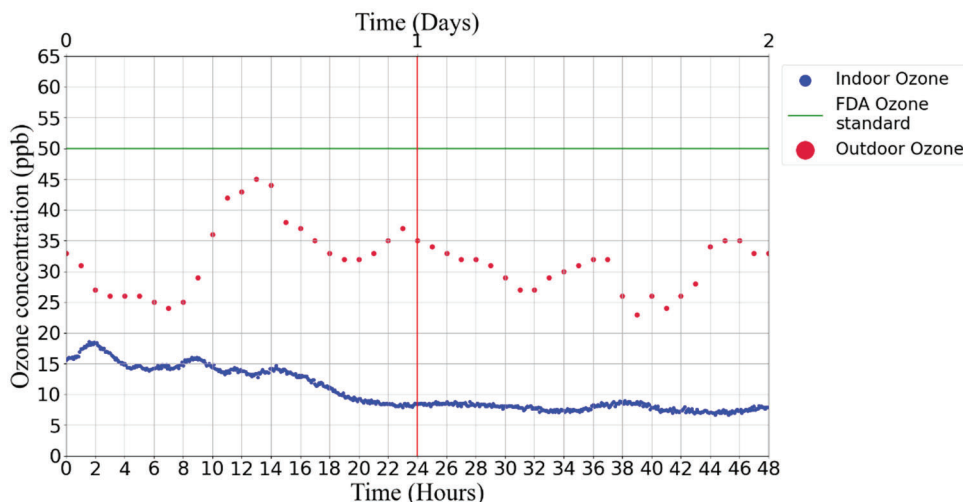


Figure 12. Ozone experiment 5 results during ES air cleaner A's testing.

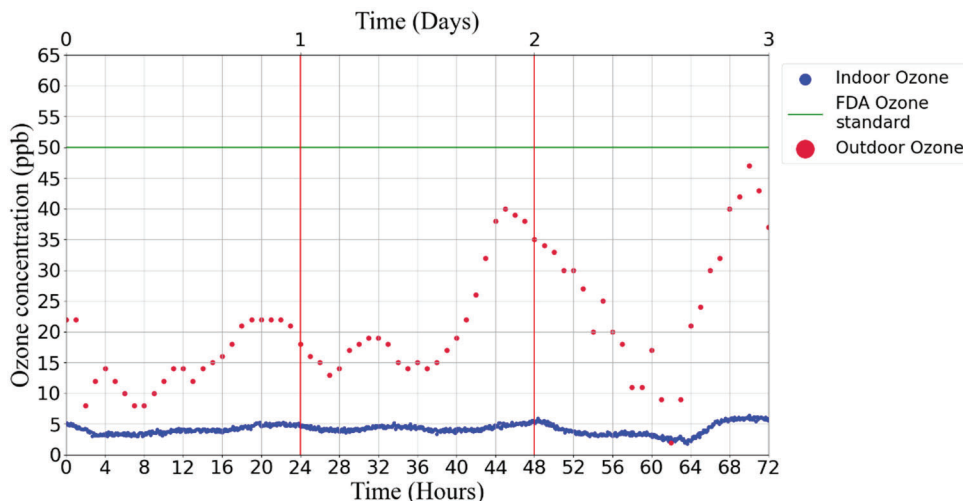


Figure 13. Ozone experiment 5 results during ES air cleaner B's testing.

Ozone experiment 5 allows for a clearer evaluation of the contribution that the ES air cleaners had in raising indoor ozone levels. In experiment 5, the only indoor sources of ozone are the ES air cleaners with indoor ozone levels being influenced by outdoor levels solely through infiltrations. This allows for a distinct comparison to made in indoor levels from ozone experiment 1 and experiment 5. For ES air cleaner A, the inside ozone levels vary around an average of  $10.5 \pm 1$  ppb (Figure 12) where in ozone experiment 1 they vary around an average of  $2.7 \pm 1$  ppb (Figure 5). ES air cleaner A, on max setting, has increased ambient ozone levels in the house by approximately  $7 \pm 2$  ppb. ES air cleaner B seems to increase the indoor ozone concentration only minimally from the ozone concentration in ozone experiment 1. ES air cleaner B contributed to indoor ozone levels that varied around an average of  $4.2 \pm 1$  ppb (Figure 13) leading to an approximate increase of approximately  $1.5 \pm 2$  ppb. As stated in *Generation of ozone from ES air cleaners*, ES air cleaners ionize incoming contaminant particles by generating a field of static electricity. In search of further reducing contaminant particles, different ES air cleaners will generate higher fields of static electricity based on respective design factors and/or higher operation options. Since ES air cleaner A has a maximum-on operation option while ES air cleaner B has an on option only, it is expected that ES air will generate more ozone due to a higher operation level of ionization. It is also important to note that the increases seen with ES air cleaner A and B were at the lower end of the 10-77 ppb increases mentioned in *Generation of ozone from ES air cleaners*.

Both air cleaners contributed to an increase in indoor ozone concentration. The statistical significance of the results was found with a hypothesis test for the difference of means. The averages of indoor ozone for experiment 5 (where the ES air cleaners were the only source of indoor ozone) of both ES air cleaners were compared to average of indoor ozone in experiment 1 (baseline ozone levels). In order for the comparison of both ES air cleaners, data was taken from the first 48 hours of ES air cleaner A's Experiment 5 to match the sample size of ES air cleaner B's Experiment 5. The null hypothesis was that the ES air cleaners did not contribute to higher ozone levels than baseline ozone levels. Both ES air cleaners had p-values of less than 0.00001 when compared to baseline indoor ozone levels, which leads to the data results being statistically significant to a significance level of 95%. This leads to the conclusion that the average indoor ozone concentration is actually higher when the ES air cleaners are powered on and is not just a result due to chance. Nevertheless, the increase in indoor ozone from either of the ES air cleaners did not exceed the FDA 21CFR801 standard of 50 ppb mentioned in the *introduction*.

The results of the final ozone experiment, experiment 6, are shown in Figures 14 and 15 for ES air cleaners A and B respectively. The duration of experiment 6 was 48 hours for ES air cleaner A and 72 for ES air cleaner B.

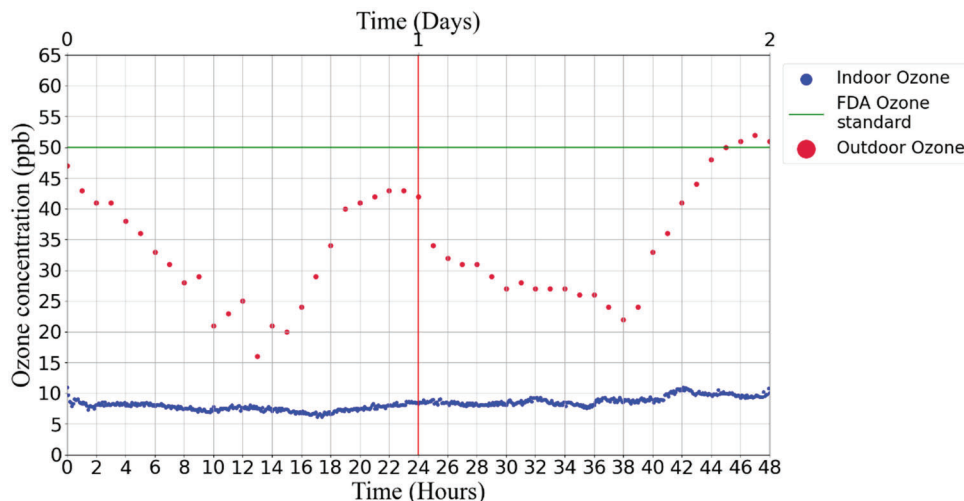


Figure 14. Ozone experiment 6 results during ES air cleaner A's testing.

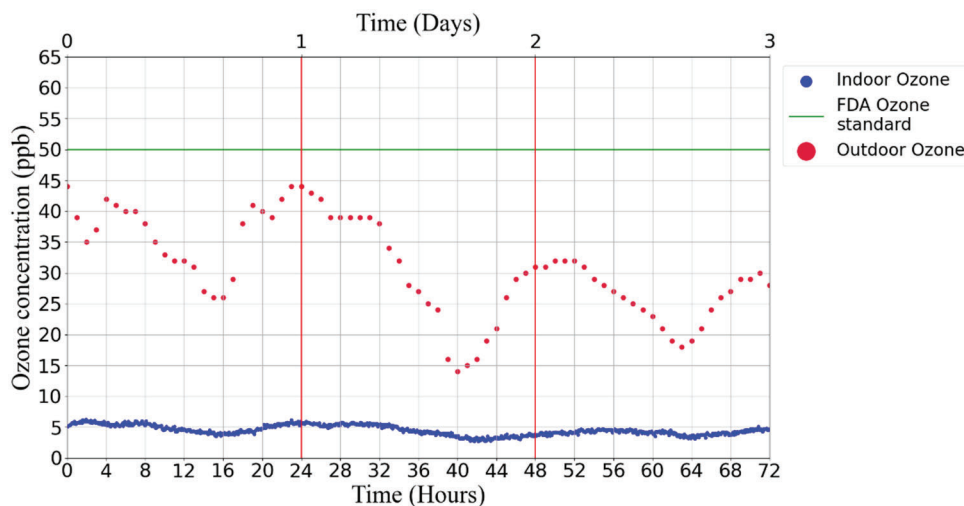


Figure 15. Ozone experiment 6 results during ES air cleaner B's testing.

Ozone experiment 6 focuses on whether there is a significant increase in ozone levels observed near the supply registers than when observed on the living space. The idea is that since the ES air cleaners are producing a by-product of ozone, ozone levels should be higher near the supply registers before diluting with the air in the living space. However, this did not seem to be the case. Indoor ozone levels for both ES air cleaners (**Figures 14 and 15**) seemed to remain very close to the indoor levels in ozone experiment 5 (**Figures 12 and 13**), when the sensor was on a stool. This concept is re-enforced in the stratification of ozone test discussed in *appendix B*.

Table 4 summarizes the results of the different ozone experiments.

Experiment	Result
1	The average baseline concentration seen in test house #2 was 2.7 ppb.
2	The average ozone levels in test house #2 (3.6 ppb) were 5 ppb lower than test house #1 (8.6 ppb).
3	The average indoor ozone levels in test house #2 increased 1.3 and 2.9 ppb for ES air cleaners A and B, respectively from experiment 1 due to the powering on of mechanical ventilation.
4	The average indoor ozone levels in test house #2 increased 2.6 and 5 ppb for ES air cleaners A and B, respectively from experiment 3 due to the powering on of the ES air cleaners and mechanical ventilation.
5	The average indoor ozone levels in test house #2 increased 7.8 and 1.5 ppb for ES air cleaners A and B, respectively from experiment 1 just due to the powering on of the ES air cleaners.
6	The average indoor ozone levels in test house #2 decreased 2.2 ppb and minimally increased by 1.5 ppb for ES air cleaners A and B, respectively from experiment 1 just due to the powering on of the ES air cleaners.

Table 4. Summary of ozone experimental results.

### CONCLUSIONS

The focus of this study was to evaluate the contribution that two ES air cleaners had in increasing indoor ozone concentrations in a research house with additional observations in different factors leading to higher indoor ozone levels. The experiments were conducted in two test houses, #1 and #2, at the University of Texas at Tyler. In test house #2, indoor ozone levels were compared when the ES air cleaners were powered on to baseline indoor ozone levels (indoor ozone levels with no indoor source of ozone and no ventilation). Both ES air cleaners contributed to increases in indoor ozone levels. ES air cleaner A showed an increase in ozone magnitude from 2.7 to 10.5 ppb (approx.  $7 \pm 2$  ppb), while ES air cleaner B showed an increase from 2.7 ppb to 4.2 ppb (approx.  $1.5 \pm 2$  ppb). These results were statistically significant with very low p-values. Even though the ES air cleaners were found to give off a by-product of ozone, neither of the ES air cleaners surpassed the indoor ozone limit for FDA standard 21CFR801 with the ES air cleaner A and B being 39.5 and 45.8 ppb below the 50 ppb ozone limit, respectively. It is also noteworthy that the indoor ozone levels observed at the supply registers were not noticeably higher than ozone levels measured at the living space. The conclusions of the additional experimental findings are that, in test house #2, the powering on of ventilation lead to an increase in the indoor ozone levels from baseline levels with indoor ozone level trends following outdoor ozone level trends closely. An additional increase in indoor ozone levels were seen with the powering on of the ES air cleaners in tandem with mechanical ventilation then when just mechanical ventilation was powered on. Also, a comparison of baseline indoor ozone levels was made for test houses #1 and #2. Higher levels of indoor ozone were seen in test house #2 which has a tighter exterior envelope than test house #1.

### NOMENCLATURE

Symbol and Acronyms	Description
UTT	University of Texas at Tyler
IAQ	Indoor Air Quality
ES	Electro-static
ppb	Parts-per-billion
HVAC	Heating, Ventilation, and Air Conditioning
PM	Particulate Matter
VOC	Volatile Organic Compounds
PCO	Photo-catalytic oxidizer
UV	Ultra-Violet
EPA	Environmental Protection Agency
FDA	Federal Drug Agency
BL	Boundary layer
I/O	Indoor/Outdoor
ACH	Air changes per hour
CARB	California Air Resources Board

## ACKNOWLEDGMENTS

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#### ABOUT STUDENT AUTHOR

Giovanni Cerrato is a recent graduate from the University of Texas (UT) at Tyler. He graduated with a bachelor's degree in mechanical engineering and will seek his master's degree in mechanical engineering at UT Tyler in the academic school year of 2022-2023. He plans to continue to do research in the space of indoor air quality and will seek to work in the HVAC industry.

#### PRESS SUMMARY

This study reveals the contributions of two electrostatic air cleaners (installed in an HVAC system) in raising ozone levels in a test home by releasing ozone as a by-product. Both electrostatic air cleaners contributed to raising ozone levels, however neither raised the ozone levels above the indoor limit of ozone set by FDA standard 21CFR801.

#### APPENDIX A – OZONE MONITOR ZERO CHECK

To ensure the quality of the ozone monitor data, the ozone monitor was periodically zeroed out throughout the experiments. The zero check was performed by zeroing the ozone monitor around a reference point of zero ozone with the use of an ozone scrubber provided by the manufacturer (see **Figure 1A**). The ozone scrubber was attached to the ozone monitor reading input (see **Figure 2A**). The ozone monitor was then calibrated to read 0 ppb with the ozone scrubber on. The ozone scrubber was then removed to make readings, and the calibration is complete.



Figure 1A. Ozone scrubber.

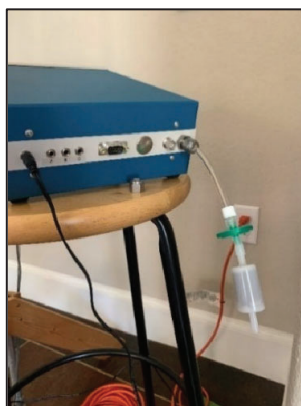


Figure 2A. Ozone scrubber attached to ozone monitor.



**APPENDIX B - JUSTIFICATION FOR THE HORIZONTAL AND VERTICAL PLACEMENT OF THE OZONE MONITOR**

The location of the ozone monitor was determined as the result of a stratification test and a test that measured the critical point of ozone in the test house. The ozone monitor was placed on a stool at the center of three bedrooms and set to read indoor ozone levels. The results are shown in **Table 1B**.

Room	Ozone (ppb)
Master Bedroom	2.8
Bedroom 2	2.9
Bedroom 3	2.7

**Table 1B:** Critical point of ozone test

The room location of the ozone monitor seemed to minimally affect the ozone readings. For this reason, the sensor was placed in a centralized location in the house in the living room.

The stratification test measured ozone concentrations at different heights from the ground. The ozone monitor was raised in increments of 11.25 inches by being placed on ladder steps. The results are shown in **Table 2B**.

Height (Inches)	Ozone (ppb)
11.25	2.8
22.50	3.0
33.75	3.5
45.00	3.6
56.25	3.6
67.50	3.4

**Table 2B:** Stratification of ozone test

The critical point of ozone was around 45-56 inches from the ground. This is considered “waistline” level. For this reason, the ozone monitor was placed on a stool in that height range.